INVESTIGATIONS INTO THE INITIATION OF FAILURE MECHANISMS UNDER UNI-AXIAL COMPRESSIVE LOADING

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Abstract

Research was conducted to investigate the effects of material quality and specimen preparation on the failure mechanisms in unidirectional carbon fiber. The mechanical testing that was used was compressive; this followed the guidelines of the ASTM D 695 M [ASTM D 695 M, Standard test method for compressive properties of rigid plastics. http://www.astm.org] test method.

Specimens conforming to this standard were produced with varying quality material. Optical and electron (SEM) microscopical techniques were used to assess initiation of failure and to quantify the damage encountered by the compressive test specimen.

The findings correlate well with the mechanical test results, additionally; from the mechanical testing there was significant evidence to suggest that the failure mechanism is dependent upon the quality and preparation of the test specimen.

1 Introduction

The nature of compressive failure in unidirectional composite laminates has been examined for more than three decades [1-4]. It is accepted that the failure process may involve both elastic and plastic microbuckling matrix failure and fiber fracture. Kink bands formed as a result of in plane buckling may also occur. Compressive failure is matrix dominated; therefore improvements in the compressive properties of the resin matrix can be expected to improve the compressive properties of the composite [5].

The performance of unidirectional composites is very dependent on the fiber alignment with respect to the applied load. It has been reported that the initial fiber misalignments of the order of 1.5-2°, significantly reduce the compressive strength [6]. Thus accurate alignment of fibers with an absence of waviness is critical to the performance under compression.

In the axial compression of unidirectional composites three basic failure modes can be observed [7]; local buckling of fibers (where production variations such as fiber waviness or non uniform fiber spacing can influence compressive strength), transverse rupture of the composite (due to differences in Poisson's ratios of the material constituents and non uniform distribution of transverse strains over the specimen length); failure in compression (shearing of the fibers at an angle of 45 degrees with no local buckling of the fibers). These principal modes of failure can be accompanied by a series of other phenomena:

- Inelastic and non-linear behaviour of fibres and matrix
- Interlaminar stresses
- Surface ply separation
- Overall loss of stability

Different combinations of all these phenomena can make it very difficult to establish the failure mode or obtain consistent results even with the same material and test procedure. Additionally defects within the laminate can alter the failure mode.

One of the most common manufacturing defects are voids, these are areas of trapped air that are found within the resin and between plies/fibres within composites.

Micrographic studies have revealed that voids are the commonest of all defects found in vacuum bag mouldings. There are several causes of void formation, but only two of them have been the focus of significant study and modelling [8,9]. Firstly, the entrapment of gases (most often wet air), and

secondly, volatiles arising from the resin itself. The trapped air originates from the different stages of the manufacturing process, (1) from the initial manufacturing stage, due to either air bubbles being trapped in the viscous resin or between the fibres and (2), voids may be formed by volatile components or contaminates, which vaporise during the high temperature part of the cure cycle. Hence the voids are areas within the composite where there are no matrix or fibres present.

Voids have been investigated by many researchers [10 and 11], and they have all concluded that the inclusion of voids within a carbon fibre laminate is detrimental to the mechanical properties.

Work conducted by Sharez et al [12] showed a clear relationship between void content and compressive strength. They found a 10% reduction in compressive strength for every 1% increase in void content. This trend, however, was only found to be true for materials with a void content of less than 4%; at a greater void content than this, the trend was not uniform. This gives some clues as to the homogeneity of the material, and suggests that at lower void contents, the voids are distributed more evenly.

Budiansky and Fleck [13] suggest that voids may contribute to the compressive failure of composites. They are largely attribute failure initiation to fibre microbuckling, but do, however, imply that as the void content increases, the initial fibre misalignment increases. However, there are reports [14] that state if the void content remains under 1% of the total measured area the effect that the voids will have on the overall mechanical properties of the laminate are negligible.

The interfaces play an important role in the behaviour of the composite. As adhesion between the fibres and matrix improves, the load transfer is more efficient and the mechanical characteristics of the composite are enhanced. In addition, the interface strength affects the path of crack propagation in the material. For example, Wo [15] shows that if the interface is weaker than the matrix, a crack that initiates perpendicular to the fibres may turn and propagate parallel to them along the interface.

Fig. 1. shows the acceptable failure modes when testing to BS EN ISO 14126: 1999 [6]. The failure mechanisms and measured properties will obviously primarily depend upon the material but will also be influenced by the construction of the test piece.

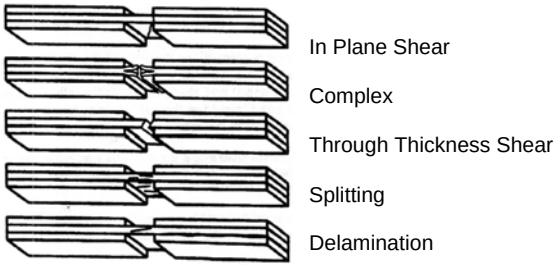

Fig. 1. Acceptable failure mechanisms as stated by BS EN ISO 14126:1999[6]

Failure will occur at the lowest possible stress and in the corresponding failure mode. The range of possible failure strengths implies that the ultimate compressive strength of a composite is not a precise term, but primarily one of definition.

The compressive properties of composites are poor in comparison with their tensile properties and ideally should not be subjected to compression. However, in many applications such as wind turbines, the loading is complex and elements of compression and flexure are unavoidable. Industry therefore requires reliable data on which to base their designs, select materials and perform structural calculations. From previous research [16] it was found that the optimum test specimen thickness is approximately 2mm thick.

The objectives of this report are to optimize the test preparation method and specimen configuration, over and above the method specified in ASTM D 695 M [17], by understanding some of the sources of variation in this test. Two areas of the compressive test were focused upon, these are: edge quality and surface preparation of the compressive test specimen. This was then applied to a different material to verify the preparation method.

2 Experimental Procedures

2.1 Material and Specimen Fabrication

The material that was used in this study was Toray T600-50C and Toray T700-50C unidirectional carbon/epoxy composite (Gurit). Test specimens were manufactured from 4 plies of T600-50C and 4 plies of T700-50C to give an approximate thickness of 2mm. The test specimens

were manufactured and tested according to ASTM D 695 M [17], Fig. X shows the compressive rig used with a specimen in position.

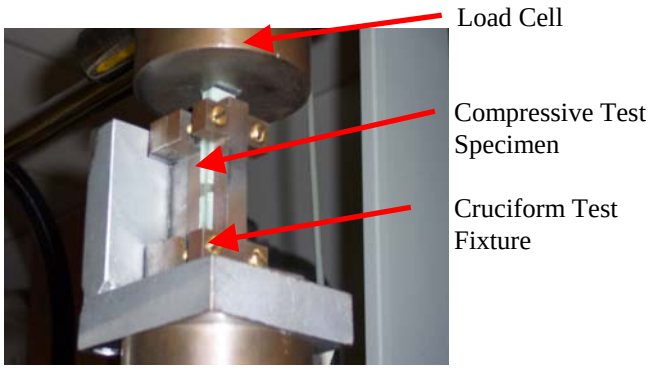

Fig. 2. ASTM D 695 M [17] test fixture with specimen in position

The test preparation of the test specimen includes the process of cutting the test specimens to size. The method by which this is done is critical to the final quality of the edges of the specimens. There are two cutting methods that have been used for the manufacture of the T600-50C, advanced cutting method (method A) and standard cutting method (method B).

Both of these techniques use a diamond tipped blade as a cutting medium. They differ in that method A uses a common lubricant mixed with water as the cooling liquid while method B uses water from the mains supply. Method A is semi-automated and achieves a dimensional accuracy of 0.05mm. Method B is manual and accuracy and quality of cut is operator dependent. Typically an accuracy of 0.5mm is achieved.

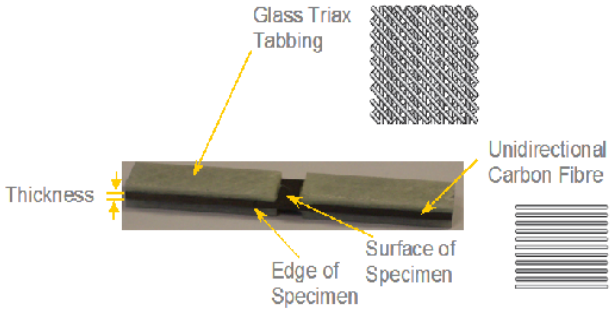

Fig. 3. Example of a compression test specimen

Due to the nature of this compressive test specimen (as shown in Fig. 3.) the surface of the carbon fiber component has to be of suitable roughness to guarantee good secondary adhesion for the tabbing. Therefore, the laminate has to undergo a surface preparation technique in order to guarantee the secondary adhesion. The most common surface preparation techniques are the use of peel plies. The three peel plies that are to be used are Release stitch A – coarse mesh, Release stitch G – medium mesh and Release B – fine mesh [18].

Additionally, there are also mechanical abrasion techniques that can be used to prepare the surface for secondary adhesion. In this research, two abrading techniques were used: wet and dry paper and grit blasting. These abrading techniques were applied to the areas on the compressive test panels where it was necessary for the secondary adhesion leaving the gauge length un-abraded. It should be noted that the peel ply covered the whole surface of the compressive test panel and hence affected the surface finish within the gauge length.

2.2 Test Procedure

The compressive strength testing was completed using a Zwick Z150 static test machine, which has a 250kN load cell. The compressive strength tests were carried out in accordance with ASTM D695 M [17]. The test machine was calibrated prior to the test program commencing. The test fixture that was used was a cruciform type as in accordance with the standard. All tests were carried out on samples at 20°C and 50±5% room humidity. The specimens were not dried prior to testing.

The two types of carbon fiber used were T600-50C to establish a beat practice route and secondly, T700-50C to verify the best practice route.

3 Results

It was assumed that the specimens would be manufactured at approximately 2mm in thickness based on the findings of Soutis [19].

3.1 The Effect of Edge Quality

Twelve batches of compressive test specimens were manufactured using 4 plies of T600-50C unidirectional carbon. The specimens were aligned prior to cutting. Six of the batches were prepared using advanced cutting method A and six prepared using standard cutting method B. These batches were evaluated on a Talyscan 150 profilometer to quantify the edge roughness that each preparation method produces. Fig. 4. shows the

effect of edge roughness on the compressive strength.

Method A consistently produced a surface finish of between 4-5µm average surface roughness, whereas cutting method B produced a surface finish in the range 3.5 -22µm. The coefficient of variation for the cutting method A (6.0%) was significantly lower than cutting method B (17.3%).

The results show a trend of increasing edge roughness reducing the compressive strength. The compressive strength at 22µm Ra was only 60% of the 4µm roughness samples which strongly suggests that edge quality plays an important role in the initiation of compressive failure and hence the results of compressive testing.

These test specimens were examined using an optical microscope prior to mechanical testing to visually assess edge condition resulting from the preparation methods. It was found that method A produced a consistent finish free from saw marks and abrasions (Fig. 5.). This contrasts with method B which caused saw abrasions and penetration marks as shown in Fig. 6. and in greater detail in the SEM image (Fig. 7.). The type of damage caused by Method B could have been due either to the alignment of the blade and/or the operator's control.

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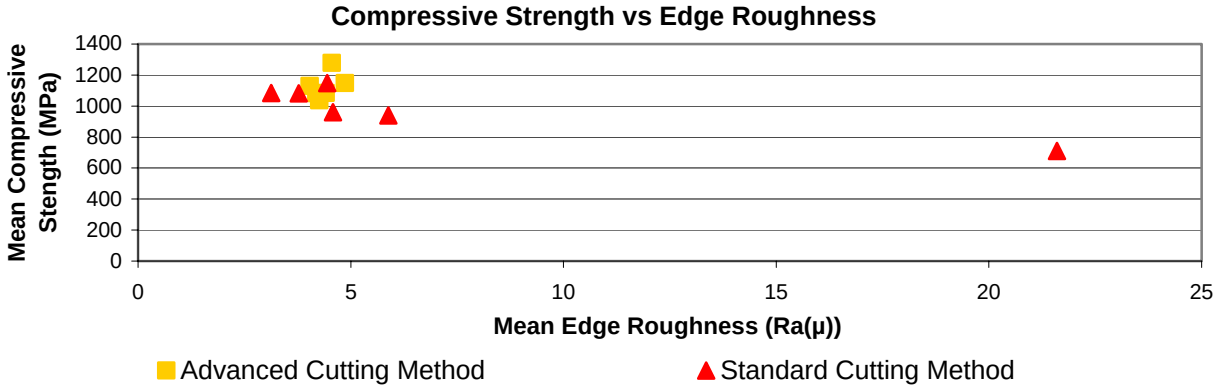

Fig.4. Graph showing the mean compressive strength against measured edge roughness

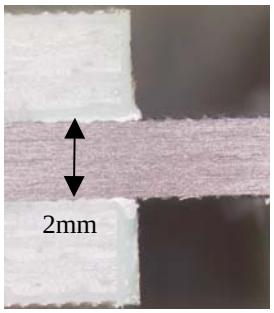

Fig. 5. Example of the Method A finish

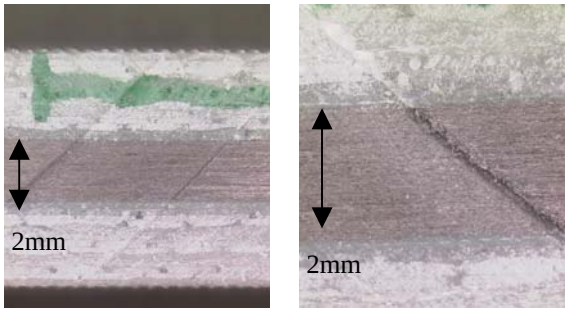

Fig. 6. (a) and (b) Example of the Method B finish

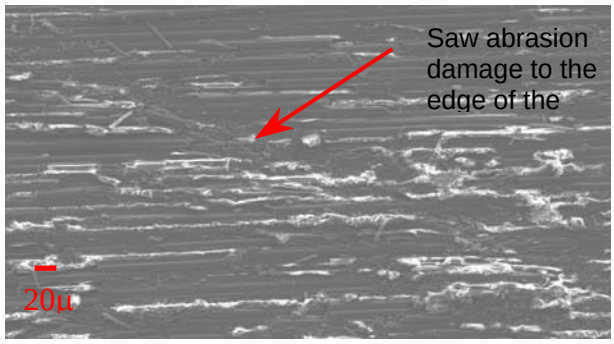

Fig. 7. SEM image of the abrasion in Fig. 6. (b)

3.2 The Effect of Surface Preparation

The five surface preparation techniques that were applied to the T600-50C unidirectional carbon fiber in order to provide a surface suitable for secondary adhesion for the end tabs were: wet and dry sandpaper (Grade 400), grit blasting (aluminum oxide 6040), Release stitch A peel ply, Release B peel ply and Release stitch G peel ply [18]. For the adhesion of the end tabs an epoxy based adhesive

was used. Fig. 8. shows the mean compressive strength achieved by the batches against the mean surface roughness recorded using the profilometer.

Wet and dry abrasion and grit blasting preparation techniques achieved the smoothest surfaces and the lowest compressive strengths. The failures were clearly tabbing (adhesion) failures caused by the surface roughness being insufficient for secondary adhesion. The compressive tests were essentially testing the construction of the test specimen rather than the compressive strength of the composite.

The three different types of peel ply range from coarse (Release stitch A) to fine (Release B) mesh grades, with Release stitch G between A and B. Release B peel ply resulted in at least 50% of the test specimens from each of the two batches failing via adhesion failure. An average surface roughness value of approximately 9µm is too smooth for consistent secondary adhesion.

Release stitch A and Release stitch G provided very similar results, in terms of mean compressive strength and coefficient of variation. There were no adhesion failures with either of these preparation methods. Release stitch A produced an average surface roughness of 14.9µm compared with Release stitch G that achieved 11.5µm average surface roughness.

The test specimens were analysed using the SEM. The Release stitch A peel ply resulted in a very coarse surface with a texture composed of peaks and troughs. Fig. 9. is an image taken on the SEM of a peak left by the Release stitch A peel ply after removal from the laminate.

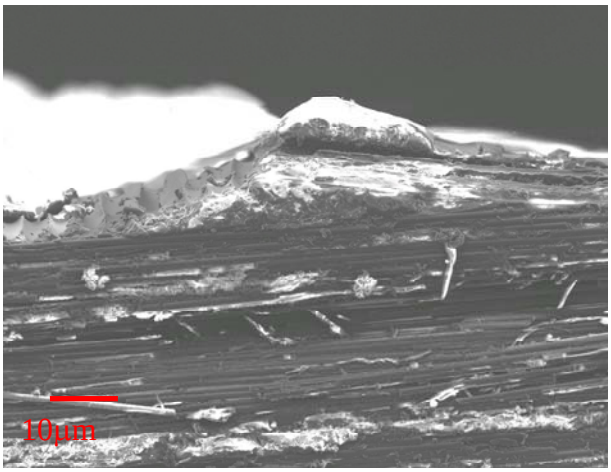

Fig. 9. SEM image of the residue left by Release peel ply A

The deposits were measured to be 0.014mm. This is a significant thickness considering the specimen is only 2mm thick and will adversely affect the calculated compressive strength. Release G also produced a textured surface comprising peaks and troughs but was slightly smoother with an average thickness of 0.01mm.

Overall the coefficient of variation from the mechanical test results correlated well with the Talyscan results (Fig 5). Method A gave the highest compressive strength results and the lowest variance. The specimen that had the highest edge roughness (prepared using method B) also achieved the lowest compressive strength value. This investigation has shown that edge condition plays a role in the initiation of failure in a compression test. To maximize the failure strength and minimize the coefficient of variation a smooth, defect free edge surface is required.

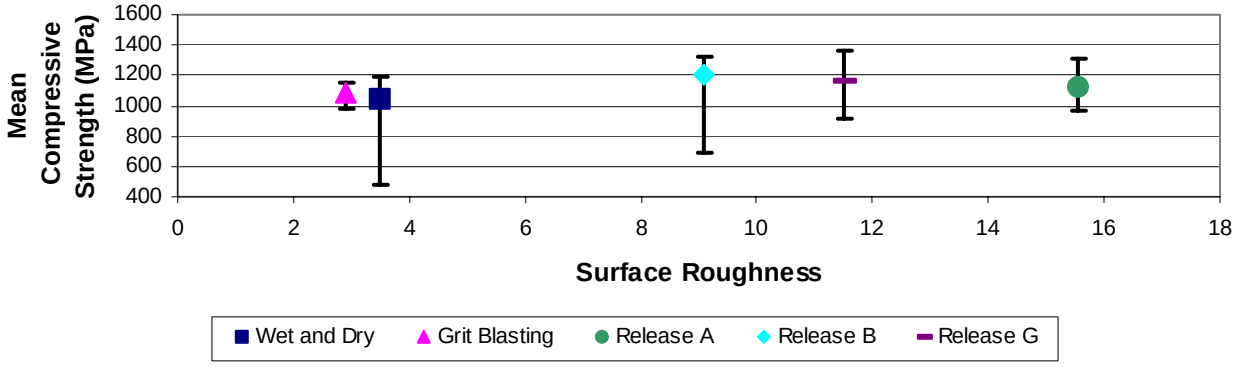

Fig. 8. Graph showing the mean compressive strength against the measured surface roughness

3.3 Verifying Compressive Test Specimen Preparation Route

One panel of 22 specimens was manufactured from the T700-50C unidirectional carbon. It is evident from the results given in Table X that the T700-50C was inferior in performance to the T600-50C specimens due to low mean failure strength and the high variance.

Table 1. Summary of compressive results recorded from the two types of unidirectional carbon

	T600-50C	T700-50C
Mean Strength (MPa)	1100	920
Standard deviation	55	156
Coefficient of Variation (%)	5	17

Fifty-five percent, over half of the specimens from the T700-50C batch failed via in plane shear failure (Table. 1.), this involves shearing of the fibers from one side of the sample to the other over the width (Fig. X). Considering the T600-50C laminate, the compressive strength is significantly better to that of the T700-50C and the variance is much lower at just 5%.

To understand further why there were such a large difference in the compressive strength and variance between the T600-50C and T700-50C, samples were polished and quantified for void content.

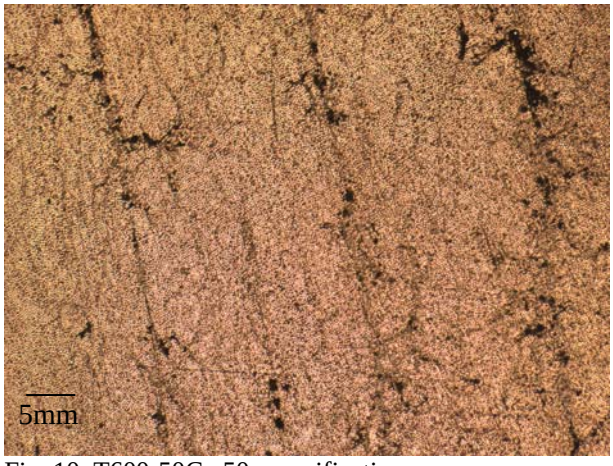

Fig. 10. T600-50C x50 magnification

Fig. 10. shows the image acquired from the T600-50C sample. It was found to have a void content of 1.2%. Figure X shows the T700-50C image that was used for void analysis. This however, gave a void content of 4.1%, this is significantly higher than the 1.2% for T600-50C.

Using this information and the findings from Budiansky and Fleck [13], it was considered that as the fibers are under compressive loading it is natural for them to have a tendency to buckle. If the area surrounding the fibres contains a high percentage of voids, there is therefore no matrix to support these fibers and prevent them from moving. Therefore, the fibers are not locally supported and are susceptible to microbuckling.

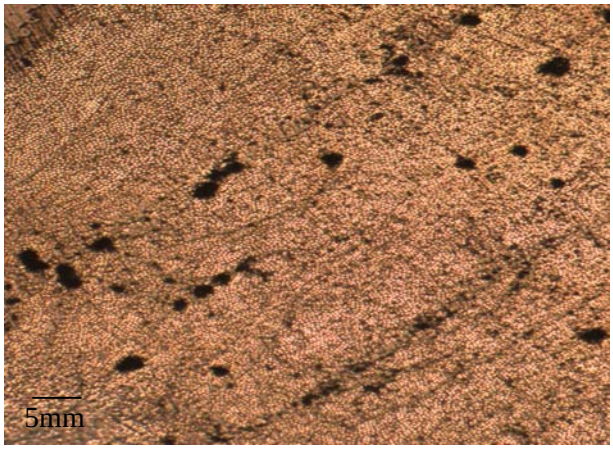

Fig. 11. T700-50C x50 magnification

Failure Modes

The failure modes observed during this research are summarized in Table 2.

Table. 2. Failure mode results

	Failure Modes		
	In Plane Shear %	**Through Thickness Shear %**	**Complex %**
T600-50C	5	70	25
T700-50C	54	36	9

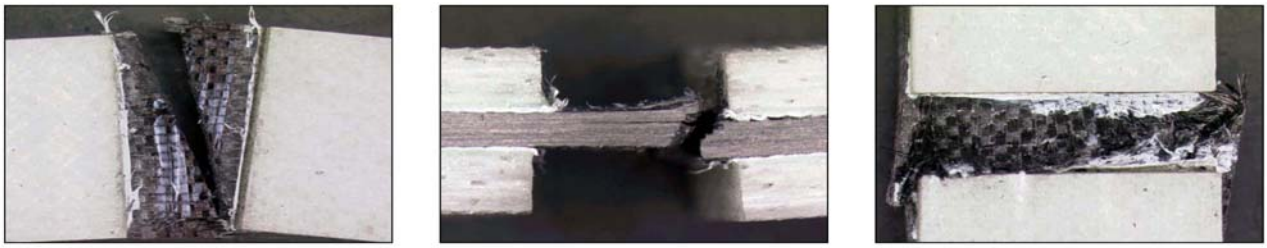

Fig.12. (a) In plane shear failure; (b) through thickness shear failure; (c) complex failure

From the T700-50C results 54% of the specimens failed by in plane shear failure. From previous research [16] is has been demonstrated that in plane shear failures initiate at the edge of the specimen indicating poor edge preparation. From the findings of this body of research it was evident that the T700-50C had over three times the amount of voids than the T600-50C the in plane shear failures are thought to have initiated from voids along the exposed edge of the specimen where even the presence of the void itself generates a weakness in the structure of the compressive test specimen. Additionally, from previous research it has been noted that in plane shear failures give the lowest resultant compressive strength.

The T600-50C results showed that 70% of the failures were due to through thickness shear failure (Figure X (b)). From previous research [16] it has been found that this failure initiates at the surface of the specimen within the gauge length. These results reinforced the fact that the release stitch G provides a far superior surface finish as only 36% of the T700-50C samples failed via this mode. All the T700-50C specimens were prepared using this release fabric.

4 Discussion

The quality of the sample cut edge proved to be an important variable because with edges containing defects such as saw abrasions failed at lower loads and batches of samples produced by operator dependent methods showed significantly higher variance in the compressive strength results. Poor edge preparation induced in plane shear failures. The results indicate that low coefficient of variation can be achieved with an edge roughness of <5μm.

The quality of the free surface is equally important. A surface, that is, too smooth will result in a low compressive strength and high coefficient of variation because of tabbing adhesion failure. Conversely a surface, which is too rough, may result in increased coefficient of variation because of through thickness shear failures initiating from high roughness sites on the free surface. The results suggest that a surface finish in the range of 10-13μm should be sought.

The verification of the “best practice” preparation method indicated that the quality of the laminate is critically important when testing for compressive strength. The difference in void content followed consistently with the drop in compressive strength from the T600-50C to the T700-50C. As the quality is reduced the variance increases.

The features that have been discussed above influence the mode of failure. With a well prepared specimen (and high quality material) the dominant failure mechanism is complex which involves the load being carried by the fibers and the matrix keeping the fibers vertical in plane.

5 Conclusions

From the results obtained through this research, it is clear that the results of compression tests are influenced by:

- Edge preparation
- Surface preparation
- Quality of carbon fiber unidirectional laminate

To achieve reliable compressive strengths from the standard compressive tests, which reflect the quality of the composite, a consistent smooth specimen edge is required and a free surface of roughness sufficient to promote tabbing adhesion without causing premature failure from roughness features on the free surface within the gauge length.

6 References

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