Journal of Mechanical Engineering Research and Developments ISSN: 1024-1752
CODEN: JERDFO
Vol. 44, No. 3, pp. 420-441
Published Year 2021

A Review of the Recent Research on the Experimental Tests of Functionally Graded Sandwich Panels

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ABSTRACT

Sandwich structures usually consist of high-strength thin skins bonded to a significantly thicker, less dense, and weaker core material. Sandwich structures are most useful in engineering applications because of their ability to provide stiffness to weight ratios, such as in many aerospace and marine applications and wherever flexural rigidity is essential and drives performance parameters. This study aimed to address these issues by investigating the existing literature on mechanical experiments and sandwich panels' recent tests. First, the survey of experimental testing of composite sandwich panels was analyzed. Second, a comprehensive study on structures made of functionally graded materials, which are the most attractive because of their lightweight and excellent energy absorption properties, was mentioned. Moreover, this article also reviews the development and application of FGM sandwich structures and different instruments and materials to demonstrate the procedures, arrangement techniques, and FGM sandwich panels' responses. Each test can be performed on a short and an extended sample or a sample loaded in two ways, and the bending stiffness and shear mode can be determined by solving the complete deflection equations for each span or each load simultaneously. It is expected that the study will provide some necessary data and design parameters related to impact, shear, and failure mechanisms, such as core height, materials, power-law index, and skin thickness. However, the experimental work on these technologies' practical application is still minimal, representing the main challenge and broad field of new research.

KEYWORDS

Composite sandwich panel, Experimental tests, Core shear stress, Flexural properties, Low-velocity impact, FGM sandwich structure.

INTRODUCTION

Due to their characteristics (low specific gravity, high bending strength, and rigidity, sandwich panels can be widely used in aerospace, automotive, naval transportation, and other fields. Such composite structures usually use a core made of rigid materials (metal, Carbon Fibre Reinforced (CFR) aminates)) and low-density materials (honeycomb construction, metal, ceramic, or polymer foam) [1-3]. The sandwich structure's mechanical properties usually depend on the face sheet, the inner core, the adhesive's bonding, and the geometrical dimensions [4]. Many authors and associates have described the mechanical behavior of composite sandwich structures in many articles [5-15]. The face sheets provide bending stiffness and strength to the panel, and the core function is to transmit shear forces between the face sheets. The core material controls the sandwich structure's response and failure under various load conditions [16]. Usually, the core is made of foam or balsa wood or made using corrugated, truss, or honeycomb structures. The corrugated core provides one-way support to the skin, while the honeycomb core provides two-way support [17-22]. The most commonly used honeycomb manufacturing materials are aluminum, polymers, and composite materials, such as Nomex [23]. C. Kyle Berkowitz and W. Steven Johnson studied fracture, fatigue testing of composite sandwich structures [24]. This work provides a comprehensive literature review of the current scientific knowledge about composite materials' experimental testing and functionally graded sandwich structures. It analyzes a wide range of research using various experimental techniques. Finally, the authors briefly outlined the composite sandwich structure's potential and challenges, accompanied by a checklist. They pointed out in the conclusion that they expect further research to be urgently needed.

MECHANICAL TESTING OF COMPOSITE SANDWICH MATERIALS

This section describes briefly experimental tests that are used to examine the behavior of sandwich panel, including but not limited to the following,

Tensile Testing

The tensile strength of the material mainly determines the mechanical characteristics of the composite sandwich structure. The tensile strength of composite materials largely depends on the bond strength between the matrix and the reinforcing material. According to ASTM C297/297M [25], a tensile test is performed on composite plastic materials; thus, the mechanical properties such as tensile strength, ductility, and elasticity parameters are evaluated [26-65]. Figure 1 shows the testing machine and the sample positioning for the tensile test [66].

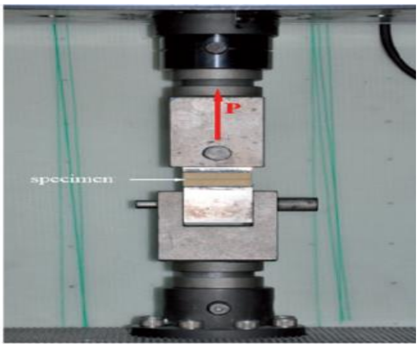


Figure 1. Tensile test of the sandwich panel, [66].

Flatwise Test

This test procedure includes the identity of the compressive strength and Young modulus of sandwich panels. Usually, these properties are generally determined perpendicular to the veneer plane for design purposes because the core material is mounted in the structural sandwich structure. This test's procedure mainly involves compression in this way, but possible small changes may also modify to determine the compression characteristics in other directions. According to ASTM C365/365M [67], each flat compression test is performed on three samples of 54×54×24mm3 at a 2 mm/min crosshead speed. Three models are used for each composite test type. In Fig. 2, a horizontally tested sample is observed [68].

Figure 2. Test setup.

Edgewise Test

The compression test describes the compressive features of the sandwich structures in the direction of movement, similar to the plane of the sandwich face [69]. According to ASTM C364 [70], each transverse compression test was performed on three samples with dimensions of (54×54×24) mm3 at a 2 mm/min crosshead speed. Figure 3 shows the loading device of the flatwise compression test of the straight-filled and pure polyurethane samples. Generally, during this test in the pure polyurethane core composite material, the composite material's energy absorption is higher due to the foam core's existence.

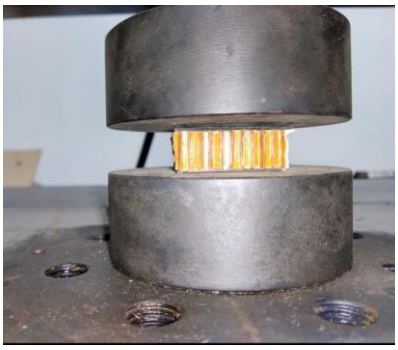


Figure 3. Loading device of the flatwise compression test.

Flexural Test

This test is usually used to study the sandwich panel's impact resistance and evaluate the bending performance. It gives the flexural strength and modulus of all types of materials and products [71]. A roller applies the load with a diameter (5mm) per ASTM standard C393-00 [72]. The crosshead speed is kept constant and selected as (4mm/sec). The displacement of the central loading point was monitored on a computer. Fig. 4 depicts a schematic of the three-point bending test.

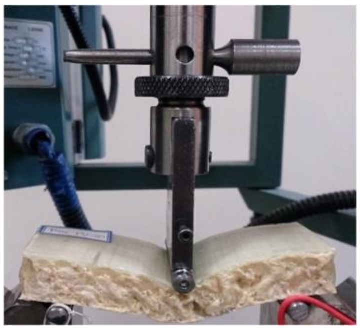
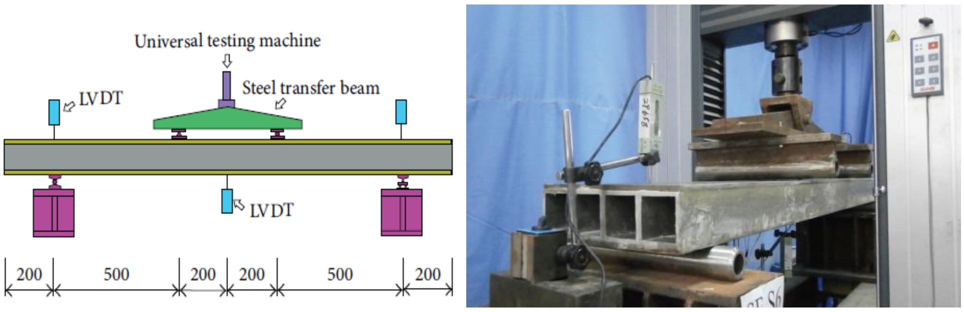


Figure 4. Three-point bending test polyurethane filled composites, [73].

Four-Point Bending Test

This test mainly evaluates the flexural rigidity and ultimate flexural strength of sandwich panels with other structures. According to the ASTM C393 [74], a 4-point static deflection test was performed on sandwich panels with various thickness cores (honeycomb, foam, aluminum, etc.). In this test, the sandwich panels bending stability was determined through the universal testing machine by applying a static load based on the experimental concept. Four-point bending tests are being performed to analyze the state of stress, strain, mid-surface deflection, and the structure's ultimate mode of failure. The schematic diagram and loading settings in the experiment are shown in Fig. 5 [75].



a. Four-point bending test b. Four-point bending machine

Figure 5. Schematic and Flexural test setup

Impact Test

A descending tower device with a free-fall mass (4.5 kg) is used to hit the wall panel (see Figure 6). The equipment can provide impact energy of 25-2000 J. The load cell measures the impact load. After release, the falling objects may fall along the two guide rails and through the thick plate's central hole, thus hitting the installation position. Due to the rebound brake, multiple shocks are avoided [76].

Figure 6. The drop tower apparatus.

RESEARCHES ON THE MECHANICAL TESTING OF SANDWICH PANEL

Sandwich structure composite material is a special kind of composite material. Its high specific strength and bending rigidity are usually used as structural panels for roofs, floors, walls, and floor bridges. Many studies have studied the performance of sandwich composite structures in flexural mode [77-80]. The top and bottom panels bear bending loads, while the inner core bears shear forces. Avery, J.L. and Sankar, B.V. [81] studied the compression failure of debonded sandwich beams. Demello et al. [82] studied the fatigue strength of a sandwich structure with Kevlar/epoxy composite surface, Nomex core, and rivet joints. Keun-Il Song et al. [83] conducted experimental work on the composite sandwich structure's inserted joint strength. Approximately 40 eight different types of sandwich samples were tested under pull-out loads to generate load-displacement curves. Herrmann et al. [84] Taking Airbus as an example, commercial aviation's sandwich technology was outlined. Frostig and Thomsen [85] analyze a three-point bending test effect of sandwich beams through experiments and compare with theoretical results. The mechanical behaviour and failure concept of sandwich composite beams proposed by Isaac and Gdoutos have been studied [86]. Zhou et al. conducted many experiments to study the effects of bending deformation and indenter shape, face sheet thickness, and core density of sandwich panels [87].

Reaching the ultimate compressive strength or tensile strength of the face sheet or the maximum shear strength of the core may fracture the sandwich element [88, 89]. Royer et al. [90] studied the influence of core thickness and intermediate layer on multilayer sandwich structures' mechanical properties, in which polypropylene honeycomb was used as the core material. Ana et al. [91] studied composite sandwich panels' experimental testing with different core and skin properties. Henrik Herranen et al. [92] investigated various types of sandwich composite panels tested under a four-point flexural environment based on ASTM D7250 and C393 [72,93]. Numerical modeling and experimental tests were carried out to prove that the shear effect improves the composite sandwich panel's stiffness and in-plane shear strength characteristics [94]. Hossein Taghipoor et al. [95] studied the mechanical properties of three types of steel grid cores, whether unfilled or foam-filled, all passed a quasi-static three-point bending test. The force-displacement relationship, the beam's collapse mode, and the impact parameters, including energy absorption, have been found. The results show that the polyurethane foam reinforcement can increase the sandwich beam's energy absorption by 80%.

Sudharshan et al. [96] A three-point bending test was performed on a sandwich beam made of a foam core and glass fiber layers on both sides, and then a finite element comparison was performed. However, some experimental work has been conducted to study many types of impacts in sandwich structures. These experiments are generally costly and time-consuming. Through experimental methods, numerical analysis such as the finite element method is widely utilized to simulate sandwich composite structures' impact response subjected to complex loads and with frequent configurations in [97-104]. Many studies have recently been conducted to examine the performance of sandwich wall panels [105-113]. Shipsha and Zenkert [114] conducted an experimental study in conjunction with a finite element model to predict sandwich panels' compressive strength on foam core. The result shows that sandwich panels' strength decreased with increasing impact velocity. Furthermore, the impact damage is mainly due to the foam core being broken and permanent dents appear on the face sheets.

Zhao et al. [115] proposed a detailed study to explore the effect of low-speed impact testing on the aluminum matrix composites lightweight plates. Based on the results obtained, it is noted that the impact will cause the failure mode to change. At the same time, compression failure strength is reduced by 10%. Chang Qi et al. [116] studied a new type of protection system's performance using a protective honeycomb core sandwich panel, which can alleviate the impact load caused by close explosions and contact high explosives. The on-site blasting test and the drop hammer test used the recommended sandwich as the concrete panel's protective layer combined with the conventional steel protective plate. Experimental work has been conducted on mechanical damage and sandwich metal honeycombs' energy absorption under dynamic loads [117-124]. S. Heimbs [125] investigated experimentally and numerically the sandwich structure's mechanical behavior with a folded core made of carbon-fiber-reinforced plastic under low-velocity impact loads. Hai Fang et al. [75] proposed a comprehensive study to examine sandwich panels' performance with GFRP cores and steel panels and obtain higher bending stiffness, strength, and ductility. Comparing the theoretical values, the experimental results, and the FEM simulation values seem very consistent. The effect of the steel plate panel's height on the mid-span deflection and stress is simulated. The graphic shows that when the steel skin's height increases, the deformation and stress decrease, while the decent speed decreases. It is recommended to use the most effective steel skin thickness.

V. Rubino [126] proposed measuring the quasi-static three-point bending stiffness of simply supported and clamped beams mounted on a rigid base. The results show that for all the structural configurations adopted, the simply supported beam's dynamic response is higher than the starting load. In contrast, the clamped beam shows a strengthened reaction due to the significant ductility of the panel. Ashby et al. [127] examined a simply supported sandwich structure response to a three-point bending behavior of a foam core metal. McCormack TM [128] studied the failure of sandwich beams with a metal foam core. In [129], the research on measuring and analyzing the honeycomb metal sandwich structure's structural performance has been completed. The same work has been done for the truss core [130]. Similarly, the static response of the clamping beam of the square honeycomb core [131] and the foam metal core [132] has also been solved. Valdevit et al. [133] proposed an evaluation to check sandwich panels' structural performance with corrugated cores. Kuldeep P.Toradmal et al. [134] studied three-point bending analysis of honeycomb sandwich panels experimentally to investigate the failure loads.

Ghanshyam G. Tejani [135] conducted various experiments tests such as bending test, tensile test, and sandwich panel composite materials. For sandwich panel composite materials, two core structures are considered, with and without hexagonal composite materials. It was also observed that the weight of the hexagonal composite material was reduced by 39% compared with the case without the hexagonal composite material. The effect of sandwich characteristics on performance has been proposed through experiments and numerical techniques [136, 137]. Syed Mudassir et al. [138] investigated two different composite sandwich foams' flexural performance with two different fiber orientations under four-point bending experiments. Shariff and Chakravarthy[139] presented a comparison of tensile strength with experimental of a rhombus sandwich panel and then verified the results through numerical analysis. It has been found that by replacing the hexagonal core structure with a rhombus-shaped core structure, the strength and rigidity of the sandwich panel increase as the weight of the panel increases, which is negligible from a safety point of view. In this work, the author compares experimental values with finite element analysis values. Li Shawkat and Ma Jianxun [140] completed the experimental research on basalt fiber's mechanical properties, and Nomex honeycomb reinforced sandwich structure. The results show that the increase of the honeycomb height under the condition of plane compression improves the structure's compressibility. An Experimental study on sandwich plates with PVC foam core subjected to blast loading has been carried out to investigate Failure modes of PVC core as well as front and rear sheets [141]. Sadiq E. et al. [142,143] conducted three-point bending experiments on honeycomb samples to study the aircraft sandwich structure's crashworthiness behavior with honeycomb core under bending load. Furthermore, the effects of spot welding parameters on aluminum honeycomb core sandwich panels' shear characteristics.

FUNCTIONALLY GRADED MATERIALS SANDWICH PANEL

FGM structures are now used in various automotive, marine, transportation, and aviation applications. It has recently attracted a lot of consideration and has been continuously checked statically and dynamically by specific researchers. Due to the high strength/weight ratio's outstanding performance, the sandwich structure is continually used in the field of micro auxiliary frames [144]. Therefore, in the wide application of functionally graded materials, it is necessary to explore additional personnel's static and dynamic behavior with FGM, such as beams and plates [145, 146].

History of FGM's Plate

In 1972, Shen and Bever [147] first proposed progressive material composition for composite and polymer materials. In order to maintain mechanical properties and reduce the effects of thermal stress, most of these materials are used as coating materials. Functionally graded materials (FGM) were developed in Japan in the 1980s for thermal insulation [148]. Since then, FGM is widely used in different industries and engineering applications such as nuclear reactors, automobiles, airplanes, spacecraft, biomedicine, and steel industries[149]. At present, the focus of material development activities for composite materials and FGM includes improving material properties and supporting optimized structural design. Materials with specific characteristics that vary with thickness are urgently needed [150]. According to the composition stage distribution, FGM can be divided into two types: continuous or discontinuous gradual changes in composition. Similarly, according to manufacturing technology, it can be divided into thin and overall FGM [151, 152].

Fabrication Process

There are various types of manufacturing techniques for fabricating functionally graded materials. Generally, FGMs can be found in two forms, either thin or bulk. The first one is thinner parts or thinner surface coatings. It uses vapor deposition, physical or chemical methods, plasma spraying, self-propagating high-temperature synthesis, and other ways to produce thin-walled coatings or surface coatings FGM. The second type is a large amount of material, which requires an intensive and expensive process. It uses powder metallurgy technology, centrifugal casting, and powder metallurgy to produce bulk FGM [153].

A. Thin FGMs, thin functionally graded materials, usually take the form of surface coatings. According to the service requirements of the process, a variety of surface deposition processes can be selected. There are many vapor deposition techniques, including sputtering, chemical vapor, and physical vapor. These techniques are used to produce FG external surface coatings. They have good composition but are used only to deposit thin layers. They consume a lot of energy and produce toxic gases as by-products. Plasma spraying, electrode placement, electrophoresis, deposition by ion beam assisted, and high-temperature synthesis of self-propagating is other methods for creating functionally graded layers [154].

B. Bulk functionally graded materials, A systematic manufacturing process used to produce bulk FGMS is as indicated below, [155],

   i. Powder metallurgy method, generally, producing functionally graded materials includes three necessary steps: sample weighing and mixing the powders according to the spatial division of the pre-designed specified by the functional requirements, then squashing, compacting into pre-mixed powders finally sintering. Powder metallurgy (PM) technology has produced progressive structures. If a continuous system is required, the centrifugation technique is preferred.

   ii. The centrifugal method is identical to the casting process. In centrifugal casting, a rotation for the mold uses gravity to form FGM. Due to the difference in material density and mold rotation, graded materials are produced in this way. Although the centrifugal method can achieve continuous classification, it can only form a cylindrical shape. Another centrifugal separation problem is that since the propensity is constructed by normal processes (i.e., centrifugal force and density difference), only this type of gradient can be generated. By using an alternative manufacturing procedure called solid free form, researchers solved these problems.

   iii. Solid freeform fabrication method, this manufacturing process has many advantages, including higher production speed, lower power consumption, ultimate material employment, fabricating complex parts, and design utilities. They are dealing with the many software programs (CAD, Solid Works,….etc.).

Areas of Application of FGM's

The original form of FGM exists in nature; bones, teeth, human skin, and bamboo trees can be considered organic forms of functionally graded materials. Recently, much research is conducted to investigate the mechanical properties of (FGMs) to obtain better performance than homogeneous materials. Due to its excellent thermal and mechanical properties, functionally graded materials (FGM) are widely used in various fields and may be used for other purposes. The most important applications include energy, defense, chemistry, dentistry, medicine, and biology [156]. Figure 7 shows different types of FGM and their application areas [157].

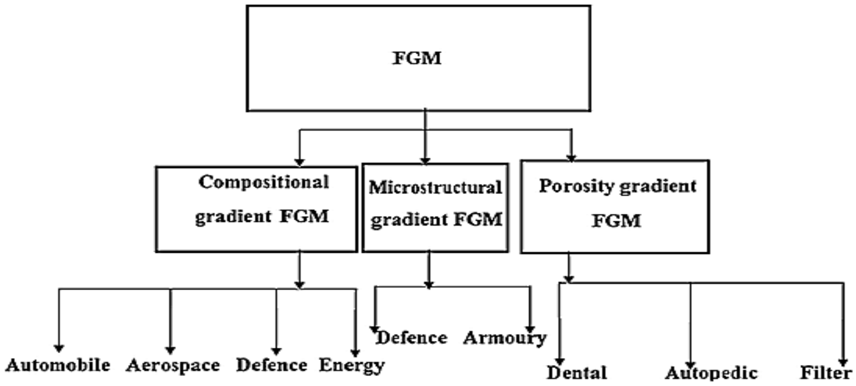


Figure 7. Areas of applications for the three types of FGM.

EXPERIMENTAL WORKS OF FGM SANDWICH PLATE

Many researchers have extensively studied the bending behavior of sandwich structures [158-163]. The FGM has the characteristics of changing the mechanical properties via thickness and can become a more effective core material than the traditional homogeneous material. Functionally graded cores can reduce damage caused by impact in sandwich structures with composites. FGM_S with chemical composition, porosity, and microstructure gradients are being modified [164]. The lightweight of functionally graded foam materials (FGFMs) and their outstanding energy absorption characteristics make them the most attractive, making them popular in developing the impact and crash resistance of systems [165-167]. Naturally, the changing of the porosity density or pore size leads to generate functionally graded materials. Three-point bending tests of FGM structure have also been studied in [168,169]. For a short-span beam, the shear test configurations were conducted by Kishore [170]. Avila [171] presented an experimental study on the segmented FG failure of a three-point bending sandwich. The bending properties of fiber-reinforced syntactic foam [172-174] and syntactic foam core sandwich composites have also been studied [175].

Sudhir et al. [176] conducted a tensile test on a nanocomposite for each weight fraction using the universal testing machine following the ASTM standard. Simultaneously, the flexural properties were determined for the FG polymer nanocomposite by conducting a three-point bending test loaded from neat and (1 wt.%) side FG. The sandwich's unique properties with the complaint FG core require attention because it has not yet been reported. M. Aydin et al. [177] completed an experimental study on ballistic performance. A 9 mm parabellum projectile hit the FG sandwich panel. Hence, the FG sandwich panel's deformation mechanism and their response to ballistic impact loads were identified. The functionally graded sandwich panel contains a mixture of ceramic (SiC) and metal (Al) phases, the proportion of which is determined by the volume fraction rule. By checking that the projectile almost completely penetrates the aluminum plate, it is determined that the functionally graded sandwich panel has better ballistic performance than the aluminum plate, where no precise penetration of the FG sandwich panel was noticed. J. Zhou et al. [178] performed a low-speed impact test on a sandwich structure based on a core made by bonding together foams of different densities. In this work, a series of various foam types are bonded together to create a three-layer core. The carbon fiber skin is then bonded to the core, and a drop hammer type impact bracket loads the structure with a hemispherical head. It has been observed that most panels break in a shear mode through the thickness, leaving transparent cylindrical holes in the multilayer core. Volker Hardenacke et al. [179] carried out a combination of gradient porous material experiments and numerical design for multifunctional aerospace applications with functionally gradient materials as sandwich cores, using combined numerical and experimental methods. After conducting the static test, the split Hopkinson bar equipment was used to study the material's dynamic response under the low-speed and high-speed impact.

Qiliang Lin et al.[180] performed a compression test on a curved circular FGM panel using the universal testing machine, as shown in Fig. 8, to obtain the external load required to flatten the FGM panel. The determined force calculates the theoretical deflection through the proposed model and compares it with the measured thermal deflection[180]. Researchers of M. Birsan et al. [181] used a direct method to model a slender body as a deformable curve with a specific microstructure, thereby studying sandwich composite elastic beams made of foam core and functionally graded or segmented homogeneous materials. Aman Garg et al. [182] studied sandwich FGM beams' bending analysis with ceramic face sheets and exponentially varying FGM core using finite element analysis and proposed a comparative study between power exponent and sigmoidal sandwich FGM beam. Lin Jing [183] conducted various experiments to study the effect of low-speed impact response on graded sandwich beams under different impact energies. The multi-objective design optimization of the sandwich beam was carried out. The simulation results show that the core percentage of absorbed energy decreases as the impact energy increases. As the impact energy increases, the balance of energy absorbed by the skin also increases.

Guangyong [184] studied the dynamic response of homogeneous and stepped gradient aluminum- foam sandwich panels through experiments and finite element simulations. At four different speeds, a low-speed impact test was performed by employ a drop hammer device. The results are compared based on the deformation curves and energy absorption. The graded foam core's density gradient significantly impacts the front face sheet deformation and failure mechanism. A. Seyedkanani et al. [185] conducted experimental bending tests on specimens 3D printed by stereolithography to confirm graded designs' practicality for developing advanced lightweight structures. A detailed finite element analysis (FEA) validates the experimental modeling method. Three-point bending and indentation tests are commonly used to calibrate mechanical models of homogeneous materials. The parameter estimation performed by this test is suitable for FGM layers of relatively large thickness. It involves the phase distribution transverse to the sample and its fracture characteristics, namely tensile strength and fracture energy, consistent with the simple, cohesive crack model [186]. Czechowski [187] studied FGM samples' strength and stiffness, consisting of two main components: WC and NiCr, and some Co. The flexural test was performed to check the proper proportion of the parts used on the bending stiffness and overall strength. Furthermore, to verify the experimental results, a micro-indentation technique simulates samples under similar loads [188-228].

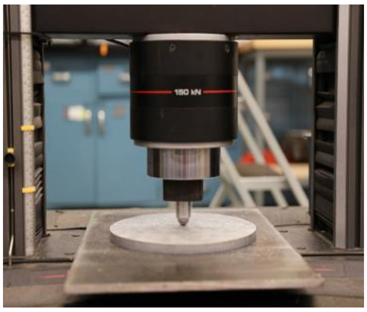


Figure 8. Compression test on FGM panel [180].

DISCUSSION

Compared with conventional sandwich panels, FGM can reduce the thermal and residual stresses generated between the face sheet and the core material, so the method of using functionally graded (FG) cores in sandwich panels has increased. Therefore, the practical applications of FG sandwich structures are growing. This paper's main goals are to describe the manufacturing process and applications of functionally graded sandwich panels to highlight these materials' specific features and functions. In addition, the necessary procedures of the experimental work of the sandwich structure are studied to explore the static and dynamic responses of the FGM core and the metal panel. Through various tests, stability and performance issues can be identified by changing multiple parameters, including gradient index, skin thickness, FGM core thickness, aspect ratio, and FGM layers. A review of the related experimental works on composite and FG sandwich structures was mentioned and included characteristics of functionally graded materials to increase the structure's flexural strength. As described in this article's full text, compared with composite materials' research, the number of research devoted to practical static and dynamic tests of functionally graded materials research is minimal. Even after about 30 years of FGM manufacturing technology and application development, these processes are still limited, complicated, and costly. Consequently, it severely impulses the research studies in this science and its real applications.

CONCLUSION

This paper is devoted to presenting a critical review of recent experimental tests of a composite structure in general and particularly functionally graded materials sandwich structures as modern structures used in an aerospace application. These test methods provide a standard procedure for obtaining the flexural strength and stiffness of sandwich panels, including tensile, compression, flexural, and impact tests. Also, the present contribution relates to the combined experiment and numerical design of the FGM sandwich structure. The conclusion statement can be summarized as follows,

1. The sandwich structure's effective stiffness coefficient is positively affected by the core height and the metal because the sandwich panel's second moment of inertia is affected by the FG core height. Therefore, the bending strength of the structure will increase as the core height and skin thickness increase.
2. Adhesion between the face sheet and core metal showed good mechanical stability. The use of a metal face sheet protects the FG core and gives suitable bending stiffness and toughness.
3. The significant increase in the metal skin thickness positively affects the bending stiffness and ultimate load of the sandwich composite beams. As the panel thickness increases, the bending stiffness is improved, and the mid-span displacement is reduced.
4. The flexural behavior of sandwich composite structures has been explored experimentally and numerically. According to the experimental research results, the composite beam fails under the bending load, and suddenly, brittle failure occurs.
5. Determining the composite sandwich structure's overall performance required a particular core and fiber orientation design.
6. The increase in bending stiffness due to the sandwich arrangement indicates that a composite sandwich beam is applied to the outermost surface to withstand tensile and compressive loads.
7. In most honeycomb composite structures, three main factors affect flexural performance: sheet thickness, honeycomb height, and honeycomb direction. Among them, the thickness of the sheet has the most significant influence on flexural performance. As the thickness of the core material increases, the flexural strength, shear strength, and flexural rigidity of the entire structure will increase. The effect of honeycomb height on the structure's flexural strength is similar to the plane compression test. The bending strength and core shear stress have an essential influence on the bending stiffness.
8. From the above comprehensive comments, it can be concluded that, so far, there are a few works of experiment used to study the functionally graded sandwich structure, and more work is needed to explore further the performance of FG Core with different parameters and effects. Adhesive materials should be studied together to develop structural components.
9. A combination of numerical and experimental methods can design and optimize functionally graded sandwich cores. Their characteristics and performance will determine the required applications and comply with multifunctional requirements.

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