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Impact resistance of composite laminate flat plates – A parametric sensitivity analysis approach

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ABSTRACT

Sensitivity analysis is a tool employed in engineering problems to identify the influence of input parameters on the state variables such as displacement, stress, strain and temperature. In the case of composite laminates the impact resistance depends on a number of parameters, which have been extensively studied by a number of researchers. But the reported work has thus far fallen short of providing the critical analysis on the order of degree of influence of the considered variables on the impact resistance of the composite laminates. In this work we present a sensitivity analysis approach to ascertain the degree of influence of various mechanical and material parameters on the impact performance of the composite laminated plates. Here we show that based on the normalized sensitivity coefficients, one can determine the influence of each individual parameter and hence identify the parameters, which need to be considered more critically in design. The normalized sensitivity coefficients hence give a numerical indicator of the factors having more influence on the impact resistance of the composite. This approach enables one to limit the number of material and geometric properties usually considered in design to the most critical ones for improving the low velocity impact behavior of the composite laminates. Our results indicate that the low velocity impact resistance of fiber reinforced polymer composite plates depends more significantly on the thickness and the stacking sequence and the effect of the elastic moduli of the fibers and matrix has less effect than the strength of the fiber and matrix materials of the composite. Initial numerical model was selected from the literature and the results verified against the available numerical and experimental results. The results show quite a good agreement with the experimental results. The results indicate that the impact performance depends significantly on the thickness and the stacking sequence and the effect of the elastic moduli of the fibers and matrix has less effect than the strength of the materials. These results will help in the further study to improve the impact resistance of the composite laminates as the focus should be more on the parameters like thickness, stacking sequence and materials having higher strengths.

1. Introduction

Fiber reinforced polymers have captured a significant market as a material of preferred choice in a wide variety of structural applications around the globe. These composite materials while offer a wide range of advantages in terms of excellent formability, high specific mechanical strength, better thermal resistance, excellent chemical and corrosion resistance, are at the same time quite susceptible to damage under impact loading. This impact damage can severely impair the otherwise excellent mechanical properties and often results in causing premature failure of the composite. The damage can be on the surface or internal and can be caused due to even low velocity impacts which on inspection cannot be detected visually. The conventional materials which are being replaced by the composite materials have well defined impact characteristics and the standards are well defined but the laminated composites are more susceptible to impact damages which is often internal and cannot be observed visually [1]. However, for composite materials, due to their orthotropic material behavior, presence of discrete material interfaces and laminated structure, their impact behavior markedly differs from that of the conventional materials, this complex behavior results in a number of types of failure mechanisms such as fiber breakage, delamination, matrix cracking and plastic deformations and large displacements occur as impact load is applied [2]. There are a number of studies including experimental [2–9] numerical [2,10–12], and analytical [13] which discuss the impact behavior of different composite laminates. There are a number of studies which have developed analytical or numerical techniques to study the impact response of composite plates and shells under low energy impact. These studies compare

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the results with the available experimental data. A number of these studies have investigated the effect of different parameters on the impact resistance of the composite laminates subjected to the low-velocity impacts. Hosseinzadeh et al. [5] discussed the effects of different materials and the energy levels on the size of damage such as diameter and edge lengths. Their study was based on both experimental and numerical results using ANSYS-LS/DYNA. Four different kinds of carbon fiber reinforced and Carbon/Glass hybrid composite plates were impacted with different energy levels, at low energies there was no significant damage in carbon based plates while with increase in energy the damage diameter in glass/epoxy the damage diameter grew larger. At higher energies the damage was unpredictable. Menna et al. [14] studied the effect of thickness at different impact energy levels in Glass fabric/Epoxy laminates using the LS/DYNA FE software. The numerical results were validated using the experiments and the force–displacement curves showed good correlation between numerical and experimental results.

Cantwell [6] studied the geometrical effects on the impact response of glass fiber reinforced polymeric composites. Flat plates of circular shape with different diameters were subjected to different levels of impact energy ranging from low to intermediate energies. Mode of damage was characterized as delamination under impact location and widespread matrix cracking. For certain impact energy, the impact force and damage was severe in curved plates with smaller diameter as compared to the sample plates with larger diameters. Karakuzu et al. [15] characterized the impact behavior of glass/epoxy composite laminates using experimental and numerical data. They presented the results of effects of impact energy, impactor mass and velocity on the impact characteristics of glass/epoxy composite laminates. Mikkor et al. [16] studied the effects of impact loads on the aircraft structures made of carbon/epoxy based composite materials. An explicit FE code was developed to study the behavior of carbon/epoxy composite plates under a range of low energy impact loads. The authors also presented the effects of preload, impact velocity and geometry of the specimen on the damage and the residual strength of the panel. Naik et al. [17] investigated the impact behavior of woven-fabric laminated composite plates under low velocity impact by using a modified Hertz Law. The effect of fabric geometry was studied and compared with unidirectional composites at two different impact velocities of 1 m/s and 3 m/s. It was suggested that the woven fabric composites are better in impact resistance than the cross-ply laminates which consists of unidirectional layers stacked orthogonally. Aktas et al. [7] in their study have reported the impact characteristics of unidirectional glass/epoxy laminated plates. Different damage modes and the effect of different stacking sequence were studied under different impact energies. Tiberkak et al. [18] used the finite element methods to evaluate the impact characteristics, a parametric study was performed to evaluate the effect of laminate configuration also mass and velocity of impactor and the effects of boundary conditions.

The above reviewed studies have studied the influence of various parameters as discussed but what is of interest for the current study is that the parameters that are directly related to the composite plates should only be considered and listed in order from having the most profound effect to the least. In view of the current study, factors like boundary conditions, geometric properties of the impactor and the environment of use are considered as invariable or out of analyst's control as they are dependent upon the scenario the structure is used. We believe that quantification of the degree of influence of various mechanical and material parameters is an important question that needs to be appropriately addressed in design with fiber reinforced polymer composites. We know that the factors such as geometric properties, dimensions, materials and boundary conditions are fixed by the design of the structure and the impactor velocity and size are circumstantial and cannot be controlled during the real time operation of the structure. The impact resistance of the composite laminate is thus only characterized by the design of the laminate itself which includes laminate configuration, material and thickness which is not bound by design considerations. However, there are still a number of factors that need to be studied and understood for design with composites. Therefore, it is essential to first identify the factors that have the most influence upon the impact resistance and then study in detail their relation with the improving the impact resistance of the fiber reinforced polymer composites.

This study therefore employs the sensitivity analysis approach to identify the parameters and quantitatively describe their degree of influence on the impact resistance of the fiber reinforced polymer composite plates. The results were then used to further study in a future study to optimize the factors in order to achieve the best impact resistance for a certain case of composite laminate under certain conditions of impact load and boundary conditions. The studies prior to the current work have studied almost all the parameters in detail such as the thickness of the ply, stacking sequence and effect of materials, but the focus of this work is to know how big the effect of one parameter is with respect to others. This is needed in order to use the results in future optimization studies where keeping the costs minimum is one criterion. It is well established that increasing thickness and using stronger fiber material increases the impact performance but to optimize with cost in mind, it is important to know how to maximize the performance without increasing the material costs. Hence, the needs to understand which parameter in addition to thickness have greater effects. Also, once known which material properties have greater influence, it would be beneficial to search from the available materials with the least cost and best properties.

2. Sensitivity analysis

Sensitivity analysis is a tool employed in engineering problems to identify the influence of input parameters on the state variables such as displacements, stresses, strains and temperature. The result of sensitivity analysis is the identification of a limited set of state or input variables that have greater influence on the output of the system. The main aim of the sensitivity analysis is the calculation of the sensitivity coefficients which is obtained by the variation of input variables one at a time or in groups and study the variation in the output variable [19].

The sensitivity coefficient is computed by partially differentiating the state function; defining the output; with respect to the input parameters. These derivatives can be computed numerically using the basic equations defining the system output or can be calculated analytically if a closed form solution exists. The computation of sensitivity coefficients is suggested to be normalized so that a direct comparison of all the input variables can be deduced. The actual benefit of normalized sensitivity coefficient (NSC) is that it provides an information about the order of magnitude of variation in the output variable with the change of one order of magnitude in the input variables [20].

2.1. Formulation

In general, the sensitivity analysis is performed by varying one input variable at a time and observing its effect on the overall output. Let us denote the independent variables or the input variables with X and the vector X denotes the set of these variables

$$X = \overline{X} \pm U \quad (1)$$