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Review of Mechanical Specifications of Sandwich Structures and its Applications

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Abstract

Researchers are working on developing sandwich beams and improve their mechanical properties because they are so important and widely used in many industries. This work provides a review of sandwich beams employed in structures in various aspects, including improving mechanical properties, fracture behaviour and energy absorption. Also, it looks at the bending, buckling, and vibration issues with sandwich beams. The main results of these researches are listed and compared.

Introduction:

Sandwich structures have several advantages over traditional monolithic structures, including their lightweight design, high specific strength, superior energy absorption performance, high specific stiffness and impact resistance. Sandwich structures are frequently used as load-carriers or functional components in industries such as automotive, aerospace, transportation and packing. Common sandwich constructions are made up of two thin faces and a lightweight core that retains the faces in their correct locations. The geometric requirements and the material of the core and face sheet, with addition to the core structure; all have an influence on the mechanical properties of sandwich construction. There is a major effect on the performance of sandwich beams by choosing a suitable core; hence, it has been carefully investigated [1]. Face sheets usually consists of composites or metals, whereas cores are lightweight materials such as corrugated core, honeycomb, metal foam, triangular lattice cores and pyramidal truss [2]. Composite sandwich structures are made up of non-metallic cores and fiber-reinforced composite face sheets , such as composite , polymer foam , balsa wood and honeycomb ,whereas metal sandwich structures are made up of metallic cores and metallic face sheets such as metallic corrugated plate, aluminium foam and aluminium honeycomb [3]. Excessive inter-laminar stresses cause sandwich structures to delaminate. Japanese researchers in the mid-1980s created a novel type of composite material named Functionally Graded Materials (FGMs), can now be employed in sandwich construction to improve structural performance. Functionally Graded Sandwich (FGS) structures can be made with a uniform variation in effective characteristics between layers, which eliminates the initial disadvantage of common sandwich structures [4]. Sandwich structures have been used in various technical sectors due to their excellent mechanical properties, such as high energy absorption and blast protection. Currently, difficult service conditions are becoming increasingly widespread, which increases the danger of damage under various stresses such as axial compression, localized impact and bending. The strength and stiffness of typical honeycomb sandwiches, in particular, require considerable improvement when subjected to bending loads [5]. In this research, a review of previous research in this field will be presented, as well as a comparison of the results of this research based on the classification of overlapping structures.

Composite Sandwich Structures

Composite Sandwich structures are very important in many industries due to their unique bending stiffness and strength values. These materials are particularly well suited to marine and aerospace applications due to their low weight and density. Composite Sandwich materials use a matrix as a base material and fibre as the reinforcement material to provide improved material qualities in any application. Because of their high stiffness to weight ratios and strength-to-weight, composite materials are commonly chosen. In various industries, control over fibre orientation and layers is enabled through composite materials. Many studies have been conducted in recent years to optimize mechanical performance and density ratios in order to give solutions for a wide range of applications [6].

(Balaban, Tee, et al. 2019) investigated the influence of various core thicknesses and densities on the strain energy release rate (SERR) of a sandwich composite made up of an E-glass weave laminates and PVC foam core [6]. While (Maleki and Toygar 2019), studied the effect of core thickness and density on the fracture behaviour of glass-epoxy woven sandwich composites at various temperature ranges [7]. Both studies concluded that increasing core density and core thickness leads to an increase in SERR as indicated in **Figures (1,2, 3, and 4)** and **Tables (1 and 2).**

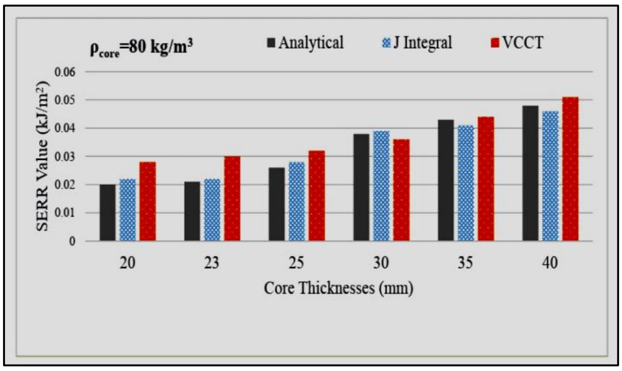

Fig. 1. Numerical and analytical results of (J Integral and VCCT) for specimens having ρ core=80kg/m3. [6]

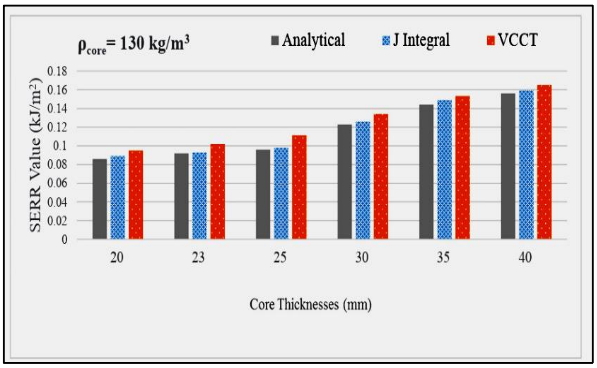

Fig. 2. Numerical and analytical results of (J Integral and VCCT) for specimens having ρ core=130kg/m3. [6]

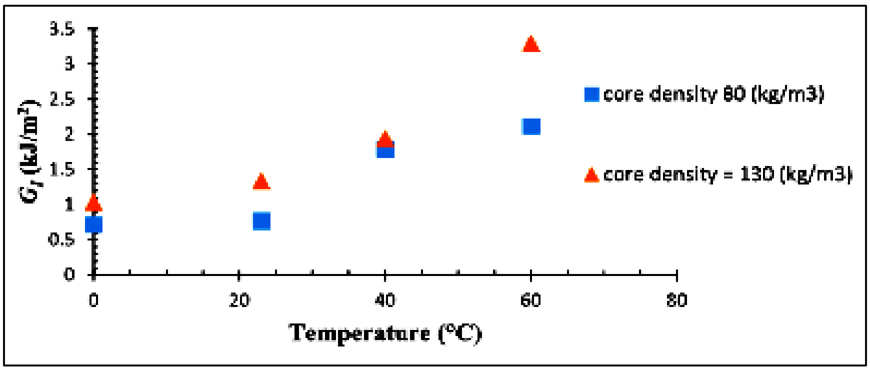

Fig. 3 .Effect of core density on the average SERR value of single cantilever beam (SCB) specimens of GFRP sandwich composites [7]

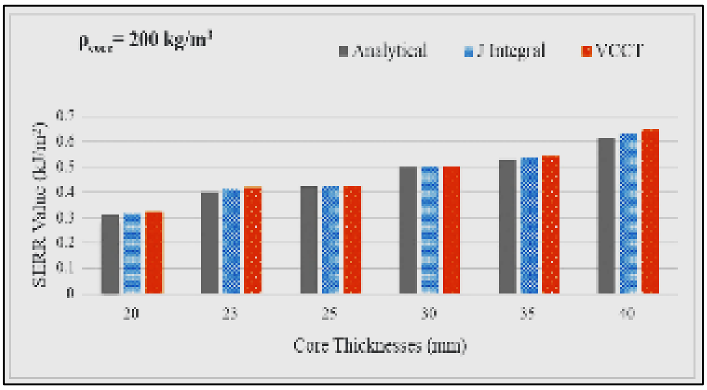

Fig. 4. Numerical and analytical results of (J Integral and VCCT) for specimens have ρ_{core}=200kg/m^3 [6]

Table. 1 SERR values of 20mm core thickness with two different core densities at different temperatures. [7]

Temperature (^{o}C)		0		23		40		60	
Core Density (kg m^{-3})		80	130	80	130	80	130	80	130
G_I (kJm^{-2})	First Specimen	0.74	1.11	0.84	1.29	1.64	2.03	1.86	3.65
	Second Specimen	0.65	0.85	0.79	1.16	2.04	1.94	2.12	3.26
	Third Specimen	0.76	1.14	0.65	1.40	1.72	1.86	2.37	2.26
	Fourth Specimen	_	_	0.79	1.50	1.97	_	_	4.01

TABLE 2. Numerical SERR values of sandwich composites with different densities. [6]

Core thickness (mm)	Numerical average SERR values (kJ/m^2) (J Integral vs VCCT)					
	ρ_{core} = 80 kg/m^3		ρ_{core} =130kg/ m^3		ρ_{core} =200kg/m^3	
	JINT	VCCT	JINT	VCCT	J INT	VCCT
20mm	0.022	0.028	0.089	0.095	0.317	0.324
23mm	0.022	0.03	0.093	0.102	0.41	0.420
25mm	0.028	0.032	0.098	0.111	0.422	0.434
30mm	0.039	0.036	0.126	0.134	0.501	0.512
35mm	0.041	0.044	0.149	0.153	0.535	0.542
40mm	0.046	0.051	0.159	0.165	0.632	0.647

(Selvaraj, Ramamoorthy et al. 2021) investigated the dynamic analysis of a three-layered sandwich beam with a core of multiwall carbon nanotubes reinforced magnetorheological elastomer (MWCNT-MRE) and thin orthotropic face sheets [8]. But in other research for them (Selvaraj, Ramamoorthy et al. 2022), analysed the free vibration for the sandwich beam made of magnetorheological elastomer reinforced by carbon nanotube (CNT-MRE) [9]. The experimental results of the free vibration indicated that the damping factors and natural frequencies for both CNT-MRE [9] and MWCNT-MRE [8] are greater than those for the MRE beam due to the usage of carbon nano tubes in MRE influences the chain-like structure, enhancing the damping characteristics and the stiffness of the sandwich structure.

(Selvaraj, Subramani et al. 2021), evaluated the double-core sandwich composite beam dynamic responses utilizing experimental and numerical approaches [10]. (Selvaraj, Gupta et al. 2021) investigated the behaviour of vibration of laminated composite sandwich beams of multicores using both numerical with experimental methods [11]. Also, (Thanikasalam and Ramamoorthy 2023), examined experimentally and numerically the vibration properties of a laminated composite sandwich beam having a dual honeycomb core [12]. Their results showed that the multi-core and dual sandwich beams have higher natural frequencies than the only one-core sandwich beams under various end conditions for all of the modes. In addition, multi and dual-core sandwich composite beam's stiffness has been demonstrated to be affected by numerous factors, including, ply angle orientations, end conditions and core thickness. Furthermore, in terms of the core thickness, it proved that increasing the thickness of the core layer leading to a significant improvement in the rigidity of the multiple and double-core sandwich beam, which therefore raised the natural frequencies, even if by a slight amount. According to the orientation of the composite face sheets, the greatest natural frequencies under different end conditions for all configurations of multi-core sandwich beams have been displayed from the ply angle orientation [0/0/0/0] because this orientation gives the highest stiffness in the laminate structure. The clamped-clamped condition exhibits higher stiffness than the clamped free condition. The results of these researches are showed in **Tables (3 and 4)** and **Figure (5)** bellow:

Tables 3. Core thickness ratio effect on the first five frequencies (Hz) for sandwich composite beam with double-core. [10]

End conditions	Natural frequencies (Hz)			
	Core thickness ratio			
	0.2	0.4	0.6	0.8
Clamped-Clamped condition	354.2	352.45	351.68	351.38
	773.64	772.14	771.54	771.32
	1265.2	1263.2	1262.4	1262.1
	1784.5	1781.1	1779.9	1779.4
	2321.4	2314.7	2312.4	2311.6
Clamped free condition	77.595	76.127	75.437	75.167
	386.08	382.81	381.31	380.73
	873.78	869.61	868.09	867.5
	1395.65	1392.2	1392.3	1392
	1936.2	1933.1	1932	1931.6

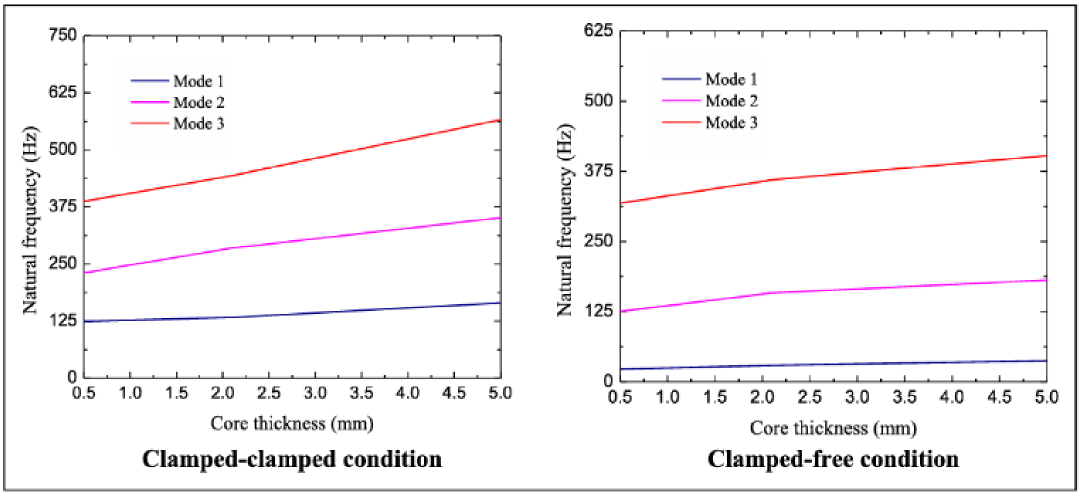

Fig.5 Influence of using different core thickness on the natural frequency of the multi-core L-R-L-R-L sandwich beam under clamped clamped and clamped free condition.[11]

Table 4. Influence of core thickness on the DC sandwich beam's natural frequencies. [12]

		Natural frequencies (Hz)			
		Core thickness, $h_c(mm)$			
Support Conditions	Modes	2	3	5	6
Cantilever	1	51.50	64.65	88.74	99.78
	2	293.74	354.44	454.72	496.69
	3	729.83	850.20	1040.83	1118.53
	4	1251.03	1416.23	1674.50	1778.46
	5	1813.84	2011.04	2322.60	2448.50
Fixed	1	188.60	231.67	306.14	338.47
	2	484.74	580.02	735.21	799.36
	3	878.94	1027.54	1262.15	1357.25
	4	1338.23	1534.31	1840.62	1964.06
	5	1841.72	2078.51	2449.07	2598.36

Sreekanth, Senthilkumar et al. (2021) used an Artificial Neural Network (ANN) to evaluate delamination by utilizing the natural frequency as a vibration parameter. Finite Element Analysis is used for producing the information needed for the ANN. Finite element models and actual modal analysis have confirmed the frequency-based delamination prediction technique. Their results illustrate that the ANN-based back propagation technique can accurately forecast the magnitude in addition to position of delamination in composites with a high degree of accuracy for the data of numerical natural frequency, but the accuracy is relatively lower for the data of experimental natural frequency [13]. On the other hand, the same researchers (Sreekanth, Senthilkumar et al. 2022) used Response Surface Methodology (RSM) and ANN to estimate delamination based on natural frequency in glass fibre reinforced polymer (GFRP) beams. The study most likely investigates the use of RSM in addition to ANN for delamination estimation, which can be considered as an extension and development of their previous research and thus a comparison between both studies. The ANN-based prediction model performs reasonably well in predicting experimental results. Compared to RSM, ANN is a better and more precise modelling method because it more accurately represents nonlinearities [14].

Metallic Sandwich Structures

The metallic sandwich structure is a novel engineering concept at the lowest cost of self-weight with excellent bending stiffness. By using a composite arrangement with two metallic face sheets separated by a lightweight core, it achieves a higher moment of inertia per unit mass. Because of this greater feature, a wide range of an engineering applications, including warships, automobiles and aircraft to effectively balance the conflict between the load capacity and self-weight by using sandwich design [15].

(Zhang, Zhu et al., 2022) investigated the energy absorption and failure behaviour of sandwich beams with Glass Laminate Reinforced Epoxy face-sheets and aluminium honeycomb core under three-point bending, using both experimental and numerical approaches. It was demonstrated that increasing honeycomb wall-thickness, the face-sheet thickness, the elasticity effect of metal materials and ratio of the core height to span length or decreasing the honeycomb cell's side length can enhance the energy absorption and load-carrying capacity of GLARE sandwich beams [16]. While (Zhang, Huang et al. 2023) used experimental and numerical methods to study the failure behaviour of sandwich beams with aluminium foam core and glass fibre-reinforced epoxy/aluminium laminates (GLARE) face sheets under three-point bending, it is demonstrated that the energy absorption and peak loads for GLARE sandwich beams increases with a reduction of span length and increase of the foam strength and face-sheet thickness. The effects of the face sheet fibre laying angle and the foam elastic modulus are quite small [17]. In conclusion, both studies investigated the sandwich beams failure behaviour by three-point bending; however, the materials chosen for the face-sheets and core differ. Both research shed light on the behaviour of sandwich beams under three-point bending, contributing to a better understanding of sandwich and thin-walled structures as shown in **Figures (6, 7, 8, and 9)**

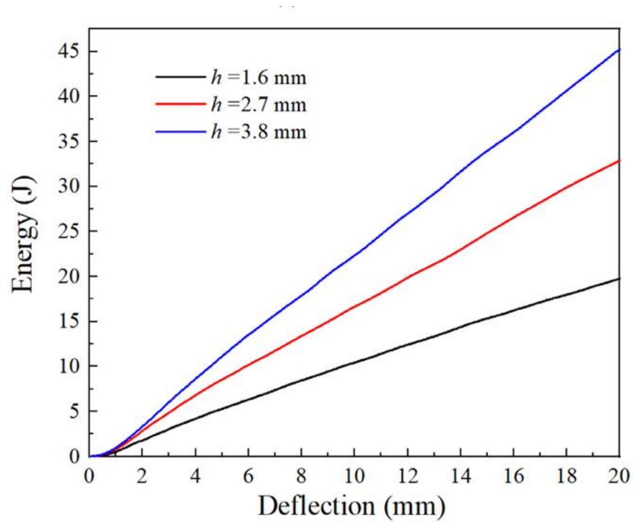

Fig 6. Effect of face-sheet thickness on the absorbed energy–displacement curves of GLARE sandwich [16]

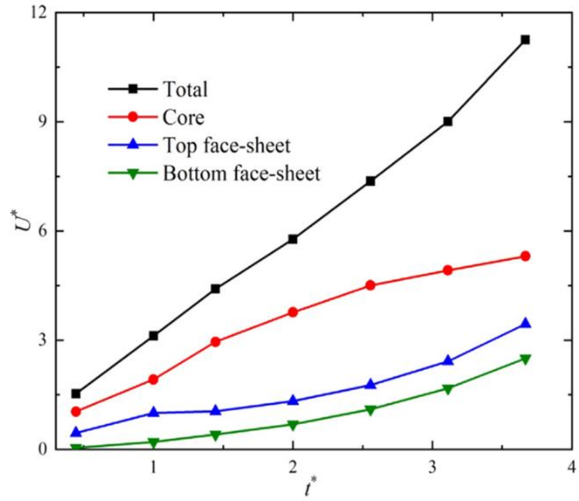

Fig 7. Relation between face-sheet thickness t and energy absorption U of sandwich beams components have GLARE face-sheets and aluminium foam core [17]

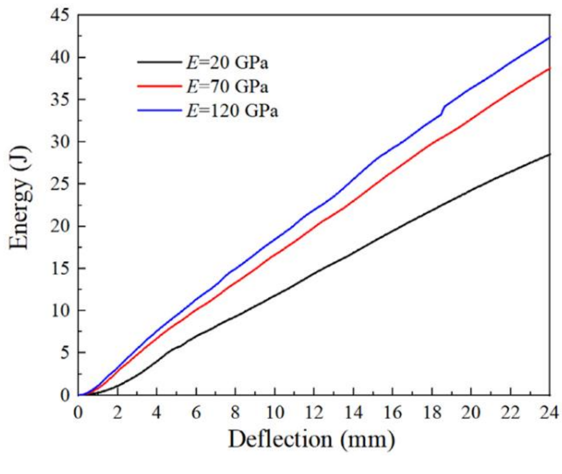

Fig 8. Elastic effect on the curves of absorbed energy–displacement for GLARE sandwich beams. [16]

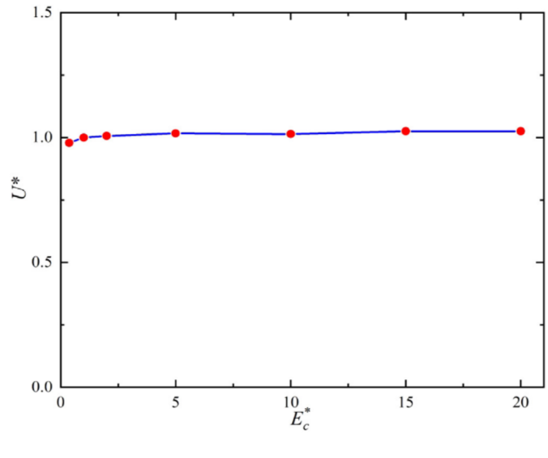

Fig 9.   Relation between face-sheet thickness t and energy absorption U of foam E_c curve for sandwich beams components have GLARE face-sheets and aluminium foam core. [17]

(Zhang, Ye et al. 2018) studied the low-velocity impact for the sandwich beams with a metal foam core and face-sheets of fibre-metal laminate that is fully clamped and struck by a large mass. For the given deflection it's found that, the sandwich beam’s impact force p_r increased when the effect of metal volume fraction f increased, and for the initial kinetic energy given, when the metal volume fraction f increased the peak deflection decreases, as shown in Fig.6(a) and(b). also The impact force increases as the composite volume fraction increases (figure 7) [18]. While (Yuan and Zhang 2022) examined, both theoretically and numerically, the effects of the low-velocity impact for thin multilayer sandwich beams made of metal foam cores and fibre-Metal Laminate (FML) face sheets. It is found that, as indicated, the dimensionless load increases with rising f, and the dimensionless maximum deflection decreases with rising dimensionless impact energy as shown in Figures 7(a) and 7(b). The dynamic response of sandwich beams with multilayer FML foam is affected by the strength ratio of the metal layer to the composite layer (q), as shown in **Figures (10, 11, 12, and 13**- (a) and (b)) [19]. Where, P_r^*: non-dimensional impact force, W_o^*: maximum deflection of the bottom face -sheet, U_K: the initial kinetic energy of the striker, W_{om}^*: the non-dimensional maximum deflection.

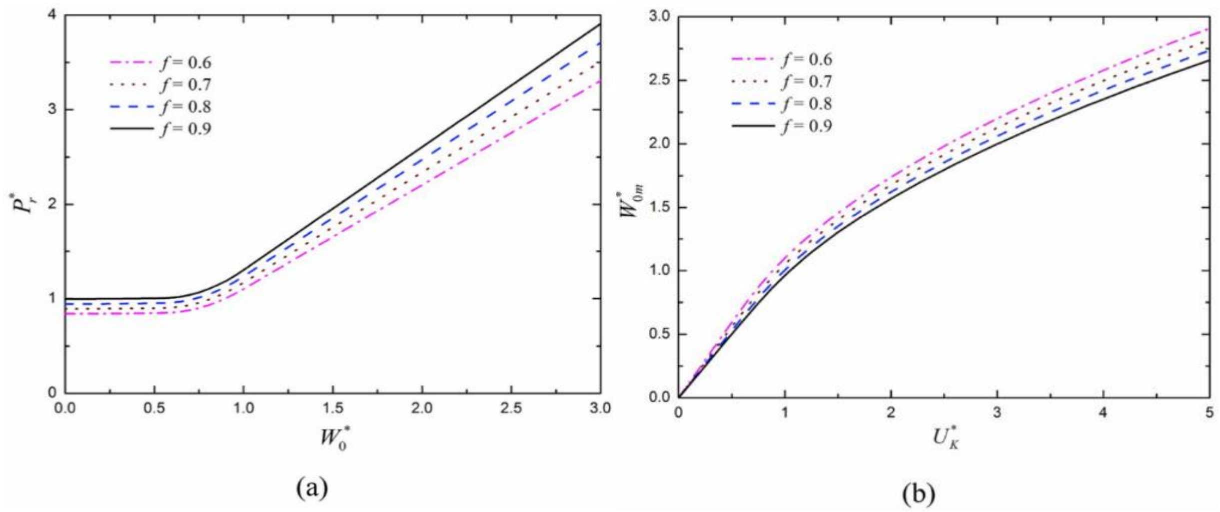

Fig 10. The impact of fully clamped sandwich beams with fiber-metal laminate face sheets at low velocities (=0.04 c, = h 0.4, = n 3, = f 0.6, = G 100) is affected by the metal volume fraction (f). (a) normalized impact force (P^*_r) versus normalized maximum deflection (W^*_o), and (b)Normalized maximum deflection (W^*_{mo}) versus normalized initial kinetic energy of the striker (U^*_k). [18]

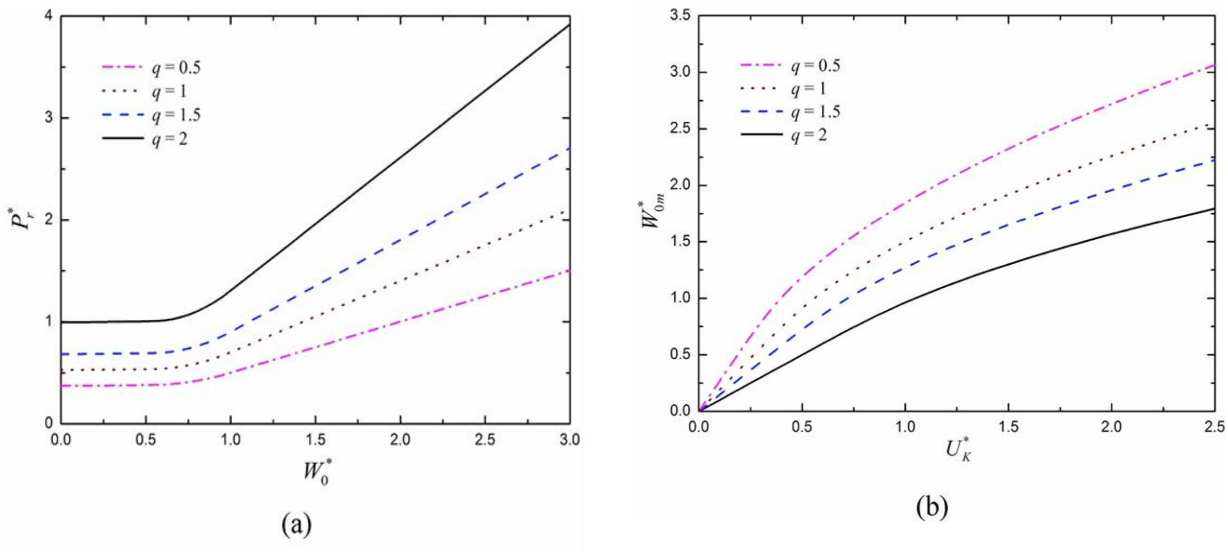

Fig 11. Influence of the ratio q between the strength of the metal layer and the composite layer on the low-velocity behaviour of fully clamped sandwich beams with face-sheets (c =0.04, h 0.4,= n 3, f = 0.6 G 100). Normalized maximum deflection versus normalized initial kinetic energy of the striker, and (a) normalized impact force versus normalized maximum deflection.[18]

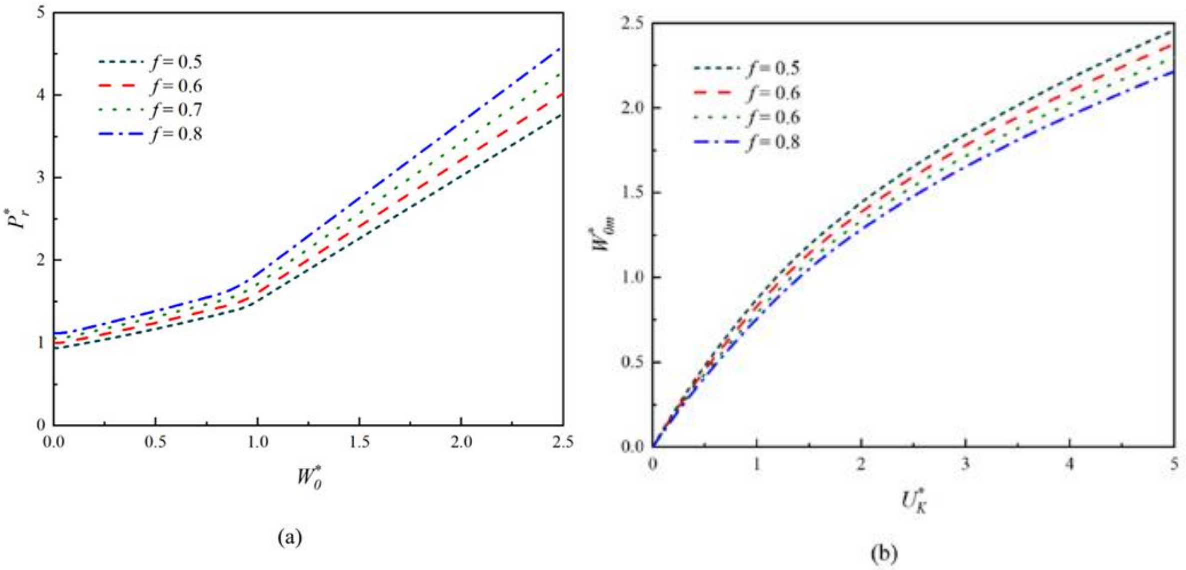

Fig 12. The effect of the metal volume fraction f on the multilayer FML foam sandwich beams' dimensionless load versus dimensionless deflection curves (a) and dimensionless maximum deflection versus dimensionless impact energy curves (b). [19]

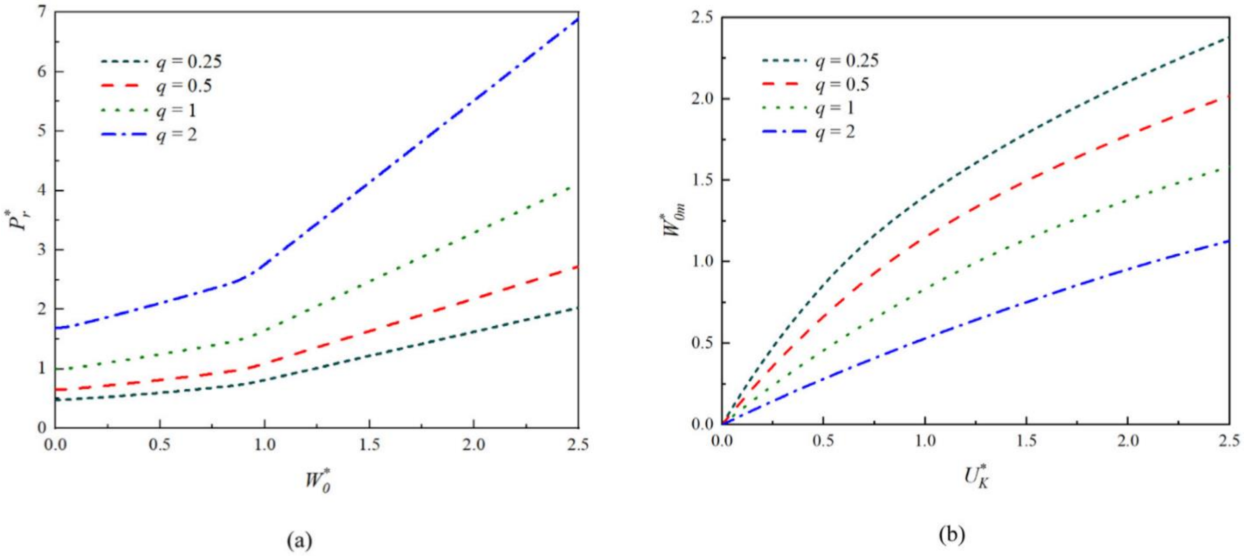

Fig. 13. The effect of the metal to composite layer strength ratio (q) in FML face sheets on the dimensionless load versus dimensionless deflection and the dimensionless maximum deflection versus dimensionless impact energy of multilayer FML foam sandwich beams were studied [19].

(Taghipoor and Noori 2018), performed a numerical and experimental investigation on energy absorption by a sandwich beam of lattice-core. The findings revealed that raising the expanded metal cell's size within a suitable limit was necessary to improve the performance of the structure during bending collapse. It was discovered that the cell size and the number of core layers were significant elements controlling the response of quasi-static for the lattice cores sandwich beams [20] .While (Taghipoor, Eyvazian et al. 2020) investigated the energy absorption and collapse behavior of a rigid polyurethane foam-filled sandwich beam with expanded metal sheets as the core, it was revealed that the polyurethane foam reinforcement could elevate the sandwich beam's energy absorption by up to 80 percent. The appropriate orientation of the lattice sheets in the core may increase energy absorption by 74.6%. The amount of specific energy absorbed increases as cell size increases. it was discovered that increasing the size of the cells in the expanded metal sheet core of the sandwich beam resulted in increment of specific energy absorption. The study discovered that bigger cell sizes resulted in greater values of specific energy absorption, implying that the geometric characteristics of the core cells had a major influence to the energy absorption capacity of the sandwich beam [21].

(Zhang, Qin, et al. 2016) looked into the initial plastic failure of completely clamped geometrical asymmetric metal foam core sandwich beams. they investigated the initial failure modes, maps of failure mechanism for these sandwich beams according to analytical formulae for initial failure loads and other specified conditions . they integrated experimental findings with mathematical equations to explore the initial failure modes and procedures of completely clamped geometrical asymmetric sandwich beams. It provides insights into the distinctions between fully clamped and simply supported sandwich beams [22]. In comparison, the study by (J. Zhang et al.) in 2014 explicitly studies the failure behavior of geometrically asymmetric metal foam core sandwich beams under three-point bending. The focus is on the behavior of these sandwich beams under a particular loading condition of three-point bending. On the other hand, they concentrated under three-point bending on the failure behavior, without a deeper examination into the initial failure modes and mechanisms. [23].

(Zhang, Qin, et al. 2016) concluded that the sandwich beam's initial failure modes are determined via their shape and material properties. Face yield, core shear and indentation have been considered to be the main first modes of the failure for asymmetric beams that is fully clamped. Due to the end limitations in completely clamped sandwich beams, mode B of the core shear became dominant. In sandwich beams that is simply supported, failure modes identified included face yield and combined indentation, indentation and combined core shear, face wrinkling,, indentation and face yield. Core shear failure modes included core shear modes A and AB regions.

(J. Zhang et al. in 2014), demonstrated that the material qualities, core height, thicknesses of top and bottom face sheets and span of the beam are considered the foundation on which the initial failure modes of sandwich beams are based.

(Wang, Yu et al. 2022), stated metal foam core sandwich beams that is physically asymmetric, and the failure modes identified were five, including face yield, core shear (Type A) and (Type AB) and (Type A-AB), indentation in the three-point bending tests [24]. In contrast (Yuan, Zhang et al. 2022), evaluated the failure behavior of sandwich beam with double-layer metal foam under three-point bending. Core shear, indentation and face yield are the three main failure types identified. Also, core shear , indentation, the combined indentation and face yield respectively [25].While there may be some similarities in the failure modes observed in the two studies, the specific types and characteristics of the failure modes may differ due to the differences in the sandwich beam configurations and loading conditions.

The results from (Wang, Yu et al. 2022) demonstrate that the initial failure modes of double-layer sandwich beams are significantly influenced by the thickness values of the face-sheets and cores. In sandwich beams with two layers, face yield is the main initial failure mode at low ratios of core thickness (c) to span thickness (L). When (c/L) increases, the face-sheet thickness determines the double-layered sandwich beam's initial failure mode. The double layered sandwich beam's main initial failure mode is indentation, Within a certain face-sheet thickness. As the thickness of the face sheet rises, the failure mode is coupled core shear and indentation. The double-layered sandwich beam's main initial failure mode is core shear, When the face-sheet thickness is big enough as indicated in Table (5).

while the results were obtained from (Yuan, Zhang et al. 2022) and as can be illustrated from Table (6) indicates that, sandwich beams that is physically asymmetric with a steel loading face (SL) primarily fail due to indentation, If the core was effectively thick. Nonetheless, indentation was achievable for the specimens of aluminium alloy loading faces (AL) with different core thicknesses. Face yield frequently happened to specimens with comparatively long spans and thin cores. Core shear is typically the mode of failure when the face was relatively thick and the span was relatively short.

Table. 5. Details of the physically asymmetric sandwich be specimens. [24]

Label	h(mm)	c(mm)	l(mm)	L+2 $l_H(mm)$	c/l	h/c	Failure mode	$P_{measured}(N)$	$P_{Predicted}(N)$	Error (%)
SL-C2-1	1.8	35	224	280	0.156	0.051	IN	3866.7	3386.2	12.4
SL-C2-2	1.8	36	224	280	0.161	0.050	IN	3110.0	3386.2	8.9
SL-C2-3	1.8	34	224	280	0.192	0.042	IN	3120.8	3386.2	8.5
SL-C2-4	0.89	12	384	480	0.031	0.074	FY	696.3	635.3	8.8
SL-C2-5	1.8	20	392	490	0.051	0.090	FY	2092.0	2097.5	0.3
SL-C2-6	2.86	16	104	130	0.154	0.179	CS(A)	4273.0	3108.6	27.3
SL-C2-7	2.86	16	120	150	0.133	0.179	CS(A)	3633.0	2978.6	18.0
SL-C2-8	2.86	23	200	250	0.115	0.124	CS(A)	3289.7	3573.8	8.6
SL-C2-9	2.86	25	152	190	0.164	0.114	CS(A)	3497.0	4000.6	14.4
SL-C2-10	2.86	18	248	310	0.073	0.159	CS(AB)	2062.1	2773.5	34.5
SL-C2-11	2.86	20	248	310	0.081	0.143	CS(AB)	2795.2	3013.5	7.8
SL-C2-12	2.86	33	248	310	0.133	0.087	CS(AB)	3460.8	4573.5	32.2
SL-C2-13	2.86	34	248	310	0.137	0.084	CS(AB)	3732.6	4693.5	25.7
SL-C2-14	2.86	36	246	310	0.145	0.079	CS(AB)	4197.5	4933.5	17.5
SL-C2-15	2.86	22	200	250	0.11	0.130	CS(A-AB)	3488.7	3537	1.4
SL-C3-1	0.89	30	248	310	0.121	0.030	IN	2818.6	2050.6	27.2
SL-C3-2	0.89	31	248	310	0.125	0.029	IN	3111.2	2050.6	34.1
SL-C3-3	1.8	34	312	390	0.109	0.053	IN	4192.5	4147.2	1.1
SL-C3-4	1.8	35	312	390	0.112	0.051	IN	4208.7	4147.2	1.5
SL-C3-5	1.8	43	224	280	0.192	0.042	IN	4271.0	4147.2	2.9
SL-C3-6	2.86	42	240	300	0.175	0.068	IN	5366.4	6589.4	22.8
SL-C3-7	2.86	43	240	300	0.179	0.067	IN	7003.2	6589.4	5.9
SL-C3-8	0.89	12	384	480	0.031	0.074	FY	712.7	665.8	6.6
SL-C3-9	0.89	13	384	480	0.034	0.068	FY	784.5	725.2	7.6
SL-C3-10	1.8	20	392	490	0.051	0.090	FY	2194.4	2180.9	0.6
SL-C3-11	2.86	17	120	150	0,142	0.168	CS(A)	4670.4	4245.2	9.1
SL-C3-12	2.86	23	200	250	0.115	0.124	CS(AB)	4866.1	4900.7	0.7
SL-C3-13	2.86	15	120	150	0.125	0.191	CS(A-AB)	4232.9	4006.1	5.4
SL-C3-14	2.86	20	120	150	0.167	0.143	CS(A-AB)	5342.5	5006.1	6.3
SL-C3-15	2.86	21	120	150	0.175	0.136	CS(A-AB)	5391.4	5206.1	3.4
SL-C3-16	2.86	25	152	190	0.164	0.114	CS(A-AB)	5221.1	5794.3	11.0
SL-C3-17	2.86	26	152	190	0.171	0.110	CS(A-AB)	5782.0	5994.3	3.7
AL-C2-1	1.8	20	392	490	0.051	0.090	IN	2266.8	2212.2	2.4
AL-C2-2	1.8	25	312	390	0.08	0.072	IN	2435.4	2212.2	9.2
AL-C2-3	1.8	35	224	280	0.156	0.051	IN	2087.7	2212.2	6.0
AL-C2-4	1.8	36	224	280	0.161	0.050	IN	2654.8	2212.2	16.7
AL-C2-5	0.89	13	384	480	0.034	0.068	FY	719.4	689.6	4.1
AL-C2-6	2.86	21	176	220	0.119	0.136	CS(AB)	4225.6	3384.4	19.9
AL-C3-1	1.8	19	216	270	0.088	0.095	IN	3327.4	2709.3	18.6
AL-C3-2	1.8	20	392	490	0.051	0.090	IN	2420.8	2709.3	11.9
AL-C3-3	2.86	20	248	310	0.081	0.143	IN	3413.4	4304.8	26.1
AL-C3-4	2.86	21	248	310	0.085	0.136	IN	3596.8	4304.8	19.7
AL-C3-5	2.86	26	152	190	0.171	0.110	IN	5338.9	4304.8	19.4
AL-C3-6	0.89	14	384	480	0.036	0.064	FY	905.3	786.0	13.2
AL-C3-7	2.86	15	104	130	0.144	0.191	CS(A)	4477.5	3975.3	11.2
AL-C3-8	2.86	17	120	150	0.142	0.168	CS(A)	4584.9	4245.2	7.4
AL-C3-9	2.86	17	216	270	0.079	0.168	CS(AB)	3870.7	3764.4	2.7
AL-C3-10	2.86	20	176	220	0.114	0.143	CS(AB)	4428.4	4464.4	0.8

Table 6. The critical failure loads and Initial failure modes of specimens [25]

Specimen	t (mm)	C(mm)	Experimental failure mode	Experimental load (N)	Analytical load (N)
1-1	0.5	5	FY & IN	767.1	708.4
1-2	0.5	5	FY & IN	739.7	708.4
2-1	0.5	15	IN	1028.4	801.4
3-1	0.5	25	IN	1377.7	801.4
4-1	1	13	IN	1544.5	1602.8
4-2	1	13	IN	1656.7	1602.8
5-1	1	23	IN	2119.6	1602.8
6-1	2	13	IN & CS A-AB	2924.4	3205.6
6-2	2	13	CS AB	2963.4	3205.6
7-1	2	23	IN	3382.1	3205.6
8-1	3	13	CS A-AB	3739.4	4810.3
9-1	3	23	IN	4598.8	4808.4

IN denotes indentation, FY denotes face yield, and CS denotes core shear.

FGM Sandwich Structure

Functionally Graded Materials (FGMs) are different kinds of materials that are often created from a combination of various components. Unlike conventional homogeneous materials, the volume fraction of FGMs can be engineered to progressively alter from one surface to another, enabling the smooth and continuous variation of physical attributes in selected directions by utilizing pertinent mathematical principles, including mass density, elastic modulus, stiffness, toughness, and mechanical strength, among others. Sandwich structures, which have been around for a century, are widely used today and have drawn a lot of attention from academics recently because of their remarkable performance. As yet another cutting-edge composite construction [26].

(Liu, Hao et al. 2021) studied using the Scaled Boundary Finite Element Method (SBFEM) the forced and free vibrations of (FGM) sandwich beams. The scaled boundary finite element method was employed as the governing formulation. The virtual work principle is used to build the second-order homogeneous differential equations for the beams, with radial coordinates serving as independent variables. The forced as well as free vibrations of (FGM) sandwich beams were solved utilizing the state space approach, the virtual work concept, Padé series expansion method and newmark time integration method respectively. The governing equations were solved using two methods: the method of the Padé series expansion in addition to the state space approach. This research found that the effect of changes in the material property on dynamic response produced by various parameters can be efficiently realized using the present method, demonstrating the method's stability [26].

(Srikarun, Songsuwan et al. 2021), performed nonlinear and linear bending studies sandwich beams with functionally graded cores under different kinds of distributed loads. These sandwich beams are made up of a porous core and two isotropic skins with varying interior porosity. Flexural stiffness has been discovered to be reduced when beams have interior pores. The governing formulations were von K'arm'an's nonlinear strain-displacement relations, Reddy's third-order shear deformation theory with the Ritz method employed to obtain the results. As a result, beams with functionally graded porous cores exhibit a greater deflection compared to beams without pores. Furthermore, beams under uniform distributed load display greater deflection than beams under other loads because the overall magnitude of a uniform distributed load is greater than linear, parabolic and sinusoidal distributed loads. And the nonlinear deflection is less than the linear deflection [27].

Le et al. (2021) propose a third-order shear deformation beam element for analyzing buckling as well as free vibration in bidirectional functionally graded sandwich beams (FGM). These beams are made up of triple layers: two face sheets and an axially functionally graded core using power-law distributions, material properties change in thickness and length directions. Material characteristics fluctuate in length and thickness directions due to power gradation laws. Two micromechanical models, the Mori-Tanaka scheme and the Voigt model are used to predict these properties. The Voigt model consistently produces larger natural frequencies and buckling loads than the Mori-Tanaka scheme, but the micromechanical model has a lesser influence on big power-law indexes [28].

(Njim, Bakhy et al. 2022), investigated sandwich beam's bending study that is made up of porous core with varying gradients of internal pores and two isotropic faces. The governing formulation was classical beam theory. The material properties were determined using the mixing rules. In regards to the power-law concept, the material properties of functionally graded beams should change along the thickness direction of the constituents. The findings demonstrate that the loads of bending drop with rising porosity factors and rise with rising gradient indexes. While the dimensionless deflection parameter for both the imperfect and perfect sandwich plate FGM grows with the power-law index value [29].

(Li, Shen et al. 2022), examined the improvement of the impact resistance of the drop-weight of composite sandwich beams with nanocomposite face sheets by making use of functionally graded (FG) topologies auxetic 3D lattice cores. Auxetic 3D lattice cores sandwich beams exhibit significantly lower dynamic deflections and transitory thickness drops. In addition, the NPR of the 3D lattice cores has special value that increases the resistance of the impact. The dynamic behavior of composite sandwich beams is significantly influenced by the section radii of the struts of 3D lattice cores [30].

(Garg, Chalak et al. 2022), examined the free vibration and bending of functionally graded carbon nanotube-reinforced sandwich beams by using finite element-based higher-order zigzag theory. The faces are expected to be composed of functionally graded reinforced carbon nanotube (FG-CNTR) composite, while the core is expected to have been made from balsa wood (softcore). It was concluded that increasing the amount of carbon nano tube (CNT) improved the beam's bending behavior. The nondimensional deflection and stresses rise as the core thickness increases. Further in face sheets increasing the amount of carbon nanotubes (CNTs), reduces the non-dimensional natural frequencies [31].

(Aslan, Noori et al. 2023), studied the analysis of the free vibration of functionally graded sandwich beams of variable cross-section using an effective numerical method. They also conducted detailed parametric studies illustrating the geometric constants, influence of layers, beam slenderness and indexes of the material volume fraction on the natural frequencies of functionally graded sandwich beams. The sandwich beam's faces are considered to be made of functionally graded materials, whereas the core of the beam is assumed to be formed from homogeneous isotropic material. It has been found that the complimentary functions technique is able to efficiently and easily used to deal with the response of the free vibration of FG sandwich beams of variable cross-section [32].

(Van Lieu, Zenkour et al. 2024) provide an exact solution for the static buckling and static bending of functionally graded (FG) sandwich nanobeams with an auxetic honeycomb core layer using an analytical technique and this is the first research of its type. One noteworthy component of this research is the application of third-order shear deformation theory for calculation. It has been demonstrated that the precise solution can handle nanobeams with varied boundary conditions, making it a highly flexible and multiuse solution [33].

(Marandi and Karimipour 2023) used an extended high order theory to investigate the effects of carbon nanotube distribution pattern, as well as free vibration of the nanoscale FG-CNTRCs sandwich beam, volume fraction, the parameter of size dependency, boundary conditions, slenderness ratio and core thickness on vibration responses. the core layer was flexible, while The faces were made of PMMA and strengthened with single-wall carbon nanotubes. The skins used first-order shear deformation theory, whereas the core used high-order sandwich panel theory (HSAPT). For both skins and cores, the modified couple stress theory (MCST) was applied. The

Hamilton principle was utilized to construct equations and related boundary conditions. It was concluded that as the length scale parameter and skin thicknesses values increase, the natural frequencies increase, and as the core thicknesses and beam’s length increase, the natural frequencies decrease [34] .

(Zheng, Shen et al. 2024) studied the effects of nonlinear low-velocity impacts on sandwich beam constructions, which consisted of two aluminum alloy and a functionally graded (FG) porous aluminum core reinforced by graphene platelets (GPLs). The results demonstrate that including GPL in CAF can enhance the impact response. However, as the weight percentage of GPLs increases, the efficiency with which impact resistance is improved decreases. A 0.5% increase in w GPL from 0.5% to 1.0% yields a 2.33% gain, whereas a 2.0% increase from 1.0% to 3.0% yields a 7.24% gain. In addition, a higher core thickness can reduce the impact vibration cycle duration [35].

Conclusions

Based on the previous research mentioned in this Paper, the following conclusions can be reached:

1- The addition of carbon nanotubes increases the sandwich structure's stiffness and damping characteristics. In addition, increasing the amount of CNT increases the beam's bending behaviour.

2- For all end conditions and modes, the single-core sandwich beam have less natural frequencies than the dual and multi-core sandwich beams. In addition, many factors influenced the stiffness of the multi and dual-core sandwich composite beams, including, end conditions, core thickness and ply angle orientations. Furthermore, the thicknesses of the face sheets and cores have a substantial effect on the initial failure modes of double-layer sandwich beams.

3- The geometric parameters of the core cells significantly affect the sandwich beam’s energy absorption capacity and it was demonstrated that increasing the honeycomb wall-thickness, face-sheet thickness, the effect of elasticity of metal materials and the ratio of the core height to span length or reducing the side length of the honeycomb cell can enhance the energy absorption and the load-carrying capacity of GLARE sandwich beams.

4- The initial failure modes of sandwich beams are affected by the geometry, the thicknesses of the bottom and top skins, material characteristics of the sandwich beams, the beam span, and core height.

5- It has been discovered that when beams have internal pores, their flexural stiffness decreases. As a result, beams with a FG porous core deflect more than beams without one.

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