

SOME EXAMPLES OF THE RELATION BETWEEN PROCESSING AND DAMAGE TOLERANCE

Alan T. Nettles
NASA Marshall Space Flight Center
Materials and Processes Laboratory
MSFC, AL 35812

ABSTRACT

Most structures made of laminated polymer matrix composites (PMCs) must be designed to some damage tolerance requirement that includes foreign object impact damage. Thus from the beginning of a part's life, impact damage is assumed to exist in the material and the part is designed to carry the required load with the prescribed impact damage present. By doing this, some processing defects may automatically be accounted for in the reduced design allowable due to these impacts. This paper will present examples of how a given level of impact damage and certain processing defects affect the compression strength of a laminate that contains both. Knowledge of the impact damage tolerance requirements, before processing begins, can broaden material options and processing techniques since the structure is not being designed to pristine properties.

1. INTRODUCTION

This paper is intended to highlight the importance of damage tolerance with respect to foreign object impact and how it may be related to some of the manufacturing aspects of a laminate. If a PMC part is designed to damage tolerance criteria that include impact damage, then some processing defects may not be critical compared to the impact damage being considered. Knowing that certain manufacturing defects will be inconsequential compared to the levels of impact damage that the structure may be designed to can potentially save time and money on processing costs by knowing that a "defect free" laminate may not necessarily give higher design allowables. This may ease some of the stringent processing parameters that add time and cost to the manufacture of a PMC part.

In order to fully characterize a reduction in strength due to impact damage and processing defects, the impact damage-processing defect interaction must be examined since a "worst-on-worst" scenario is typically considered.

The simple study in this paper will examine the compression strength of laminates since this is the property most widely tested with respect to damage tolerance. Both pristine laminates and laminates with processing defects will be tested for unimpacted compression strength. These laminates will also be tested for Compression After Impact (CAI) strength with barely visible impact damage (BVID). The reduction in strength of the laminates due to foreign object impact, processing defects, and combination of both will be examined. Since the data generated in this study is only for demonstration purposes, only one impact and processing defect severity level will be examined. Three types of processing defects and one material comparison (unidirectional

tape versus woven fabric prepreg) will be considered giving a total of 4 types of laminates (types of specimens) to be tested. These are discussed in the following sections.

1.1 Co-Cured versus Pre-Cured Face Sheets on Honeycomb

If a honeycomb sandwich structure is being manufactured, whether the face sheets are co-cured, or pre-cured and then bonded to the honeycomb in a secondary bonding process, can affect the compression strength of the face sheet material. For co-cured laminates a “knockdown” factor is typically used to account for the “pillowing” and increase in void content that takes place [1-2]. Sandwich specimens will be manufactured using both of these fabrication methods and compared with regard to undamaged and impacted compression strength.

1.2 Foreign Object Debris (FOD)

During processing it is possible for a piece of debris (typically a film material used during processing) to get embedded between plies. This is obviously not desirable, but the presence of such may not preclude the use of an otherwise well-made laminate if the compression strength degradation does not exceed that due to impact damage and the impact damage and FOD do not interact to cause a larger decrease in compression strength than either alone. Sandwich specimens with a small piece of FOD embedded in one of the face sheets will be made from woven fabric pre-preg and the compression strength compared to identical specimens without FOD. Specimens with and without FOD will be impacted and compared to unimpacted specimens to determine the reduction in compression strength due to FOD, impact or both FOD and impact at the same location.

1.3 Porosity

Porosity (voids) within a laminate are usually not desirable but nearly impossible to completely eliminate. Porosity can reduce the compression strength of a composite laminate with as little as 1-2% void content [3]. If designing to impact damage tolerance requirements, porosity may not be of consequence to the compression strength of the part as long as the porosity and impact damage do not interact to cause a larger decrease in compression strength than impact alone. Laminates will be intentionally manufactured with a high level of porosity to compare to identical specimens with little to no porosity. The reduction in compression strength due to foreign object impact, porosity and both porosity and impact damage will be examined

1.4 Prepreg Fabric versus Unidirectional Tape (Material Comparison)

It is generally acknowledged that laminates made from unidirectional tape prepreg will have higher strength and stiffness than a laminate of the same material and lay-up constructed from woven fabric prepreg. However, if designing to damage tolerance requirements, the advantage of the laminate made from unidirectional tape prepreg may be lost if it cannot withstand impact damage as well as laminates made from woven fabric prepreg.

While not a “processing defect” making a laminate from woven fabric prepreg will typically result in a laminate with less compression strength than an equivalent laminate made from

unidirectional tape prepreg. Thus a laminate made with woven fabric is analogous to a “processing defect” for the purposes of this paper.

Quasi-isotropic face sheet sandwich panels will be manufactured from both woven fabric prepreg and unidirectional tape prepreg with the same resin system and compared for compression and CAI strengths.

2. EXPERIMENTATION

The three processing defects and one material comparison mentioned in the introduction were tested for compression and CAI strength in this study. The amount of impact damage imparted into the laminates was such that BVID was produced, which is somewhat arbitrary but will help to demonstrate the comparisons to be made in this paper. All of the laminates tested were of a $\pi/4$, quasi-isotropic lay-up. The specifics for each of the 4 types of laminates tested follow.

2.1 Co-Cured versus Pre-Cured Face Sheets on Honeycomb

The carbon/epoxy fiber/resin system used for manufacturing these specimens was T800/5320. The honeycomb core was 3.81 cm thick aluminum of 50 kg/m³ density with a cell size of 3.2 mm. The sandwich panels that were co-cured were manufactured with 0.276 MPa of pressure and the face sheets that were pre-cured were manufactured at a pressure of 0.552 MPa. A secondary bonding process was used to attach the pre-cured face sheets to the core and utilized FM-300 film adhesive. The lay-up of the face sheets was $[+45,0,-45,90]_s$ giving a nominal thickness of 1.02 mm. A cross section photomicrograph of each type of sandwich specimen is shown in Figure 1.

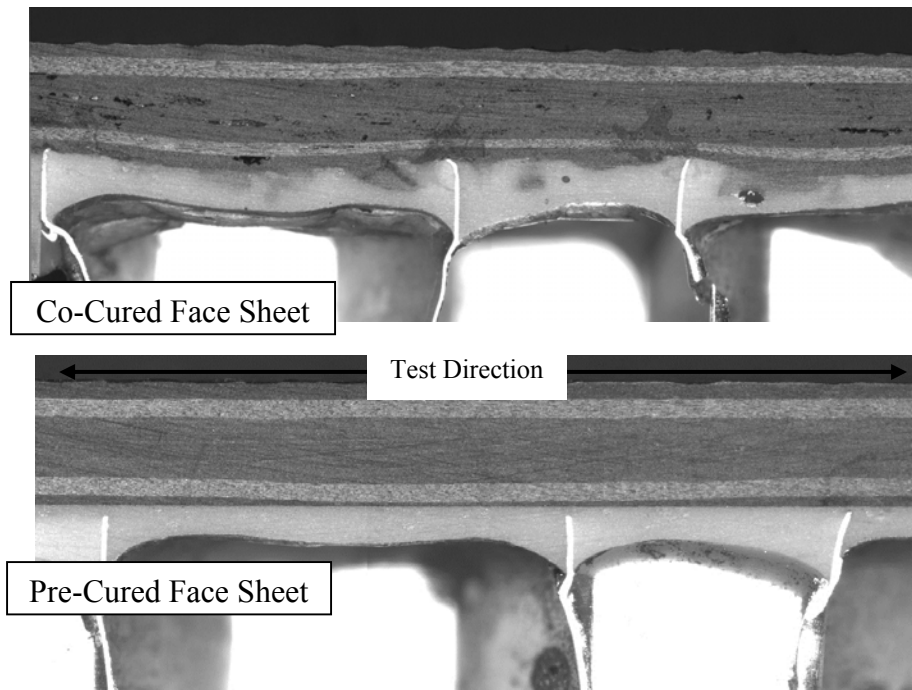


Figure 1. Cross sections of face sheet from Co-Cured (top) and Pre-Cured (bottom) sandwich specimens.

Note that the laminate that was pre-cured (bottom of Figure 1) has straighter lamina, particularly on those plies nearest the core. This laminate also has less porosity, although the porosity of the co-cured laminate is still under 0.5%. This indicates that the pre-cured laminate should have higher compression strength than the co-cured laminate.

The processed sandwich panels were cut into 10.2 cm wide by 15.2 cm tall specimens and select ones were impacted with a 12.7 mm diameter impactor at their geometric centers. The panels were supported over a steel plate during impact. Approximately 4.0 J/mm of impact energy was used for all of the impacts to produce BVID. Since each laminate was approximately 1.02 mm thick, this gave typical impact energy of about 4.08 J.

Compression specimens were made by embedding the ends of each sandwich specimen in potting compound within an aluminum frame and then precision machining the ends [4]. These specimens were then end loaded to failure. A photograph of this test is shown in Figure 2.

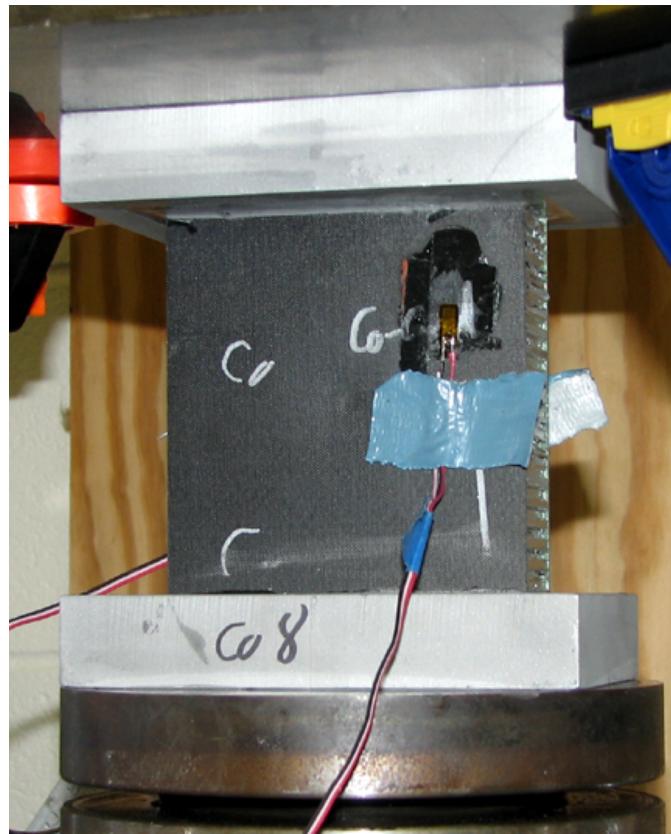


Figure 2. Photograph of test used to determine compression strength for co-cured/pre-cured specimens.

2.2 Foreign Object Debris

The sandwich specimens used for this testing had face sheets made from AS4/8552 plain weave carbon/epoxy prepreg. The face sheets were co-cured onto 3.81 cm thick 50 kg/m³ density aluminum honeycomb core that had a cell size of 3.2 mm. The laminates that comprised the face sheets had a lay-up of $(45_f/0_f)_S$ and a nominal thickness of 1.02 mm. Circular pieces of Teflon film 12.7 mm in diameter were placed at the mid-plane of half the laminates during processing to simulate FOD. This FOD was positioned such that it would be at the geometric center of the 10.2 cm by 15.2 cm specimens that were to be excised from the panel. A flash thermography image of a specimen showing FOD is given in Figure 3. The compression specimens used for this part of the study were identical to those used in the previous section. For specimens that were to have impact damage, a 12.7 mm diameter impactor was used with impact energy of 4.4 J/mm to produce BVID. The impact location was at, or within 5 mm of, the center of the FOD to obtain a “worst on worst” scenario.

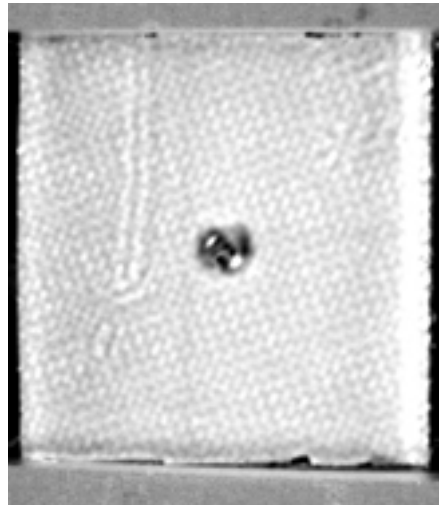


Figure 3. Flash thermography image of FOD in specimen.

2.3 Porosity

The specimens used for testing the effect of porosity on compression strength were manufactured from T800/5320 carbon/epoxy unidirectional prepreg. The lay-up of the two laminates manufactured was $[+45,0,-45,90]_{2S}$.

Porosity was introduced into one of the laminates by curing the laminate only at atmospheric pressure. Most of the voids were removed in the other laminate which was cured at 0.552 MPa of pressure. Cross-sections of the laminates with and without porosity are given in Figure 4. The void content of the porous laminate was determined to be about 4-5%. The thickness of the void free laminate was 2.03 mm whereas the porosity caused a slight increase in laminate thickness to 2.20 mm. For subsequent calculations the thickness of both are considered to be 2.03 mm since the additional thickness of the porous laminates is entrapped gas.

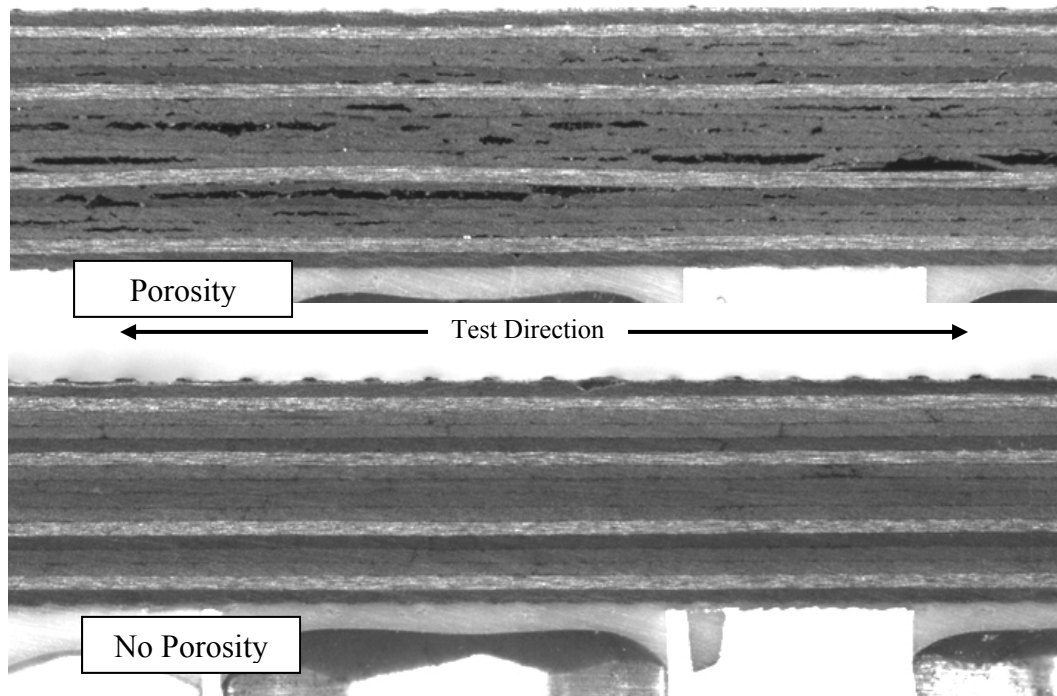


Figure 4. Cross-sections of laminates with porosity (top) and without porosity (bottom).

These laminates were tested in compression utilizing the four-point bend method [5] since their thickness precluded the use of end loading due to equipment availability.

These laminates were bonded onto high density aluminum honeycomb (200 kg/m^3) with FM-300 film adhesive and then cut into 5.1 cm wide by 61 cm long beams.

The sandwich beams to be impacted were impacted with a 6.3 mm diameter impactor at their geometric centers. The panels were supported over a steel plate during impact and approximately 3.3 J/mm of impact energy were used for all of the impacts to produce BVID. Since each laminate was approximately 2.03 mm thick, this gave typical impact energy of about 6.7 J.

2.4 Woven Cloth versus Unidirectional Tape

These specimens were manufactured with either AS4/8552 Woven Fabric/Epoxy prepreg or IM7/8552 unidirectional prepreg tape. The resin systems were identical but the fibers were not. The IM7 fiber is reported to have ~18% more compression strength than the AS4 fiber when in 8552 resin [6,7]. This must be considered when evaluating the CAI strength results.

Both types of laminates had a quasi-isotropic lay-up and nominal thickness of 1.02 mm. The laminates were co-cured onto 200 kg/m^3 density aluminum honeycomb for subsequent compression testing via the four point bend method.

The sandwich panels were cut into 5.1 cm wide by 35.6 cm long beams and impacted with a 6.3 mm diameter impactor at their geometric centers. The beams were supported over a steel plate during impact and approximately 3.6 J/mm of impact energy were used for all of the impacts to produce BVID. Since each laminate was approximately 1.02 mm thick, this gave typical impact energy of about 3.7 J.

Representative cross-sections of these two types of specimens are shown in Figure 5.

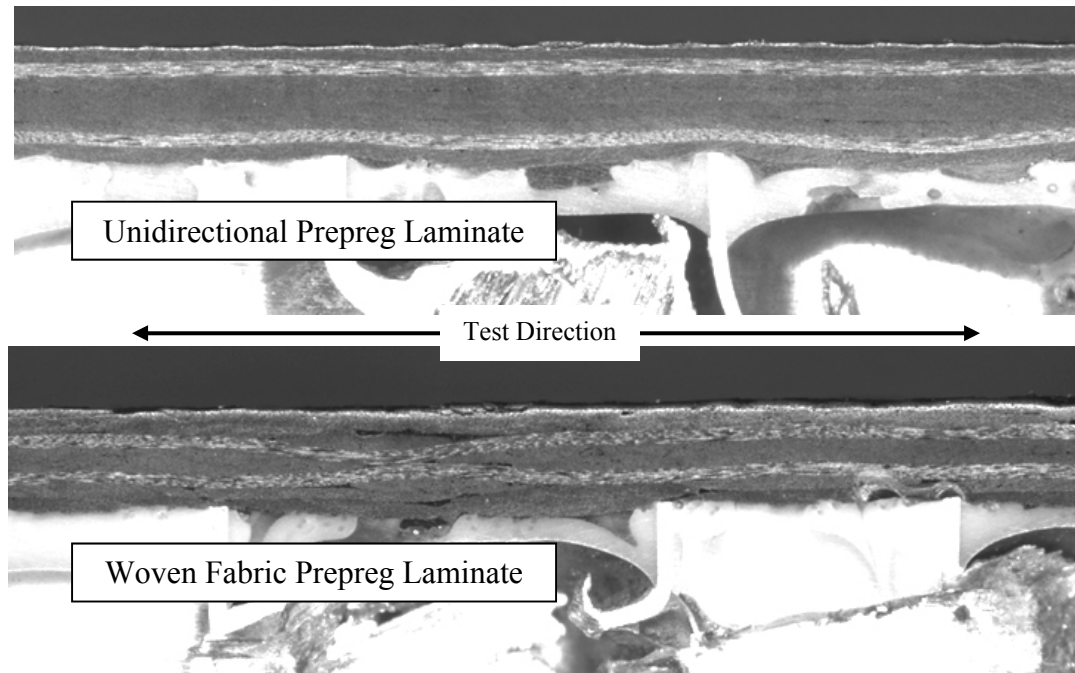


Figure 5. Cross-sections of laminates made from unidirectional prepreg tape (top) and woven fabric prepreg (bottom).

3. RESULTS

The results from each of the 4 sets of tests will be given in the specific sections below.

3.1 Co-Cured versus Pre-Cured Face Sheets on Honeycomb

The results of compression testing for these specimens are shown graphically in Figure 6.

As expected, the undamaged strength is greater (by 33 %) for the pre-cured laminate compared to the co-cured laminate. However, when impacted at a level to cause BVID (in this case 4.0 J/mm), the laminates have essentially the same strength whether pre-cured or co-cured.

Thus from this limited data, it appears that if a honeycomb sandwich structure is designed to carry compressive loads, once impact damage is considered there is no difference between co-curing or pre-curing the face sheets. Knowing this can save processing costs since a multi-step, more costly pre-cured face sheet process, while giving higher pristine compression strength, ultimately may not give higher CAI strength design allowable.

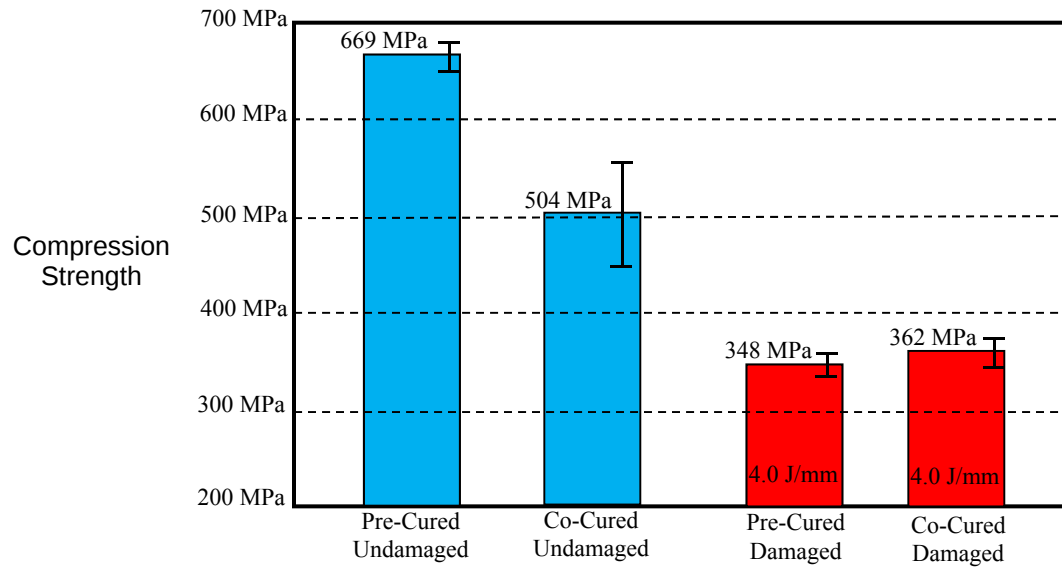


Figure 6. Results for compression testing of undamaged and impacted co-cured and pre-cured specimens.

3.2 Foreign Object Debris

The results of compression testing for these specimens are shown graphically in Figure 7.

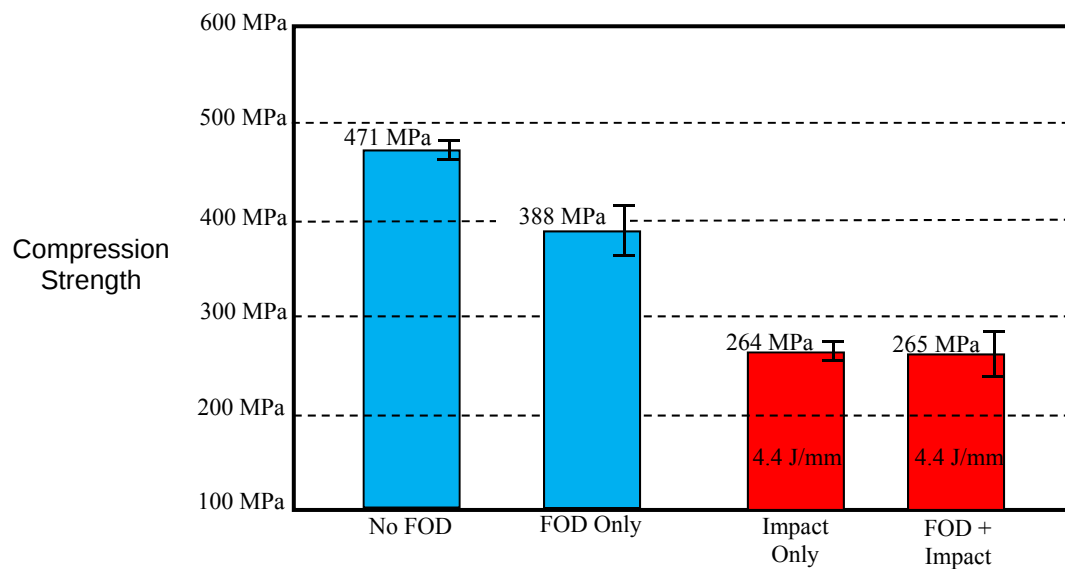


Figure 7. Results for compression testing of no FOD and FOD specimens with and without impact damage.

The laminates with FOD have an average compression strength that is lower (by 18 %) than for the laminates without FOD. However, when impacted (in this case with 4.4 J/mm), the laminates have essentially the same strength whether FOD is or is not present. This demonstrates that a processing defect (in this case FOD) that lowers the compression strength of a laminate may not necessarily result in part rejection once impact damage requirements are considered.

3.3 Porosity

The results of compression testing for these specimens are shown graphically in Figure 8.

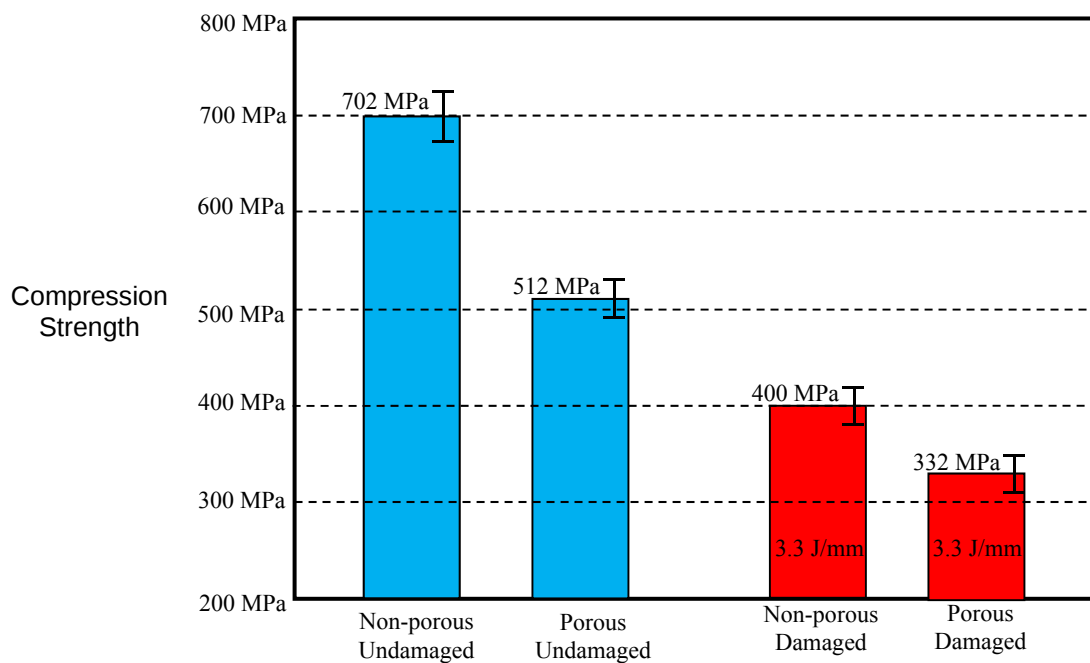


Figure 8. Results for compression testing of non-porous and porous specimens.

As expected, the compression strength is greater (by 37 %) for the non-porous laminate compared to the one with 5-6% porosity. When impacted to a BVID level (in this case with 3.3 J/mm), the porous laminate still has less strength but the percent difference is not as great (20% greater compression strength for the non-porous laminate) as in the undamaged case.

For the laminates tested in this part of the study, the impact damage caused a larger reduction in compression strength than the high porosity. However, since the impact damage, when superimposed upon the porosity, causes an even greater decrease in compression strength than either impact damage or porosity alone, the porosity interacts with the impact damage and the two combine to give a lower CAI strength than either porosity or impact damage alone. Thus unlike the two previous examples the processing defect examined here (porosity) lowers the CAI strength more than a “well processed” laminate.

3.4 Woven Cloth versus Unidirectional Tape

The results of compression testing for these specimens are shown graphically in Figure 9.

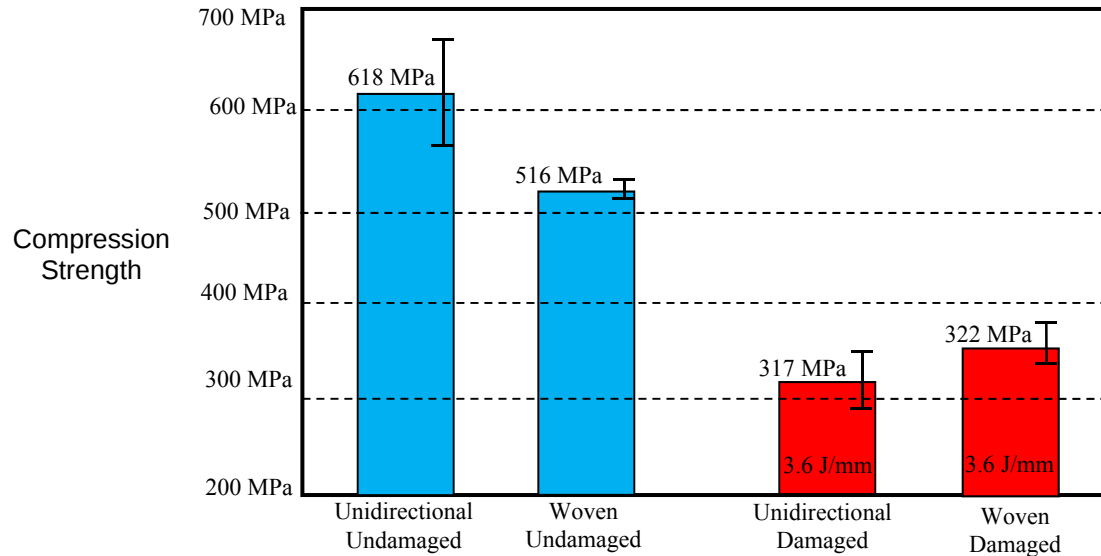


Figure 9. Results for compression testing of unidirectional and woven specimens.

The undamaged strength is greater (by 20 %) for the laminate made from unidirectional prepreg tape compared to the laminate made from woven fabric prepreg. Some of this difference is attributed to the carbon fiber in the specimens made from unidirectional prepreg having a compression strength $\sim 18\%$ higher than the carbon fiber used in the specimens made from woven fabric prepreg. However, when impacted to a BVID severity level (in this case with 3.6 J/mm), the woven fabric laminate has about the same strength than the unidirectional tape laminate.

For the laminates tested in this part of the study, the impact damage reduces the compression strength of a laminate made from unidirectional prepreg tape more compared to a laminate made from woven fabric prepreg. Thus if a part is to be designed to BVID impact damage requirements, there may be no advantage in using unidirectional prepreg tape to manufacture the laminate than using woven fabric prepreg, even with a lower grade fiber. This knowledge can open up more processing options.

4. DISCUSSION

The results of section 3 will be compared in this section and quantitative examples of the conservatism incurred by considering processing defects and impact damage separately, rather than together, will be given.

As an example, consider the results from the FOD and no-FOD specimens. The following average compression strength values were obtained;

No FOD = 471 MPa

FOD only = 388 MPa

Impact only = 264 MPa

FOD and Impact = 265 MPa

The decrease in compression strength due to the FOD used in this study is seen to be $(471 \text{ MPa} - 388 \text{ MPa})/471 \text{ MPa} \times 100\% = 18\%$. At the impact severity level used in this study, the undamaged compression strength decreases by $(471 \text{ MPa} - 264 \text{ MPa})/471 \text{ MPa} \times 100\% = 44\%$. If the two defects are considered independently, then an impacted specimen with FOD should have a compression strength calculated as 82% of undamaged compression strength due to FOD and then this new value retaining only 56% of compression strength due to impact damage. For the specimens in this study this would be a predicted FOD + impact damage compression strength of about $(0.82 (471 \text{ MPa}))(0.56) = 216 \text{ MPa}$. However; the measured values have an average of 265 MPa indicating that if the two flaws are considered separately, the actual compression strength is underestimated by 18%. The end result will result in an overly conservative design. Table 1 presents similarly analyzed data from all 4 types of manufacturing defects considered in this study.

Table 1. Predicted and measured values of compression strength of specimens examined in this study with both manufacturing flaws and impact damage.

Type Defect	% Retention of Strength With Defect	% Retention of Strength With Impact	Predicted % Retention With Both	Measured % Retention With Both	Difference
Co-Cure	75	52	39	46	Predicted 15% lower
FOD	82	56	46	56	Predicted 18% lower
Porosity	73	57	42	47	Predicted 11% lower
Woven Fabric Prepreg*	84	51	43	52	Predicted 17% lower

*Compared to unidirectional prepreg

From Table 1 it can be seen that “stacking” process defects and impact damage without measuring the compression strength of laminates with both will typically result in a predicted value that is lower than what the laminate actually has. Obviously the defect and impact severity levels will change the values shown.

5. CONCLUSIONS

From the four sets of tests performed in this study that examined processing defects and/or impact damage, it appears that impact damage can be more of a design driver than the 3 processing defects examined. Obviously the severity of each type of defect needs to be

considered, but it was the intent of this paper to demonstrate the importance of designing to damage requirements (in this case impact) and by doing such, some manufacturing defects (or material types) will be of no consequence since they do not reduce the compression strength of a laminate more than an impact of BVID severity. However interaction of the defect and impact damage must be considered since, like in the case of porosity, the two can interact to cause a lower CAI strength than either impact or processing defect alone.. However, for those cases in which impact damage and processing defects do not interact, such as “pillowing” due to co-cure over honeycomb, attempting to reduce the pillowing will not result in a laminate with a higher CAI strength.

An interesting result, within the parameters of this study, is that structures made from unidirectional prepreg are not necessarily “stronger” in compression than similar structure made from woven prepreg fabric once impact damage is considered. Depending on the application this (using woven fabric prepreg rather than uni-directional prepreg) can potentially save money, especially if hand lay-up is the only processing option.

It should be noted that in this paper, the mechanical property of interest was compression strength; however the property of interest can be something other than compression strength depending on the end use application of the laminate.

6. REFERENCES

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