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The effect of pre-stress on impact response of concave and convex composite laminates

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Abstract

Curved composite laminates are used in many applications while in the majority of the studies present in literature, flat laminates are investigated. Therefore in this paper, the influence of the curvature type (convex or concave) and preloading on impact response of curved laminates is considered. For this aim, a specific fixture and specimen were designed. The impact tests were performed at four different impact energies with the specimens fixed only in their straight sides. The results show that the effect of preloading on damaged area of concave laminates is lower than for convex ones. For considering the damage mechanism in different situations some optical pictures are also presented.

Keywords: Convex and concave laminates; pre-stress; impact loading.

1. Introduction

A major weakness of laminated composites is that low-velocity impacts, introduced accidentally during manufacture, operation or maintenance of the component, may result in delamination between the plies. Most of the available literature deals with impact on structures without any pre-stresses [1-2]. Usually, in addition to impact loading, composite structures may experience pre-stresses produced either by service loads or by the

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manufacturing/assembly process [3–4]. Delamination plays a minor role on the residual strength of impacted composite structures subjected to tensile load. On the contrary, in damaged structures subjected to compressive loading, delamination is most detrimental damage mechanism affecting the structural damage resistance [5,6]. On the other hand, most of the studies regarding the effect of low velocity impact damage reported in the literature are focused on thicker flat plates that are typically used for aircraft wing structures, but there are a few studies that address the low velocity impact response of thinner curved composite panels that are typical of fuselage skins or wind energy generators blades [7,8]. Although there is some information about these two topics in the literature separately and some papers [9,10] consider tubes impacted under torsional preload, there is only one study about the combined effect of curvature and pre-stress effects during low-velocity impact loading [11]. In this study, Saghafi et al used two different specimens to consider the effect of pre-stress on the impact response of curved (convex) laminates: 1- A specimen with initial curvature radius of 190mm and without preloading. 2- A preloaded specimen in which the initial radius of curvature was 190mm and after applying the load it decreased to 125mm. Their results show that increasing the curvature and the stress through the thickness affected significantly the impact parameters such as maximum load and damaged area.

As a follow up of the last study, in this research the effect of preloading is considered for concave and convex laminates under low velocity impact loading and their results are compared.

2. Experimental program

2.1. Materials and specimen manufacturing

Unidirectional glass/epoxy prepreg (Ref. 1017) supplied by G. Angeloni Srl was used in this research; its mechanical properties are presented in [9]. Fig. 1 shows the configuration of all samples. The stacking sequence of the laminates is \([0/90/0/90/0]_s\) (10 layers), width and thickness of the specimens are 100mm and 3.3 ± 0.1mm, respectively. Test panels were cured using a vacuum bag in autoclave at 150°C for 1 h, according to supplier’s specification. Specimens were cut from the laminates using a rotating diamond disk. The configuration of the specimen is shown in Fig. 1. Each straight side of the specimen consists of a flange containing 3 holes. It is designed considering the membrane effect during impact loading for concave and convex laminates. In convex sample, the specimen is under compression, while in concave one, it is under tension. Therefore the specimens should be fixed to withstand this load condition. It should be mentioned that for each impact energy and specimen shape, convex or concave, 2 or 3 specimen were considered. If the results of the first 2 impact tests were near to each other, the third one was waived.
2.2. Test setup

The tests were conducted in a custom built drop-weight machine equipped with a piezoelectric load cell attached to the impactor. The signals of the load cell was acquired at 100 kHz sampling frequency without any filtering except the intrinsic one due to the measurement chain. The hemispherical head of the load cell had a diameter of 12.7 mm and the total mass of the impactor was 1.26 kg. The curved laminates were positioned under this drop tower and preloaded by means of a special fixture designed and fabricated to meet the goals of this research [9]. The impact tests were conducted under 6, 12, 24 and 36J and two different preloading: 0 and 4500με. It should be mentioned that the specimen is only fixed in the straight sides and the curved ones are completely free.
3. Results and discussion

3.1. Impact Parameters

The Force-Displacement curves obtained from impact tests are shown in Figure 2. Each situation has a specific code in this figure which is defined as follows: The type of curvature (Convex and Concave) – The amount of preloading (0 or 4500με) – Impact energy (6, 12, 24, or 36). As shown in all impact energies, the maximum force and maximum displacement in concave laminates are higher and lower, respectively, in comparison with convex laminates. This phenomenon proves that generally Concave laminates is more stiff than Convex ones. It is because the membrane stress induced on curved laminates during impact: fixing the in-plane boundary condition amplifies the compressive membrane stresses developed in the initial loading of the convex shells, while it is completely opposite regarding concave laminates in which boundary conditions cause tensile stress.

It is also shown that the preloading at 4500με could increase the maximum impact force and decrease maximum displacement, significantly. An interesting phenomenon that can be seen in the figure is that maximum force of the non-preloaded concave laminates is lower than preloaded
convex ones under 12J impact energy, but by increasing the impact energy to 24J the behavior of their Force-Displacement curves is very similar to each other and finally in impact energy of 36J their response is completely inverse in comparison with what seen 12J impact test.

Impact parameters, i.e. maximum force, maximum displacement, time-duration of impact, and damaged area, are shown in Fig. 3. The effect of curvature type and preloading on maximum force and maximum displacement were considered in the last paragraph. The only matter that should be added is that the influence of preloading on these two parameters is almost the same for concave and convex laminates. For example, by applying preload on concave and convex laminates and conducting tests under 36J, maximum force increased 13.3% and 15.5% that is very similar. This fact is not true for all impact parameters. For instance, preloading affects significantly the damaged area of convex laminates. While damaged area in convex laminates increased 68% under impact energy of 36J, it increased only 11.5% in concave ones. Another interesting phenomenon that can be seen in this section is regarding the difference between the damaged area of concave and convex laminates. While the maximum force is lower in convex laminates at all impact energies, its damaged area is higher in comparison with concave specimens. This is related to compression stress during impact loading of convex laminates. This stress causes sub-laminate buckling that promotes delamination growth. According to this figure, it is proved that changing the curvature type from convex to concave and applying preload lead to decrease the time-duration of impact.
Fig. 3. Impact parameters, maximum force, maximum displacement, time duration of time, and damaged area, for all situation
Fig. 4. The image of damaged area in back surface.
3.2. Damage mechanism

The damaged area in the lowermost surface (non-impacted one) of the convex and concave laminates is shown in Fig. 4. As seen delamination and matrix cracks are the dominant failure. There is a very interesting difference between the failure of convex and concave laminates: in convex specimens, when preloading was applied on the specimen the matrix cracks are much less than in specimens without preloading. It is due to the compression stress applied by preloading system [9]. On the other hand, in concave laminates the density of cracks is almost the same for preloaded and non-preloaded laminates. As mentioned before, the enhancement of delamination caused by preloading is much higher in convex laminates. Therefore, it is possible to claim that the effect of preloading on damaging of concave laminates is negligible in comparison with convex laminates.

4. Conclusions

In this study, low velocity impact tests were conducted on preloaded/non-preloaded concave and convex laminates to consider the effect of specimen configuration (curvature type) and pre-stress on impact parameters. The following results can be concluded:

1- Due to the membrane effect the concave laminates are stiffer than convex laminates. So the maximum load is higher and on the other hand maximum displacement and time duration of impact are lower in concave laminates.

2- The effect of preloading on damaged area of concave laminates is much lower than on the convex ones.

3- In convex laminates, pre-stress could decrease the matrix cracks, while in concave specimens the amount of matrix cracks in preloaded and non-preloaded laminates is almost the same.

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