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Experimental and analytical study of buckling strength of new quaternary hybrid nanocomposite using Taguchi method for optimization

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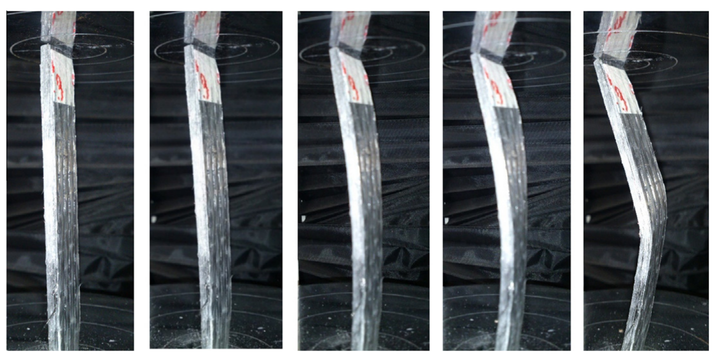
HIGHLIGHTS

- Investigating the effect of three variables on the buckling force of nanocomposite.
- Taguchi method was selected in order to design experiments.
- The fiber orientation was the most effective parameter.
- Observing synergistic effect with the addition of CNT and clay as nano fillers.

GRAPHICAL ABSTRACT



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ABSTRACT

In the current study the influence of three independent variables (carbon fiber orientation, nano clay and CNT wt%) on the buckling force of hybrid laminated nanocomposite was investigated. Taguchi method was selected in order to design experiments. Each variable had four designed levels and L16 orthogonal array was chosen for designing. Samples were prepared according to the designed levels obtained from the software and buckling tests were done on each sample, and the collected results obtained from the tests were generated in a designed Taguchi worksheet in Minitab software. Results showed that the maximum and minimum value of buckling load occurred at levels 2 and 16 respectively. Analysis of variance for signal to noise ratios described that the fiber orientation was the most effective parameter with probability value more than 99%. The CNT and clay content were standing on the next step respectively. Furthermore, the synergistic effect was observed with the addition of two nano fillers. From 2D contour plots, it was concluded that two component interactions fiber orientation/nanoclay and fiber orientation/CNT had the reverse effect on buckling load properties while the interaction between nano clay and the CNT had a synergistic effective term. Moreover, the results obtained from experimental tests were compared with the results obtained from analytical analysis, and it was concluded that the buckling load for certain laminated composite with carbon fiber orientation 600 was about 495 N, which was close to the analytical value (523 N).

1. Introduction

Composite materials have an environmentally friendly nature, high chemical resistance, high stiffness and strength; superior

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mechanical behavior and high thermal properties [1–4]. These reasons have made them the most useful in industries such as automobile, gas-turbine engines and aerospace [2,5]. In recent years, researchers have widely used, some materials to improve mechanical and thermal properties of composites such as fibers, macro, micro and nano materials as reinforcement [2]. For example, the fibers distribute the stress throughout the composite structure and improves the structural properties of material by acting as crack stoppers [6], or nano materials prevent crack growth in compressive loading conditions [7]. Composite laminates with the carbon fiber as reinforcement are used to improve mechanical properties of carbon, metal, ceramic and epoxy matrices because of specific strength and modulus, relative flexibility and low expansion coefficient [4]. Carbon fibers have been extensively used as fillers in polymer composites due to increase compressive strength of structures because of the superior modulus, so it can lead the loads between the contacting surfaces during the sliding process [6,8]. Epoxy resins are considered as one of the most important classes of polymer matrix composite materials, due to their superior mechanical properties [9–12]. Resin matrix, protects fiber with good geometrical arrangement and also supports the reinforcement. But epoxy resins are brittle in nature because of their tight three dimensional molecular network structures [13]. To overcome this issue, researchers use nano materials such as carbon nanotube (CNT), nano clay, alumina and nano silica as reinforcement [13]. Among of these nanomaterials, CNT has a high potential to improve mechanical properties of epoxy resins because of the high aspect ratio with large specific area, high flexibility and modulus [14]. For example, adding 0.2–10 wt% CNT into the epoxy improves modulus and mechanical strength of epoxy resins. Bekyarova et al. [15] reported that using carbon fiber/epoxy reinforced with carbon nanotubes shows a great laminar strength (~50 MPa). Also, inorganic nanoparticles have the potential to be used as a reinforcing material due to their low cost, ease of fabrication, and environmentally friendly nature. Mirmohseni et al. [16] used 2.5 % organically modifies clay as reinforcement in resin matrix and noted that its tensile modulus and strength, and its impact strength were improved in compared those of the neat epoxy. Mohan et al. [17] showed that an epoxy/clay binary nanocomposite possessed increases flexural and tensile strength.

Researchers were persuaded to use hybrid nanocomposites in order to achieve higher mechanical properties and crack propagation resistant. If used two or more kinds of nano or micro particle in the matrix, the composite is named hybrid nanocomposite [18]. Rostamiyan et al. [18] used hybrid of nano clay as nano reinforcement and high-impact polystyrene as thermoplastic phase to increase mechanical properties and improvement in tensile, compression and izod impact was obtained.

Buckling resistance is an important consideration in the design of laminated composite structures. Most of the laminated composite structures are often at risk of failure, such as buckling phenomena because of their lightweight and thin thickness, which lead to the breaking mode [19,20]. Reducing structural weight while at the same time increasing buckling capacity enables the composite materials to exhibit high strength-to-weight and stiffness-to-weight ratios, which is ideal for aerospace vehicle structural components. Nanotube-reinforced laminated composites represent a new class of structural materials to be exploited for potential development of a variety of new, advanced applications [21]. The buckling load of a laminated composite is related to various factors, such as, fiber orientation, laminate structure, reinforcement and boundary condition [19].

For preparation and making of hybrid nanocomposite laminate samples, a variety of parameters may be effective which control of these factors for optimizing them is very important and necessary. Taguchi is one of the optimization methods that uses an orthogonal array, signal-to-noise (S/N) ratio and analyses of variance (ANOVA) [1,16]. Cost and time required to carry out the experiments can be reduced by using Taguchi [22]. To measure the quality characterization deviating from the desired values, the experimental results are transformed into the S/N ratio. The experimental response has better characteristics when the S/N ratio becomes greater (optimal level of the process parameter). To evaluate the influence of parameters in final response, analyses of variance can be done. Also ANOVA table can determine which parameter has a significant effect on results. Taguchi method is wildly used in engineering area and in a few papers. This method is used as experimental design for preparation of hybrid nanocomposite samples. Mirmohseni and Zavareh [16] used this method to optimize the mechanical properties of epoxy/nano clay/nano Tio_2/ ABS quadratic hybrid nanocomposite [18].

In the current study, Taguchi method will be used for optimizing buckling strength of epoxy/carbon-fiber/CNT/clay quadratic hybrid nano composites. Also, the weight percentage of MWCNT, nano clay and also orientation of carbon fiber, will be selected as independent variables. The morphological and structural characteristics of hybrid mechanism will be investigated by using scanning electron microscopy (SEM). Furthermore, the effect of two nano fillers in corporately, will be investigated and compared with binary (epoxy/CF) and ternary hybrids (epoxy/CF/clay).

2. Experimental section

2.1. Details of materials

Epoxy resin utilized for this study was an undiluted clear dysfunctional bisphenol A, Epon 828 provided by Shell Chemicals Co. With epoxide equivalent weight 185–192 g/eqiv Epon 828 is basically DGEBA (Diglycidyl ether of bisphenol-A). The curing agent was a nominally cycloaliphatic polyamine, Aradur® 42 supplied by Huntsman Co. The multi-walled carbon nanotubes used in this study as a nano reinforcement in the epoxy matrix were purchased from Research Institute of Petroleum Industry (RIPI) of Iran with an outer diameter 10–20 nm, purity of more than 95% and maximum length of <30 μm. The organo clay Cloisite 30B was purchased from Southern Clay Products (Gonzales, TX, USA). The carbon fiber (T700-12K) used in this research was unidirectional type and was purchased from Toray Company. The solvent was Tetrahydrofuran (THF) with purity (GC) more than 99% provided from Merck Co (Germany).

2.2. Characterization

The critical buckling loads of carbon-fiber/epoxy nanocomposite plates were determined experimentally. The buckling test samples, were cut with saw from the original sample. The dimension of the samples was 12 mm × 140 mm in width × length and the thickness of the samples were 4.8 mm. The buckling samples were tested by applying compressive loads in axial direction using ASTM D: 6641 standard with a loading rate of 1 mm/min. The results of this mechanical test were measured by an ASTM-150 universal testing machine from Santam Company (Iran). In each case, at least five sample specimens were used to calculate the mean values and standard deviation. All experiments were performed at room temperature. The critical buckling load of each composite was determined from the load–displacement curves. The initial point of the load–deflection curve deviated straight line represents the critical buckling load. Fig. 1 indicates destroying the samples under buckling load.

2.3. Preparation of samples

The laminate plates were prepared with 16 layers and different fiber orientations based on Taguchi method. For preparing each sample, carbon fiber was hand laid-up with the specific steps. The whole procedure of reinforcing the resin was done in a suitable solvent to prepare the homogenous mixture. Tetrahydrofuran was employed as the solvent for all the mixture components, including epoxy resin, nano clay and CNT. Liquid epoxy resin was poured into an adequate amount of THF solvent, so in this way comparable neat epoxy samples could be prepared mixing by using of a magnetic stirrer at least two hours with 2000 RPM. Then the solvent was completely evaporated using a vacuum erlenmeyer. In the current study, the mixture was homogenized by ultrasonicating (ultrasonic SONOPLUS-HD3200, 50% amplitude, 20 kHz and pulsation; On for 10 s and Off for 3 s) for 8 min. At this stage 23 per (per hundred resins) of cycloaliphatic polyamine was added as hardener based on stoichiometric ratio. The mixture degassed using the vacuum pump to remove air bubbles. All the specimens were prepared with the handy lay-up