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Comparison of the Effect of Preload and Curvature of Composite Laminate Under Impact Loading

In this paper, the effect of preload on impact response of composite laminates is considered. To this aim, three specimens were manufactured and tested under 4 different impact conditions: 1- A curved laminate without preload. 2- A preloaded curved laminate, showing a lower radius of curvature due to the preload. 3- A curved laminate without preload but initial reduced curvature. The particular test conditions studied here allow estimating and discerning the effect of pre-stress and curvature on the impact response. Results show that the preload leads to an increased curvature, to which it follows that the maximum impact force and the damaged area increase significantly. The comparison of the impact response of the second and the third specimens show that, in the case of similar curvature, the preload leads to a lower damaged area. These results are particularly important for designing of curved composite components.

Keywords: *Composite laminates, GFRP, Curvature, 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 aircraft, may result in delaminations between the plies. Most of the available literature deals with impact on structures without any pre-stresses [1-5]. Usually, in addition to impact loading, composite structures may experience pre-stresses produced either by service loads or by the manufacturing/assembly process [6–7]. Delamination plays a minor role on the residual strength of impacted composite structures subjected to tensile load. Instead, in damaged structures subjected to compressive loading, delamination is the most detrimental damage mechanism affecting the structural damage resistance [8-9]. Most of the studies regarding the effect of low velocity impact damage reported in the literature focus on thick plates, which are typical of those used in wing structures. Instead, there are a very few studies addressing the low velocity impact response of thin curved composite panels that are typical of fuselage skins [10-11]. Although there is some information about these two topics (curvature and pre-stress effects) in the literature, separately, but there is only a limited number of studies about their effects when both of them attend simultaneously during low-velocity impact loading [12-14]. In this study, Saghafi et al. used two different specimens to consider the effect of pre-stress on the impact response of curved laminates: 1- A specimen with initial curvature radius of 190 mm and without preloading. 2- A preloaded specimen with orgiginal radius of curvature of 190 mm which reduces to 125 mm after the preload. Results presented therein showed that increasing the curvature and the stress through the thickness significantly affect the impact response in terms of maximum load and damaged area. The shortage of this study is that it does not discern the contribution of the curvature with respect to the preload, as both of them changed during the preloading.

In the following study, we perform a new test campaign to discern the contribution of the curvature from the preload. Results report all the major impact parameters i.e.: maximum load, maximum displacement, impact duration, and damaged area..

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 [12]. To discern the effect of preload and curvature on the impact response three different kind of specimens were manufactured:

1- Nine curved specimens not to be subjected to any preload during the impact test (Type A).

2- Nine specimens with similar initial curvature to the previous group, which decreases under the preload (preloaded Type A).

3- Nine specimens with reduced original curvature but not subjected to any preload (Type B).

It should be mentioned that the curvature of the Type A specimens is about 190 mm and the curvature of the two others is about 125 mm. Since the curvature of the second

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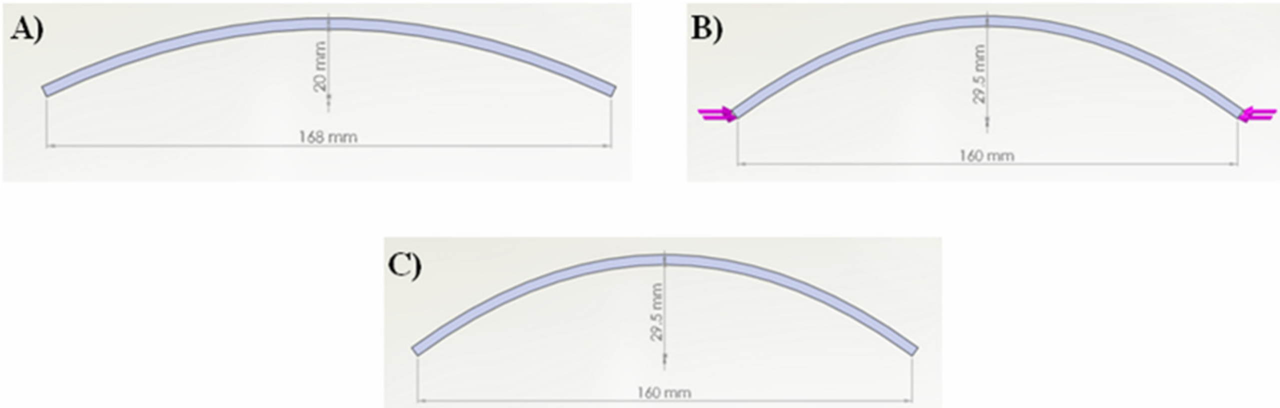

Figure 1. The configuration of all samples provided for considering the effect of curvature and pre-stress: A) Type A B) Preloaded Type A C) Type B

and third groups is similar, so the effect of the preload on the impact response can be determined. Figure 1 shows the configuration of all the samples. The stacking sequence is $[0/90/0/90/0]_S$ (10 layers), and width and thickness of the specimens are 100 mm and 3.3 mm, respectively. Test panels were cured using a vacuum bag in autoclave at 150^{o}C for 1h, according to the supplier's specifications. Specimens were cut from the laminates using a rotating diamond disk.

2.2 Test setup

Four different drop heights of 0.5, 1, 2, and 3 m corresponding to a nominal potential energy of 6, 12, 24, and 36 J, and pre-strain of 5300 με for group 2 (pre-loaded Type A) were chosen to consider the effect of pre-stress under different impact energies. For each configuration, at least 2 samples were tested. If the results of the first two tests were not near to each other, then a third test has been conducted.

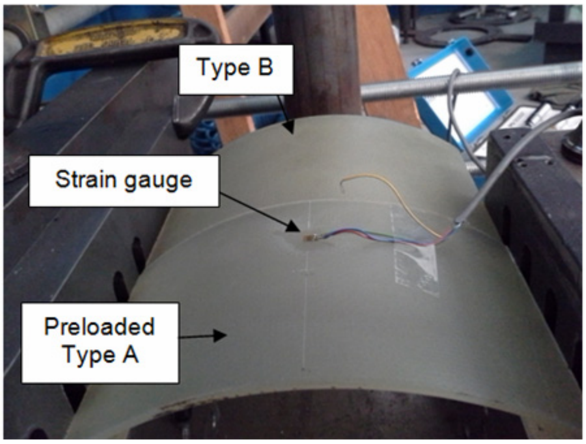

Figure 2. Visual comparison of the specimens of group 2 (preloaded Type A) and 3 (Type B)

The tests were conducted on 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 a sampling frequency of 100 kHz 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 the drop tower and preloaded through a special fixture designed and assembled to meet the goals of this research [9]. Figure 2 compares the specimens between the second (preloaded Type A) and the third group (Type B). As mentioned before, the configuration is similar, but the preloaded Type A has tension stress on the front face (impacted side) and compression stress on the back face, while Type-B sample is not subjected to any preload. Therefore, by comparing the results of these two groups the effect of pre-stress can be identified. All information about the fixture and the method of applying the load can be found in [12] and is not reported here for brevity. It should be mentioned that there is no fixture on the curved sides of the sample and they are free in all directions.

3. RESULTS AND DISCUSSION

The Force-Displacement curves obtained from impact tests are shown in Figure 3. As seen the group of "Type B" and "Preloaded Type A" have a very similar behavior, while the group of "Type A" follows a completely a different trend. "Type A" specimens have lower curvature and are not subjected to any preload, hence showing lower stiffness. Differently, the other two groups show comparable stiffness, suggesting that the stiffness is more dependent from the curvature rather than from the preload. For considering more details, the impact parameters: maximum load, maximum displacement, time-duration of impact, and damaged area are presented in Figures 4 and 5.

According to Figure 4, all impact response parameters are very similar to each other for the "Preloaded Type A" and "Type B" specimens, which shows pre-stress does not affect significantly the beahvior. On the other hand, the "Type A" specimen, having lower curvature and no pre-stress, the impact response is completely different. These show larger maximum displacement and contact duration, whereby the maximum force is lower in comparison with the two other configurations. This should be ascribed to the fact that when the curvature is lower the stiffness decreases; it follows that less force can be transferred to the specimen during the impact.

The effect of pre-stress and curvature on the damaged area is reported in Figure 5. Results show that the preload increases the curvature and the pre-stress, le-

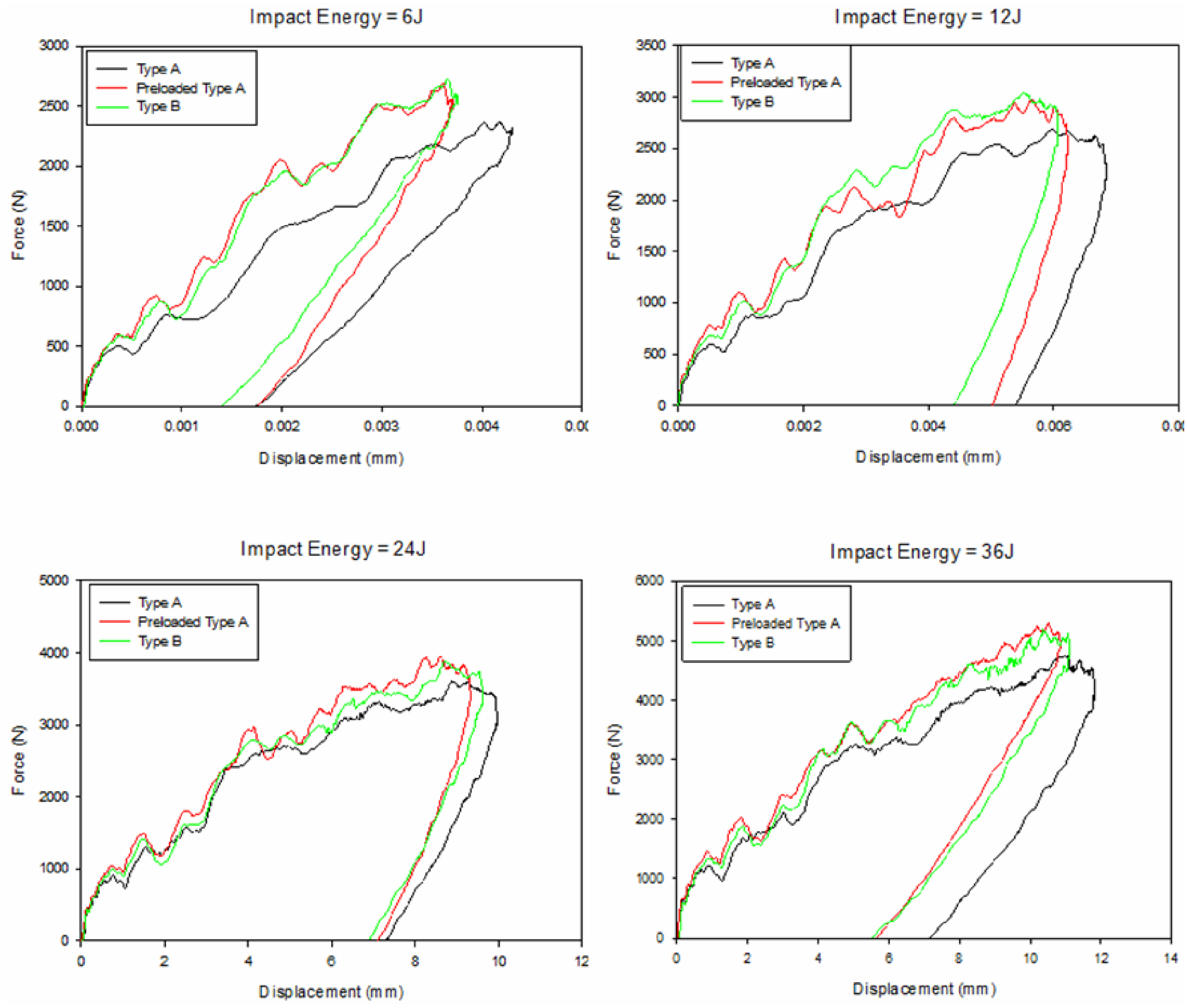

Figure 3. Force versus impactor displacement for impact energies of: 6J, 12J, 24J, and 36J

ading to a larger damaged area. To discern the contribution of pre-stress and curvature in this situation, "Type B" specimens with similar curvature to th "Pre-loaded Type A" specimens, but without preload were studied. As shown in Figure 5, the damaged area in "Type B" specimen is much larger than "preloaded Type A", suggesting that the preload might decrease the damage in the laminate. This result is very important in designing of structures made of curved composite components, as a preload might increase the strength resistance against impact loadings. Comparing the damaged area of the Type A and Type B specimens shows the effect of curvature. According to Figure 4 and 5 the maximum force and damaged area increase, whereby the maximum displacement and impact duration decrease by increasing the curvature.

Table 1 presents the details about the effect of curvature and pre-stress on damaged area. As shown, decreasing the radius of curvature from 190mm (Type A) to 125mm (Type B) increases the damaged area about 100% in various impact energies. On the other hand, by applying a pre-stress on the specimens (Preloaded Type A) the damaged area increases by 36% to 62% depending from the impact energy. The comparison between "Preloaded Type A" and "Type B", having similar curvature, shows the effect of the preload. It is found that the preload, decreases the damaged area by 16% to 32% depending from impact energies.

The damaged area of the "Type A", "preloaded Type A", and "Type B" specimens under 36 J of impact energy is reported in Figure 6. According to these pictures, matrix cracks and delamination are the main failure modes. The configuration of the specimen is also found to influene the shape of the damage. While the damage shapes in "Type A" and "Preloaded Type A" are rhomboid-like, the damaged area of the "Type B" specimen is almost irregular. With the first glance at the pictures, it is obviously possible to understand that the matrix cracks in the "Type A" specimens are much more than in the two other configurations.

Table 1. Damaged area in different configuration under various impact energies

	6J			12J		
	Type A	Preloaded Type A	Type B	Type A	Preloaded Type A	Type B
Damaged Area	27.3	43	57	51	72	107
Variation (%)	---	57.5	109	---	+41	+110

	24J			36J		
	Type A	Preloaded Type A	Type B	Type A	Preloaded Type A	Type B
Damaged Area	151	205	244	211	342	473.5
Variation (%)	---	+36	+92	---	+62	+124

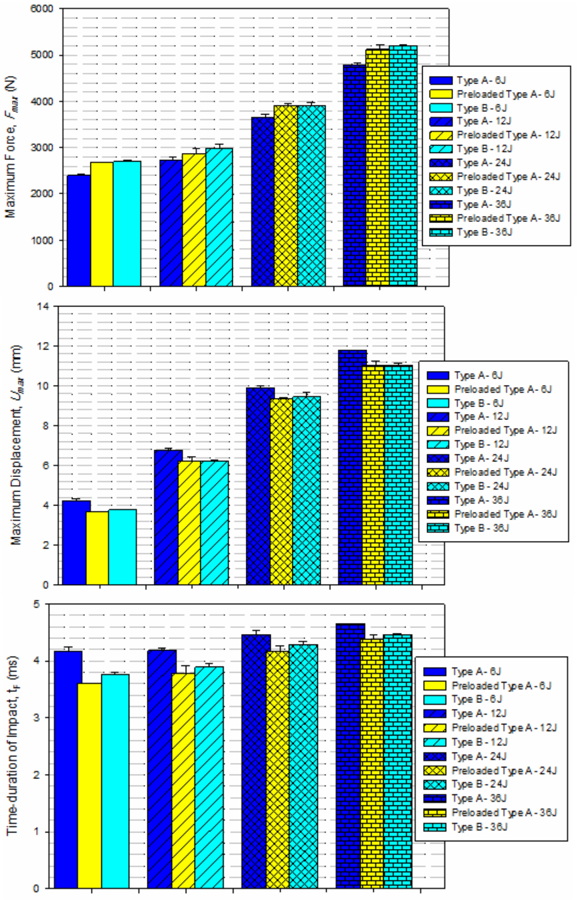

Figure 4. The effect of different configuration on: A) maximum load B) maximum displacement and C) time-duration of impact

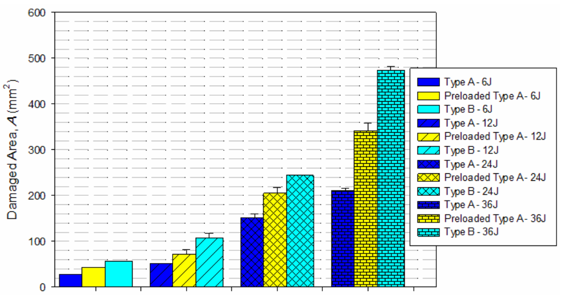

Figure 5. The effect of different configuration on damaged area

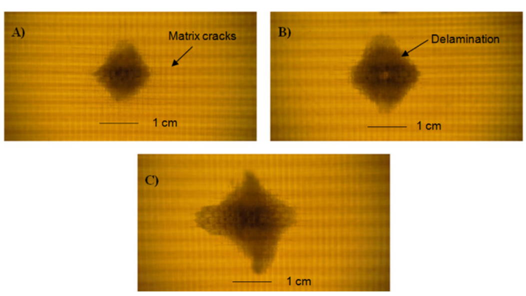

Figure 6. The damaged area of: A) Type A B) Preloaded Type A C)Type B specimens under 36J impact energy.

4. CONCLUSION

This research focused on shading light on the effect of preload and curvature on the impact behavior of curved laminates. Three different specimens were prepared for this goal: 1- "Type A" whose initial radius of curvature was 190mm and without pre-stress. 2- "Preloaded Type A" that was under pre-stress and its radius of curvature was 125mm during the impact test. 3- "Type B" whose initial radius of curvature was 125mm and without preload. According to the outcomes obtained from the impact tests, the following conclusions can be made:

1- The maximum force and damaged area increase with the curvature, whereby the maximum displacement and the contact duration.

2- The comparison between "Preloaded Type A" and "Type B" specimens shows that pre-stress might significantly decrease the damaged area. This result is very important for designing the structures containing curved composite laminates.

3- Matrix cracks and delaminations dominate the failure modes, whereby matrix cracks is more in "Type A" specimen, whereas the delaminationn on the two other specimens are larger.

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УПОРЕЂИВАЊЕ ЕФЕКТА ПРЕДОПТЕ–РЕЋЕЊА И ЗАКРИВЉЕНОСТИ КОМПО–ЗИТНИХ ЛАМИНАТА ПОД УТИЦАЈЕМ УДАРА

Х. Сагафи, Т. М. Бруго, А. Зукели, К. Фрагаса, Г. Минак

У овом раду је разматран ефекат преднапрезања при удару на композитне ламинате. У том циљу, три узорка су произведена и испитана под 4 различита услова удара: 1- закривљен ламинат без пред–напрезања. 2- преднапрегнут закривљен ламинат, показујући нижи полупречник закривљености због преднапрезања. 3- закривљен ламинат без пред–напрезања, али са почетним смањењем закривље–ности. Посебни услови тестирања који су проучавани омогућили су процену и откривање ефеката преднапрезања и закривљености приликом тестирања на удар. Резултати показују да пред–напрезање доводи до повећане закривљености, након чега следи да се максимална ударна снага оштећења значајно повећава. Поређење релузтата удара другог и трећег узорка показују да у случају сличне закривљености преднапрезање доводи до нижег оштећеног подручја. Ови резултати су од посебног значаја за пројектовање закривљених композитних компонената.