# CHARACTERISATION OF DEFECTS – DURABILITY RELATIONSHIPS FOR COMPLEX GEOMETRY PREPREG LAMINATES

Mark Battley, Simon Bickerton, Alex Mordasini, Abhiram Ramesh, Nathan Connell and Logan Dunning Beck

Centre for Advanced Composite Materials, University of Auckland
Private Bag 92019, Auckland 1142, New Zealand
Email: m.battley@auckland.ac.nz, Web Page: http://www.cacm.auckland.ac.nz

**Keywords:** Defect, durability, manufacturing, void, wrinkle

**Abstract**
The focus of this paper is on the formation of manufacturing related defects during manufacture of corner sections in thick carbon-fibre epoxy prepreg laminates and characterisation of their effect on damage initiation and durability. Test panels were manufactured using autoclave cure, then sectioned for microscopy and micro-CT imaging based defect characterisation. Measurements were taken during layup, vacuum deconsolidation, and after autoclave cure, in order to observe at which phase defects are forming. Typical defect types included increased laminate thickness, ply wrinkles and pinching, small needle shaped voids typically associated with wrinkling and larger bridging voids. The characteristics and size of the defects depended strongly on the manufacturing process.

## 1. Introduction

Carbon-fibre reinforced prepreg materials are widely used for high performance applications in the land, air and sea transportation sectors. In all cases long-term durability is essential for reliable operation. Autoclave based manufacturing processes are generally considered to enable the manufacture of high quality laminates, and industry sectors such as aviation have developed guidelines to quantify quality, such as acceptable average void levels. Recent increases in resolution and sample size for techniques such as micro X-ray computer tomography have enabled significant insight to be obtained into how defects such as voids and lamina discontinuities such as wrinkles affect damage initiation and propagation [1,2], in particular highlighting that distribution of voids and their size have much greater effects on damage initiation than the average void content [3]. Most of this research has been for relatively thin laminates, and the types of defects and their effects on the durability of thick laminates are not well understood.

Depending on laminate details and processing parameters, manufacturing of part geometries with tight radius corners can result in imperfections and defects such as local lamina wrinkling and voids. The overall aim of this work is to investigate the formation of manufacturing related defects during manufacture of corner sections in thick carbon-fibre epoxy prepreg laminates and determine their effect on damage initiation and durability. This paper describes the characteristics of the defects and investigates factors affecting their formation. Testing methods for evaluation of the effect of the defects on durability are also discussed.

Excerpt from ISBN 978-3-00-053387-7

## 2. Specimen Manufacture

Seven panels were produced with different variations in the manufacturing technique used. The two first panels used a tubular vacuum bag for the debulk process. Panels 3 to 6 were produced using a fitted vacuum bag on the mould for the debulk process to enable the thickness of the laminate inside the mould to be measured during the layup process. Panel 7 was produced using a tubular vacuum bag for a debulk process that was applied every five plies.

The material was a Toray T700 standard modulus carbon fibre with a Hankuk RS4545S Epoxy resin system. The debulk vacuum bag was a mono extruded polyethylene and the curing vacuum bag was a 0.125 mm thickness nylon film. A nylon peel ply, polyester breather cloth and polyolefin perforated release film were used. The samples were laminated on a U-shaped female aluminium mould, coated with a polytetrafluoroethylene film. The mould geometry is shown in Figure 1.

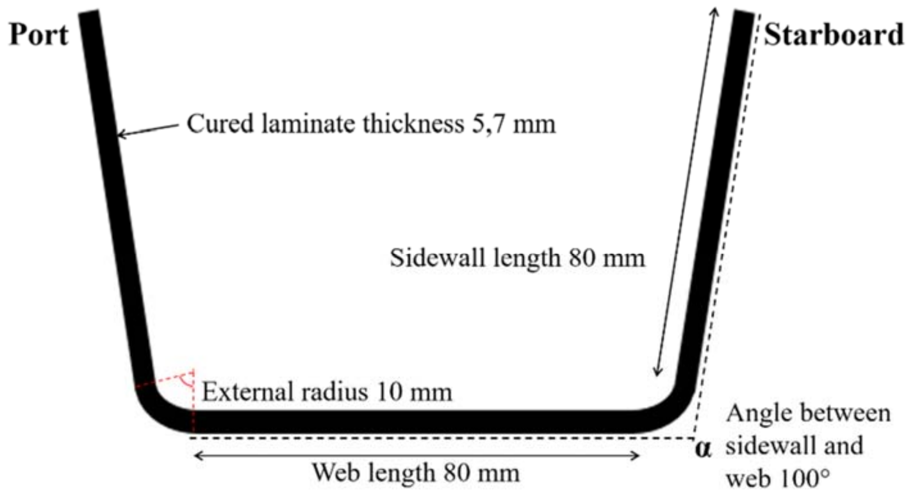


**Figure 1.** Mould geometry.

The mould geometry and nominal 5.7mm laminate thickness were chosen based on previous work within this research programme that found that this configuration was prone to corner defects. The mould length enabled two 400mm long samples to be manufactured at the same time and also ensured that fibres of a 45° ply were continuous from one top angle of the panel to his opposite top angle. Prepreg sheets had a width of 268 mm. The laminate comprised of 28 plies, (12 x 0°, 12 x ±45° and 4 x 90°) with a sequence: [0, 90, 0, +45, -45, 0, ±45]n. The 0° ply had a 300 g/m2 prepreg fibre content with an average 0.30 mm thickness before debulk while the 90° and ± 45° plies were 150 g/m2 with an average 0.15 mm thickness before debulk. A manual lay-up process was used. Each prepreg ply was applied on the web part initially and then conforming to the corner with care taken avoid bridging over corners. For 90° plies, a high density polyethylene tool was used to help the conformation to the corner.

To enable the thickness of the laminate to be measured during the layup process the mould was mounted to a coordinate measuring machine (CMM) table with two laser distance sensors (Keyence (IL-030) as shown in Figure 2. Two lines were scanned, the first was 20 mm from the panel edge on the sidewall (P1) and the second was on starboard corner (P2), enabling the thickness profiles of the flat sidewall and the corner to be measured during the lay-up. Calibration tests demonstrated that devices had a resolution of 0.01 mm, and an accuracy of 0.05 mm on uncured prepreg surface. Each scan consisted of the measurement of 250 points, with a distance of 2 mm between steps. This test was performed for every layer before and after debulk. Curing was undertaken in an autoclave and the panels demoulded at room temperature.

Excerpt from ISBN 978-3-00-053387-7

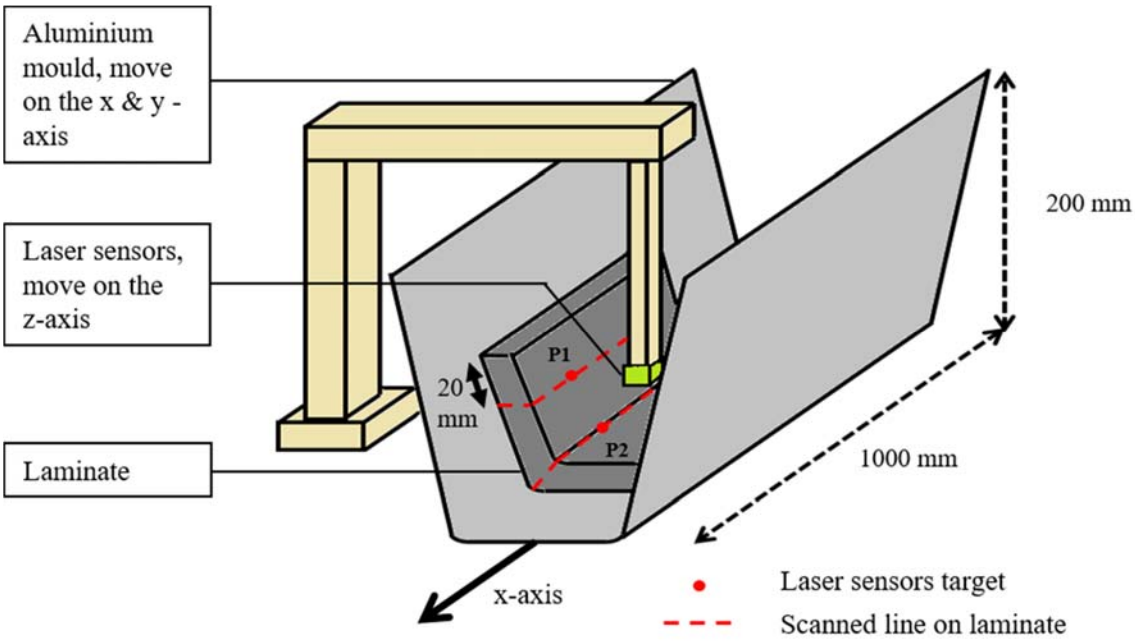


**Figure 2.** Laminate thickness measurement method.

## 3. Defect Characterisation

### 3.1. Approach

The manufactured laminates where characterised by laminate thickness measurements, optical microscopy of sectioned laminates and micro-CT imaging. For the thickness measurements three 20mm wide sections were cut equally distributed on the 0° axis of the laminate and cured thickness measured at 29 position across the wide of the U shaped sample using a calliper. Samples were prepared for optical microscopy using a wet grinder-polisher machine, initially using P120 paper grit followed by with P1200 paper grit. Corner cross-sections were then imaged on a Leica MZ16 Stereomicroscope at 0.7 low magnification. The micro-CT imaging was undertaken using a SkyScan 1272 desktop X-Ray micro-tomography system and Matlab based image analysis used obtain quantitative information such as volumes and aspect ratios of voids.

### 3.2. Typical Defects

Figure 3 shows images of corner cross-sections showing typical defect types which include increased laminate thickness, ply wrinkles and pinching, small needle shaped voids (typically associated with wrinkling) and larger bridging voids. The characteristics and size of the defects depend strongly on the manufacturing process. Figure 4 shows typical reconstructed 3D micro-CT images of a corner section and Figure 5 an example of image processing of the micro-CT images to identify defect characteristics. The micro-CT images highlight that the needle voids are discrete voids with very high aspect ratios.

Excerpt from ISBN 978-3-00-053387-7

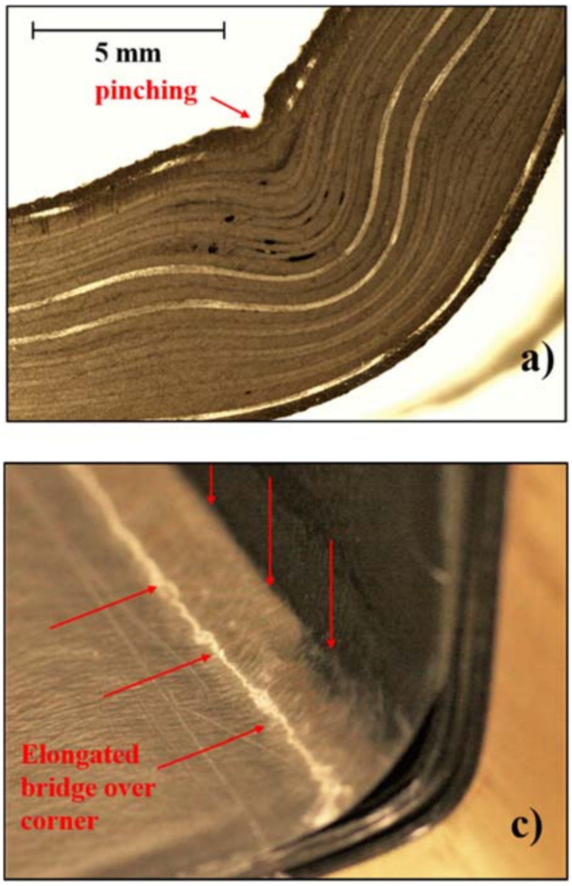


**Figure 3.** Panel corner images.

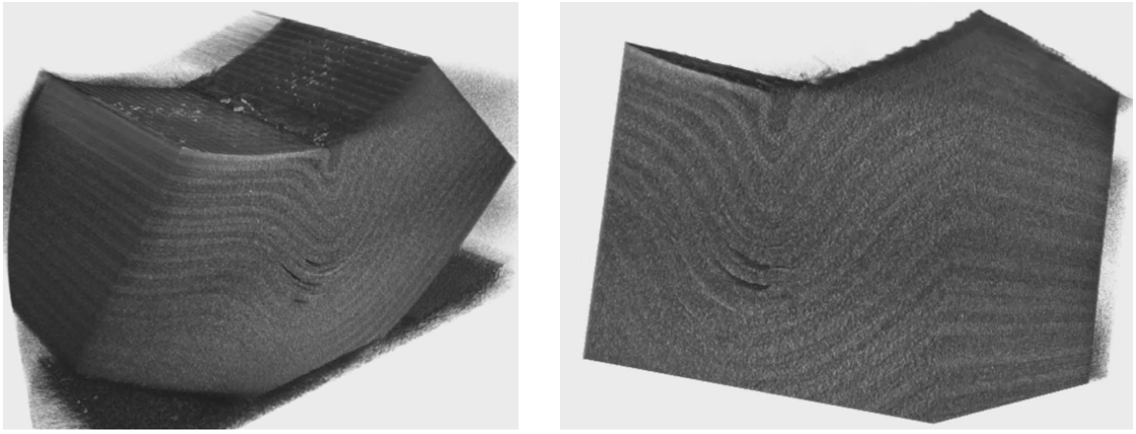

**Figure 4.** Reconstructed micro-CT images of corner section.

Excerpt from ISBN 978-3-00-053387-7

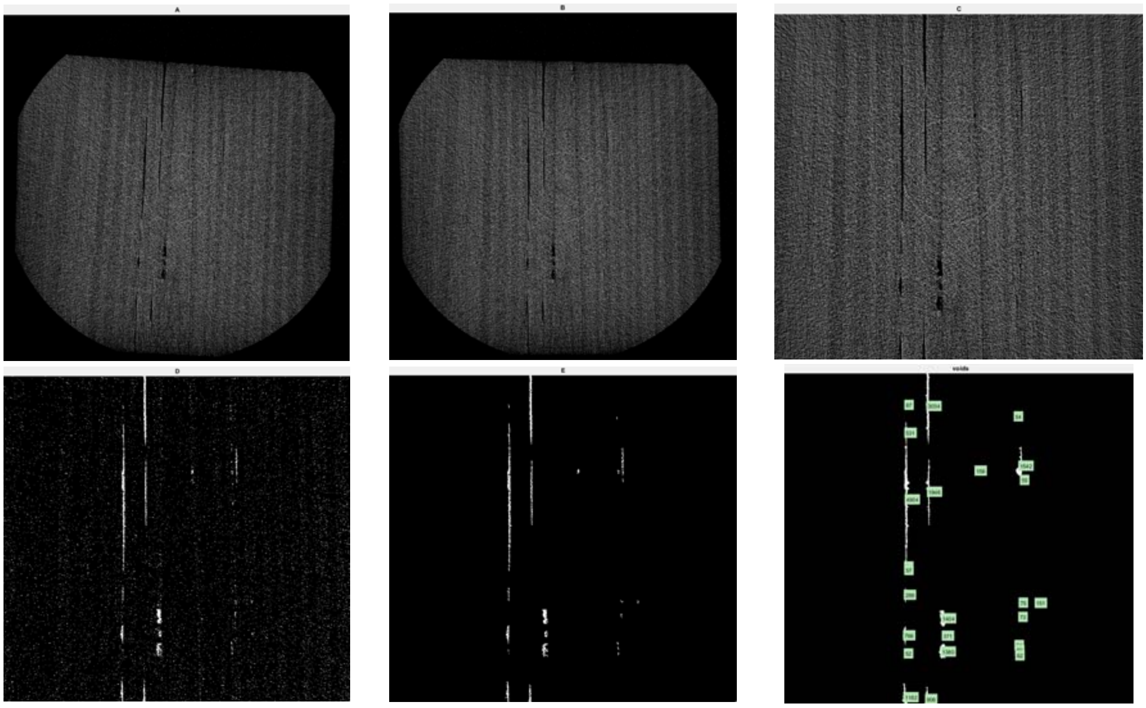

**Figure 5.** Image processing of the micro-CT images to identify defect characteristics.

## 4. Process Effects on Defect Formation

Figure 6 displays the thickness measurement results of the seven panels. When comparing the average thickness of flat sections and corners for the different cured laminates, the corners are about 25% thicker on average. The flat parts are all similar, with an average thickness of 5.69 ±0.07 mm. Thickness variations were more significant at the corners, with 7.13 mm thickness average, and a standard deviation of ±0.24 mm. The thickest corner was observed in panel 4 (7.58 mm), resulting in a difference of 32%, while thinnest corner is associated with panel 2 (6.80 mm), a difference of 22%. The difference in manufacturing parameters between those two panels was the bagging technique used for the debulk process, with panel 4 using a fitted bag for de-bulking and panel 2 a tubular bag.

Analysis of the micrographs of corner cross sections provided insight into laminate quality. Table 1 presents degree of wrinkling for port and starboard corners, and the degree of voids at corners found for each panel. A clear correlation between the manufacturing technique, part thickness and voids could not be established. In some cases, thin corners with low degree of wrinkling possessed large voids located at the centre of the laminate, and in other cases, large degree of wrinkling was not necessarily accompanied with prominent voids. However, for every panel, large voids were systematically observed in-between plies. For most of the cases, voids were located at centre of wrinkles.

Wrinkling also seemed to be closely related to the manufacturing process. With the exception of panel 5, samples using a fitted bagging techniques for debulk process had an average degree of wrinkling of 0.32 ±0.03, whereas an average wrinkling degree of 0.25 ±0.03 was observed with samples using the tubular bagging technique. The bagging technique appears to have a higher influence on corner quality than the number of debulk cycles, as panel 7 does not show critical wrinkles and has only moderate corner thickening.

Excerpt from ISBN 978-3-00-053387-7

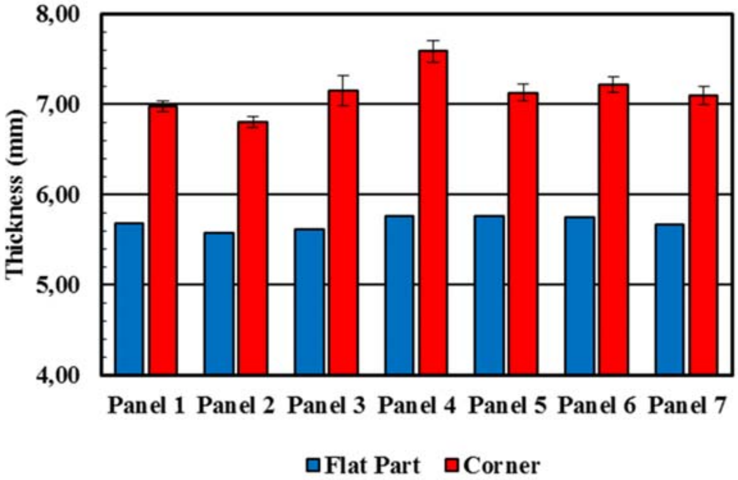


**Figure 6.** Specimen thickness variations.

**Table 1.** Panel corner defects observed by OM.

| Sample name | Wrinkling degree (16 ply) | | Large voids degree |
|---|---|---|---|
| | Port | Starboard | |
| Panel 1 | 0,29 | 0,24 | 1 |
| Panel 2 | 0,22 | 0,22 | 0,80 |
| Panel 3 | 0,28 | 0,33 | 0,83 |
| Panel 4 | 0,32 | 0,37 | 1,33 |
| Panel 5 | 0,30 | 0,24 | 0,80 |
| Panel 6 | 0,34 | 0,30 | 1,00 |
| Panel 7 | 0,22 | 0,26 | 1,50 |

Fig. 7 shows typical results from the thickness analysis of the layup and debulk process for the corner and sidewall laminates. Blue lines are 90° and ±45° plies and green lines represent 0° plies. Red lines show the 7th ply of each lay-up series, highlighting the four repeated stacking sequences. The red dashed line on both graphs relates to the 14th ply that is missing. This is situated at the unique place in the prepreg stack where two plies with identical orientation are laid-up in succession, enabling a single debulk process to be undertaken for those two plies.

The results enable specific behaviour to be identified, such as a 0.3 mm height wrinkle starting at the 15th ply around 125 mm on the panel axis which then impacts the following layers. Comparisons of the Corner and Sidewall graphs in Fig. 7 show significant differences in the thickness profiles. Similar results are obtained until the 8th ply, and then layer profiles dramatically change for the corner, while the side wall stays consistent. Analysis of average thickness for all scanned plies demonstrated that corner thickening could be identified at the 9th ply, and then grew proportionally as the stack is built, to end with an average difference in thickness of 0.5 mm. From Fig. 7 this appears to be related to ply 9 where ply bulges of 0.1 mm can be observed on the corner graph. These corresponded to entrapped air formed at the corner after a debulk process on a 0° ply. These kinds of surface inhomogeneity were only observed on 0° plies which also had a high standard deviation of thickness which tended to become larger as the laminate got thicker. The buckling that occurred with 0° plies may be a result of its low bending stiffness in the corner axis compared to the two other ply orientations. In general the debulk process was effective at compacting the sidewall and reducing its thickness variations, however it tended to induced variations at the corner thickness.

Excerpt from ISBN 978-3-00-053387-7

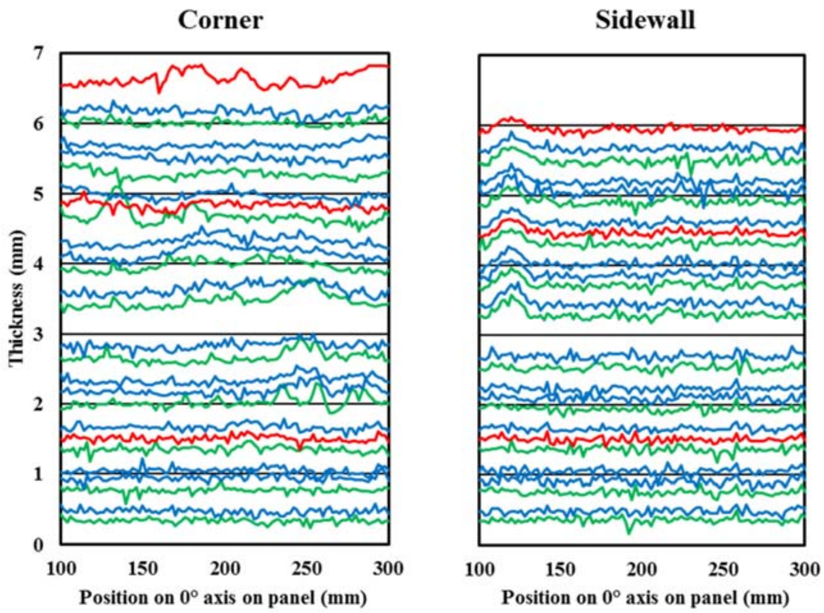


**Figure 7.** Ply stacking profile by scanning lines after debulk inside the mould on the corner and sidewall: blue lines represent 150 g/m$^2$ 90° and ±45° plies using, green lines are 300 g/m$^2$ 0° plies with 300 g/m$^2$ and red lines show last ply of the stacking sequence, highlighting the four repeats of the layup sequence.

## 6. Effect of Defects on Durability

In addition to understanding the formation of defects, an important goal of this work is to determine the criticality of the different defect types, and their effect on durability. This is being undertaken through development of test methods to characterise strength and damage progression of corner sections with defects, and modelling of the defect effects on damage initiation. Testing of corner sections is challenging, particularly avoiding end failure or edge buckling as shown in Fig. 8. Finite element modelling has been undertaken of the specimen design to develop a dog-bone configuration (Fig. 9)

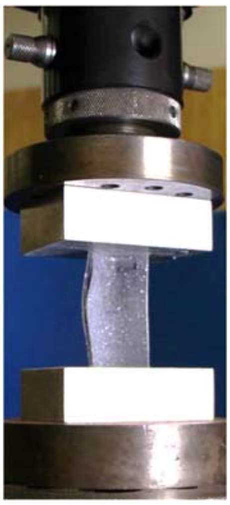

**Figure 8.** Buckling of corner compression test sample

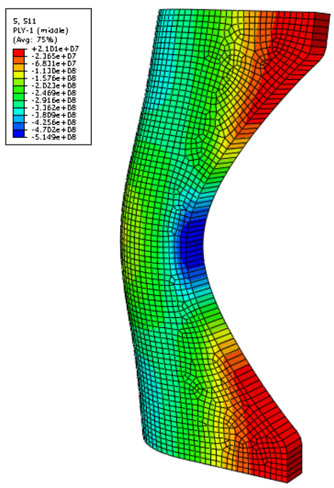

**Figure 9.** Finite element model of dog-bone corner specimen

Excerpt from ISBN 978-3-00-053387-7

## 7. Conclusions

The application of laser-based thickness measurement during lamination, post cure sectioning with optical microscopy and micro-CT imaging has provided significant insight into the effect of manufacturing processes on defect formation in complex geometry prepreg laminates. Typical defect types included increased laminate thickness, ply wrinkles and pinching, small needle shaped voids typically associated with wrinkling and larger bridging voids. The characteristics and size of the defects depended strongly on the manufacturing process.

Thickness variations were more significant at the corners than flat faces, with a tubular bag having lower variations than a fitted bag. In most cases, voids were located at centre of wrinkles and samples using a fitted bagging techniques for debulk process had a higher degree of wrinkling than was observed with samples using the tubular bagging technique. The bagging technique appears to have a higher influence on corner quality than the number of debulk cycles.

In general, 0° plies seemed to be more susceptible to local wrinkling defects than off-axis plies. This may be a result of the low bending stiffness in the corner axis compared to off-axis orientations. The debulk process was effective at compacting the sidewall and reducing its thickness variations, however it tended to induced variations at the corner thickness.

## Acknowledgments

This project has been funded by the New Zealand Ministry of Business, Employment and Innovation through grant UOAX1415.

## References

[1] B. Yu, R. Blanc, C. Soutis and P. Withers. Evolution of damage during the fatigue of 3D woven glass-fibre reinforced composites subjected to tension–tension loading observed by time-lapse X-ray tomography. *Composites Part A: Applied Science and Manufacturing*, 82, 279-290, 2016.

[2] A. Sandhu and A. Rhead. X-ray computed tomography of damage formation under in-situ loading. Proceedings of the *20th International Conference on Composite Materials ICCM-20, Copenhagen, Denmark*, July 19-24 2015.

[3] J. Lambert, A.R. Chambers, I. Sinclair and S.M. Spearing. Damage characterisation and the role of voids in the fatigue of wind turbine blade materials. Proceedings of the *18th International Conference on Composite Materials ICCM-18, Jeju Island, S. Korea,* August 21-26, 2011.

*Excerpt from ISBN 978-3-00-053387-7*