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Effects of multiple delaminations on the compressive, tensile, flexural, and buckling behaviour of E-glass/epoxy composites

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ABSTRACT

The goal of this study is to investigate the effect of multiple delaminations on the compressive, tensile and flexural strength of E-glass/epoxy composites and to evaluate their effects on the first critical buckling and re-buckling loads. Artificial delaminations of different sizes were inserted into four interlayers of $[45°_2/0°_2/-45°_2/90°_2]_s$ oriented E-glass/epoxy composite using a hand lay-up method and a hot press. The effects of through-the-width strip, circular and peanut shaped delaminations and triangle and inverted triangle patterned delaminations through the thickness direction were investigated experimentally. According to the results, the presence of multiple large delaminations influences the compressive and flexural strength and critical buckling load significantly. However, tensile strength is less affected by multiple delamination.

1. Introduction

Laminated composites, also known as advanced materials, are widely used in a variety of engineering applications. Though these materials offer several advantages, they must be used with caution. Damage mechanisms involved in laminated composite materials are unlike that of conventional metal materials. One of the most important types of damage encountered in laminated composite materials is the decomposition of two layers. This damage is known as delamination, which is not visible to the naked eye. The material strength decreases significantly due to delamination. The out-of-plane forces such as low velocity impact loading cause interlaminar stresses and delamination [1]. Different shapes of delaminations, such as strip through the width, circular, elliptical or peanut, can occur depending on the stacking sequence of laminate and the shape, velocity and mass of the impactor. Single or multiple delaminations can occur between the layers.

In recent years, significant research has been carried out towards understanding the effects of delamination on the mechanical properties of polymer-matrix composites. Chen and Sun [2] numerically investigated the residual compressive strength of a unidirectional and cross-ply laminated plate with a single circular delamination, using Von Karman's nonlinearity assumption. Short et al. [3] studied the effect of the geometry and location of a single square delamination. Results from their experiments and finite element analysis show that the delamination size and through thickness position affected the compressive failure load. Naik and Ramasimha [4] proposed an analytical method for a woven composite plate with single square delamination subjected to uniaxial compression loading. They investigated the effect of delamination size and location through the thickness on the compression behaviour for plain weave E-glass/epoxy laminates and carbon/epoxy laminates. Short et al. [5] compared the compressive strengths of curved glass fibre reinforced plastic (GFRP) specimens subjected to real impact and artificially square delaminated. They concluded that the results from specimens subjected to real impact were similar to that of artificially delaminated specimens, for similar delaminated areas. Reis et al. [6] investigated the effect of an artificial single delamination on the static and fatigue behaviour of carbon/epoxy laminates. They found that the presence of embedded delaminations decreased the tensile strength. Importantly, they observed that the size of the delamination affects slightly the static tensile strength. However, artificial delamination did not have a significant influence on the fatigue strength for tensile cycle loadings [6]. Ovesy et al. [7] investigated the critical buckling load of composite plates with artificial rectangular and circular single delamination. They established a semi-analytical

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buckling analysis method by using the first order shear deformation theory and a polynomial series. Huimin and Yongbo [8] determined the compressive strength of laminates with single interlayer circular delamination, both experimentally and numerically. They found that while the delamination size affected the compressive strength, the effect of the delamination location through the laminate thickness was negligible on the compressive strength. Amaro et al. [9] studied the bending behaviour of artificially delaminated carbon-epoxy composites. They performed three-point bending tests on laminated composites containing a single through-the-width delamination. They concluded that the delamination damage significantly influenced the bending behaviour.

Most of the studies focus on the effects of single delamination. Kutlu and Chang [10] reported one of the first studies on the effects of multiple (one or two) delaminations on the compression behaviour of laminated composites. They carried out an analytical and experimental analysis to determine the effects of size and position of through-the-width delamination. Kyoung et al. [11] used a non-linear finite element formulation to investigate the effects of a buckling load on cross-ply laminates with through-the-width and circular type multiple delamination. Hwang and Liu [12] conducted the non-linear buckling analysis of different types of multiple delaminations. They numerically investigated the effects of the length of lower level delaminations and near surface delaminations on buckling stress and critical buckling load. Wang et al. [13] investigated the effects of single and multiple square delaminations on the compressive strength of glass fibre reinforced composite. Their experimental and numerical results show that multiple delaminations reduce the compressive strength to a greater degree than a single delamination. Zhou and Rivera [14] investigated the effect of damage from real impact and multiple artificial delaminations on the in-plane compressive strength of carbon/epoxy panels. Their results show that the residual compressive strength of a sample with multiple artificial delaminations is lower than that of a sample damaged through real impact. The size and the number of delaminations significantly affect the compressive behaviour of the composite panel [14]. Degeorges [15] studied single and multiple delaminations in aerospace composite structures and investigated the local delamination and the damage from low velocity impact. He explained that the typical helix geometry shaped multiple delaminations simulate the damage from low velocity impact of laminated composites. Using experimental and numerical analysis, Aoki et al. [16] studied the effect of multiple artificial circular delaminations on the mechanical behaviour, under a compression load. To simulate the delamination propagation, a numerical model based on fracture mechanics was developed using Abaqus. Importantly, their results show that the local buckling occurring in the delaminated zone and the delamination growth affect the critical buckling force. Aslan and Sahin [17] obtained the uniaxial buckling and the compressive failure loads for multiple large delaminated cross-ply E-glass/epoxy composites. Liu and Zheng [18] numerically determined the buckling and post-buckling behaviours of through-the-width and double delaminated T300/976 composites. Li et al. [19] used an extended Layerwise method to investigate the effects of the size and position of multiple delaminations for unidirectional and cross-ply beams.

Hwang and Huang [20] investigated the effect of two delaminations on the buckling stress and post-buckling behaviour. They found that the location of the long and short delaminations effect on the buckling stress and delamination propagation. Wang and Zhang [21] numerically evaluated the buckling and delamination growth in laminates with single and double delaminations. According to their results, the effect of delamination growth on the strength of the composite laminates is very important and the effect of multiple delaminations is not similar to that of a single delamination because of the interaction between the delaminations under a buckling load [21]. The effect of multiple delaminations in a graphite/epoxy composite under buckling load was investigated using ANSYS by Cappello and Tumino [22]. Their results show that the delamination length and location affects the critical buckling load. Composite columns with multiple delaminations subjected to compressive axial forces were studied analytically using Reissner's beam theory to determine the delamination number, length and longitudinal symmetry or asymmetry position effects by Rodman et al. [23]. The longitudinal asymmetry of delaminations and delamination length influence the critical buckling load and mode shapes [23]. Suemasu et al. [24] determined the compressive behaviour and the failure mechanism of composites with multiple circular delaminations using cohesive interface elements. Their results indicate that the load carrying capacity of a composite structure with multiple delaminations depends on the delamination growth [24]. Craven et al. [25] developed a finite element model of a composite plate with multiple peanut shaped delaminations under compression load to define the effect of the delamination size and shape.

To determine the buckling and post-buckling behaviour of single and double through-the-width delaminated composites, a novel layerwise theory was proposed by Ovesy et al. [26]. Liu et al. [27] numerically investigated the effect of cohesive law parameters in double through-the-width delaminated composites subjected to a compressive force. Mohammadi and Shahabi [28] studied the post-buckling behaviour of multiple delaminated composites to determine the effects of size, position and distribution of delaminations by using ANSYS. Lee et al. [29] compared the compressive behaviour of single and double through-the-width delaminated composites. Their results showed that the compressive behaviour of double delaminated composites was more complicated than that of single delaminated composites and the delamination position in thickness direction affects the load carrying capacity of the composite structures [29].

Most studies involve one or two embedded artificial delaminations. However, delamination damage can occur at multiple interlayers of laminated composite plates and their dimensions are generally different. On the other hand, the overall mechanical properties (such as compressive, tensile and flexural strength and critical buckling load) have not been investigated simultaneously in most studies. In this study, triangle and inverted triangle patterned delaminations through the thickness direction were investigated experimentally. Polytetrafluoroethylene (PTFE) films of different sizes were inserted to four interlayers of angle-ply E-glass/epoxy composite to create artificial delaminations. The effect of the multiple delaminations of different sizes on the compressive, tensile and flexural strength and critical buckling load were determined experimentally. The effect of the length of the biggest delamination and the length of the other delaminations (lower level delaminations) and the effect of the delamination shape (through-the-width-strip, circular and peanut) were also investigated.

2. Experimental procedure

2.1. Material production and creation of artificial delamination damage

The laminated composite materials with and without artificially embedded multiple delamination damage were manufactured using a hand lay-up method at the Izoreel Company, Izmir. Ciba Geigy Bisphenol A Epoxy CY-225 resin and Ciba Geigy Anhyride HY-225