21st International Conference on Composite Materials
Xi'an, 20-25th August 2017

ANGLE-PLY LAMINATES WITH PARTIAL-DEPTH NOTCHES FOR DAMAGE TOLERANT DESIGN OF COMPOSITE PRESSURE VESSELS

Calum P. Fowler[1], Mathew W. Joosten[2], Adrian C. Orifici[3] and Chun H. Wang[4]

[1,3] Sir Lawrence Wackett Aerospace Research Centre, School of Engineering, RMIT University, Melbourne, Australia

[2] School of Engineering, Faculty of Science, Engineering and Built Environment, Deakin University, Waurn Ponds, Australia

[4] School of Mechanical and Manufacturing Engineering, University of New South Wales, Kensington, Australia

Keywords: Carbon fibre composite, Composite flaw tolerance, Discrete ply modelling.

ABSTRACT

The research presented in this paper focuses on the understanding and prediction of the failure mechanisms of angle-ply ($[\pm\alpha]_{4s}$) carbon fibre composite laminates with part-depth longitudinal notches, which is a key test configuration for demonstrating compliance with composite flaw tolerance requirements according to ISO 11439. Experimental investigations are carried out to characterise the deformation and failure of centre-notched carbon fibre composite specimens with $[\pm\alpha]_{4s}$ lay-ups, where α = 35°, 45°, 55°. The influence of notch depth and fibre angle on the tensile strength and failure mechanisms is analysed with the aid of both digital image correlation and X-ray computed tomography. Significant differences in damage onset and development are observed between full-depth and partial-depth notches leading to different strain-to-failure and strength knockdown. Development of delamination at the interface between notched and un-notched sub-laminates is observed to be a critical mechanism in part-depth damage development. This work provides new insight into the effect of part-depth notch on the load carrying capacity of filament wound vessels thus providing new insight into the damage tolerant design of composite pressure vessels.

1 INTRODUCTION

The use of renewable energy sources such as hydrogen gas and natural gas in transport vehicles requires lightweight storage vessels capable of high pressure. Fibre-reinforced composites have been a material of choice in manufacturing lightweight storage tanks. However, the certification of composite tanks relies on extensive experimental testing to qualify composite pressure vessel designs [1, 2] due to the lack of predictive modeling capability tailored for the analysis and optimisation of such fibre patterns and structures. Fibre-reinforced polymers are susceptible to damage induced by low-velocity impact caused by loading in the through-thickness direction (i.e. accidental drops, falling hand tools [3]). This leads to matrix micro-cracking, delamination and even localised fibre fracture, which affects mechanical performance and reduces structural integrity. Composite pressure vessels (CPV) must therefore be able to withstand loads for safe operation if they are to be commercially manufactured – so long as any damage can be quantified and assured to be within safe operating levels.

To ensure CPVs are able to operate safely in the event of impact damage (via leak-before-burst), leading international design standards such as ISO 11439 [1] require the pressurisation of full-scale vessels in the presence of various impact damage and man-made flaws. A composite flaw tolerance

(CFT) test is one such case which requires man-made flaws, in the form of longitudinal slots (Figure 1), to be machined into cylindrical vessel sections prior to cyclic pressurization [1, 4]. This is done to ensure non-destructive inspection methods are able to identify similar sized flaws during periodic inspection of vessels and to ensure the vessel is able to sustain the operating load after damage events. Slot sizes defined in ISO 11439 [1] are (1) 25 mm long/1.25 mm deep and (2) 200 mm long/0.75 mm deep and must be made in the middle of cylindrical vessel sections in their longitudinal direction.

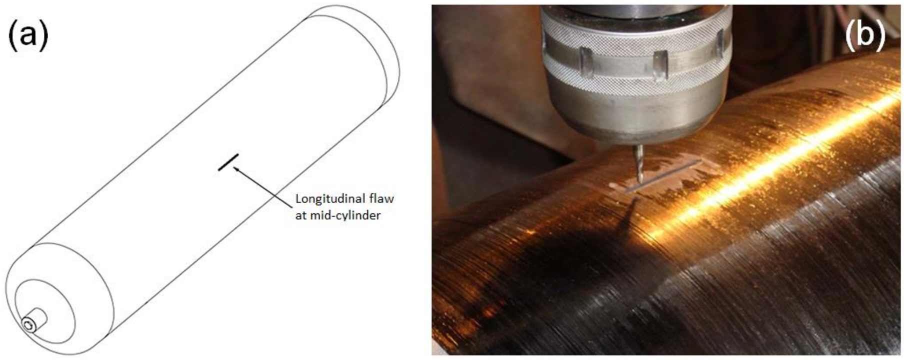

Figure 1: (a) Position and orientation of notch required in CFT test (adapted from [5]), (b) creation of notch in a composite pressure vessel using CNC-guided drill [6]

This full-scale, vessel-based experimental approach is costly and time-consuming, so there is a need to develop computational techniques to aid in the damage tolerant design of CPVs and reduce the number of required experiments. A building block approach [7] to CPV design can also minimise costs by relying more heavily on smaller-scale coupon tests before progressing to full-scale vessel testing. This has recently been achieved in a series of papers under the "OSIRHYS IV project" [8], which utilised uniaxial tensile testing of double-notched wound composite specimens to develop and validate numerical models for full-scale CPV design optimization [9-12]. The use of double-notched specimens is effective in inducing multiple damage modes to validate numerical models; however the use of centre-notch specimens with circular and slot-shaped flaws provides a more realistic representation of CPV design requirements. Centre-notch specimens with slot-shaped cut-outs lend themselves well to CFT optimisation, which was not a focus of the OSIRHYS IV project. This is particularly relevant to toroidal CPVs, which currently lack any design standards, where CFT requirements would include added complexity due to variable hoop stress distributions and shell thicknesses [2]. Moreover, the vast majority of research on toroidal CPVs has been limited to numerical analyses due to difficulties associated with manufacture and the assumption of angle-ply/helical ($[\pm\alpha]_n$) winding patterns [13-17] (Figure 1) and vessels in pristine condition. As such, there is a critical need to experimentally investigate angle-ply laminates in un-notched and notched configurations, and to develop models for damage and failure.

The aims of the present work are to characterise the failure mechanisms of notched angle-ply composite laminates that represent composite vessel winding patterns to aid in the development of predictive models in a follow-on study. The uniaxial tensile behaviour of partial-depth notched carbon fibre composite specimens with angle-ply stacking sequences is investigated experimentally. The influences of ply angle and notch depth on the tensile strength, damage mechanisms and failure modes are analysed using digital image correlation (DIC) and X-ray computed tomography (XCT).

2 SPECIMEN PREPARATION

Rectangular carbon fibre composite coupons were manufactured for use in notched tension tests according to ASTM D3039/D3039M-08 [18] and ASTM D5766/D5766M-11 [19], where applicable.

Rectangular laminated panels were made using T700/VTM264 carbon fibre/epoxy unidirectional prepreg material, which was produced by hand lay-up of sixteen 0.2175 mm thick, symmetrically-laid plies. Panels were autoclave cured before being cut into rectangular coupons. Coupons then had notches formed at their centres using a CNC-guided drilling machine with a 1.0 mm dia. slot drill bit. Gripped regions were roughened with sandpaper to increase friction between specimen surfaces and emery cloth. Notch depths of 25%, 50%, 75% and 100% (full-depth) of the total laminate thickness were produced among the specimens. Final coupon dimensions are given in Table 1.

Table 1: Partial-depth notch specimen geometry

Gauge length (L_{gauge})	Tab length (L_{tab})	Specimen Width (W)	Notch Length ($2a$)	Notch width/notch tip dia. (D)
160.0 mm	60.0 mm	60.0 mm	15.0 mm	1.0 mm

A non-contact, full-field strain measurement technique (DIC) was used to extract strain data and aid in the validation of numerical models. To achieve reliable strain data, all specimens required an appropriate speckle pattern on both their front (notched) and rear (un-notched) surfaces. Speckle patterns were created by applying a white base coat before lightly spraying with black spray paint.

With respect to CPVs, the fibre angle is taken with respect to the longitudinal axis of the cylindrical body as seen in Figure 2b. It is also known that composite cylindrical vessels typically possess hoop-to-axial stress ratios of 2:1. Composite theory, along with many previous studies [16, 20, 21], have thus proven that a lay-up of $[\pm 55]_n$ is required to obtain vessels of minimum weight for a given strength under such a biaxial load ratio. This results in an angle-ply lay-up orientated at ±35° with respect to the larger hoop-direction loading and ±55° with respect to the smaller axial-directed loading. Both these lay-ups have been chosen for use in this work. Angle-ply ±45˚ laminates were also included as this is the optimal lay-up for a 1:1 biaxial load ratio, which is likely to be encountered in toroidal CPVs as the hoop-to-axial ratio changes around the vessel cross-section. In summary, stacking sequences of $[(\pm\alpha)_4]_s$ were chosen for this study, where α = 35°, 45° and 55° (offset from the axis of loading as seen in Figure 2a).

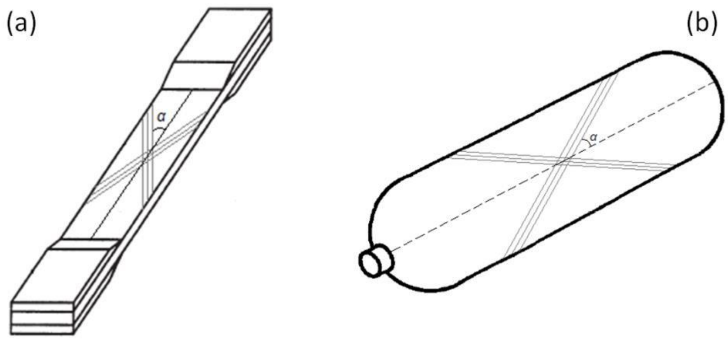

Figure 2: Angle-ply fibre orientations for (a) uniaxial tensile coupon and (b) cylindrical CPV

3 EXPERIMENTAL METHODOLOGY

Notched tensile testing methods were determined according to ASTM D3039/D3039M-08 [18] and ASTM D5766/D5766M-11 [19], respectively. Coupons were loaded at a displacement rate of 1.0 mm/min until failure using an MTS tensile testing machine with hydraulic wedge grips. Failure had to occur in the gauge length for data to be accepted and used. For most test cases, failure occurred at the notch. Load and cross-head displacement were recorded using computers directly linked to the MTS machine while axial displacement and strain were obtained using DIC software. The DIC software utilised in this work is version 4.2 of a freely available Matlab-based code which is periodically updated, user-customisable and validated with multiple sets of experimental data [22, 23]. Strain values shown in the following results section were extracted at a far-field location away from the notch and specimen edges to ensure strain concentrations and outer-ply matrix cracking would not affect the data.

4 EXPERIMENTAL RESULTS AND DISCUSSION

A summary of notched specimen tensile behaviour can be seen in Figure 3. It was immediately obvious that different angle-ply fibre orientations led to very different ultimate tensile strengths, stress-strain behaviour and strain-to-failure. As to be expected, tensile strength decreased as fibre orientations deviated further from the axis of loading, while the presence of notches also reduced both the tensile strength and strain-to-failure for all lay-ups. Significant non-linear behaviour and large strain-to-failure was observed in both ±35 and ±45 specimens due to large shear dominance whereas ±55 specimens fail at low strengths and strain-to-failures due to matrix dominance.

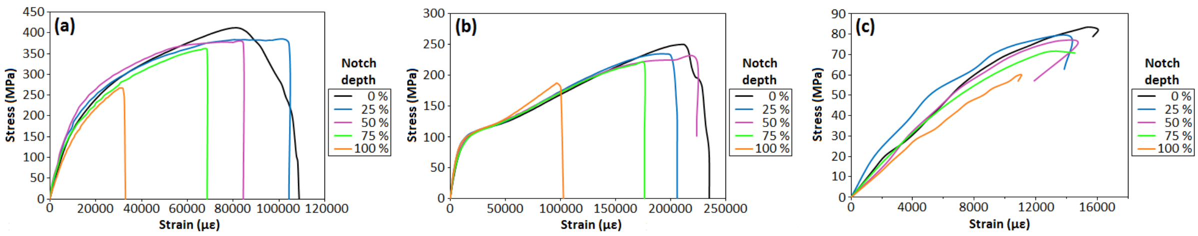

Figure 3: Experimental stress-strain curves; α = (a) 35°, (b) 45°, (c) 55°

A significant finding from the analysis of Figure 3 was that partial-depth notches result in minor strength losses compared to un-notched configurations for all angle-ply lay-ups and notch depths. To assess whether specimen configurations are "notch sensitive", strength loss was plotted against loss in net-section area from the notched condition (Figure 4). A specimen can be considered notch sensitive if the loss in strength is greater than the loss in net section area. It was observed that only a ±35 lay-up with a full-depth notch provided notch sensitive behaviour. In general, strength loss was less than the loss in net-section area. Several tests were stopped prior to gross specimen failure and then subjected to XCT imaging in order to identify damage mechanisms leading to this behaviour.

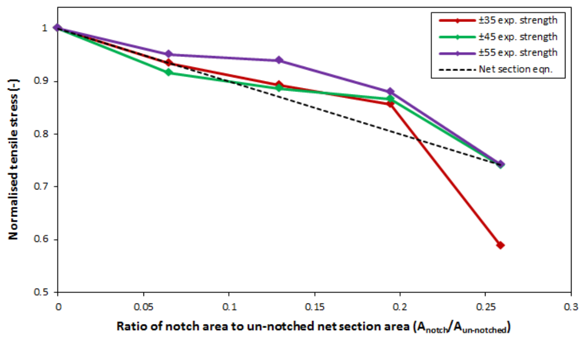

Figure 4: Strength knockdown versus loss in net-section area of partial-depth notch configurations

Delamination at the bottom of notches was consistently observed across all partial-depth notch specimens during post-experiment analyses. A typical progression of this damage in a deep notch (75% depth) can be seen in Figure 5 for a ±35 specimen. A specimen stopped at 80% ultimate strength already exhibits significant delamination growth from the bottom of the notch. Other forms of damage such as notch tip matrix split cracking and shear cracking in outer and mid-plane plies – that are typically observed in full-depth notch configurations [24-26] – are not present. As applied load increases, the delamination front moves further into the laminate and the notched sub-laminate exhibits out-of-plane displacement. This damage progression relieves stress concentrations about the notch, leading to stress re-distribution throughout the specimen and eventual gross failure in the un-notched sub-laminate (Figure 6). These observations aid in understanding the non-linear stress-strain behaviour (Figure 3a) and lack of "notch sensitivity" (Figure 4) of the specimen configuration.

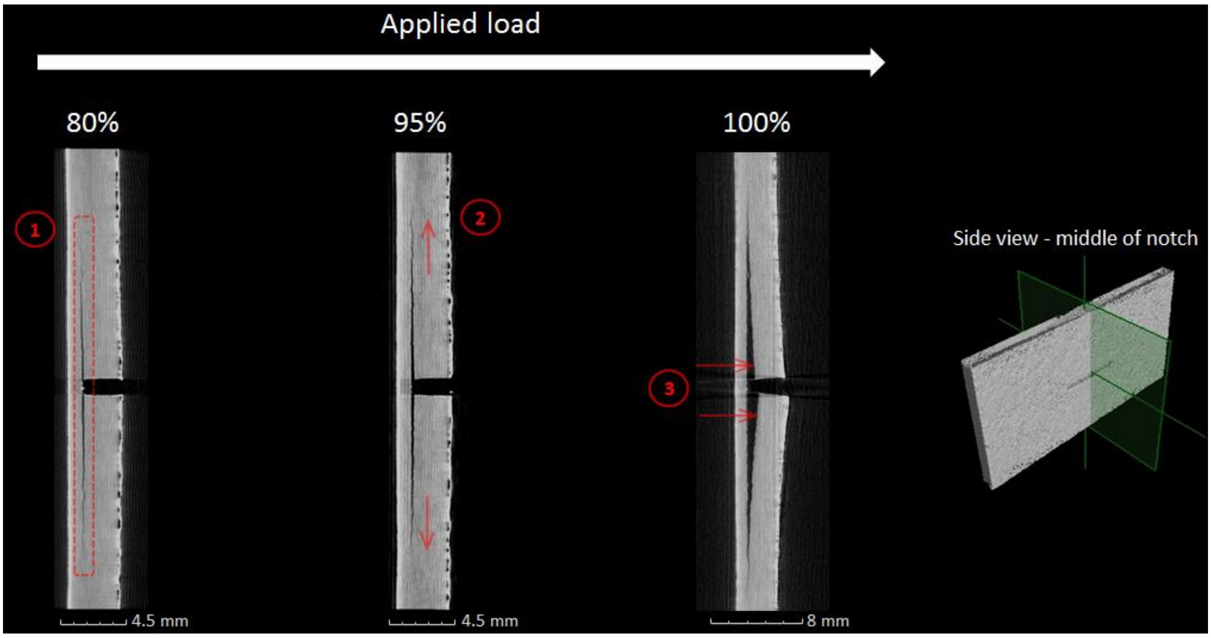

Figure 5: Progression of damage in a ±35 specimen with a 75% depth notch

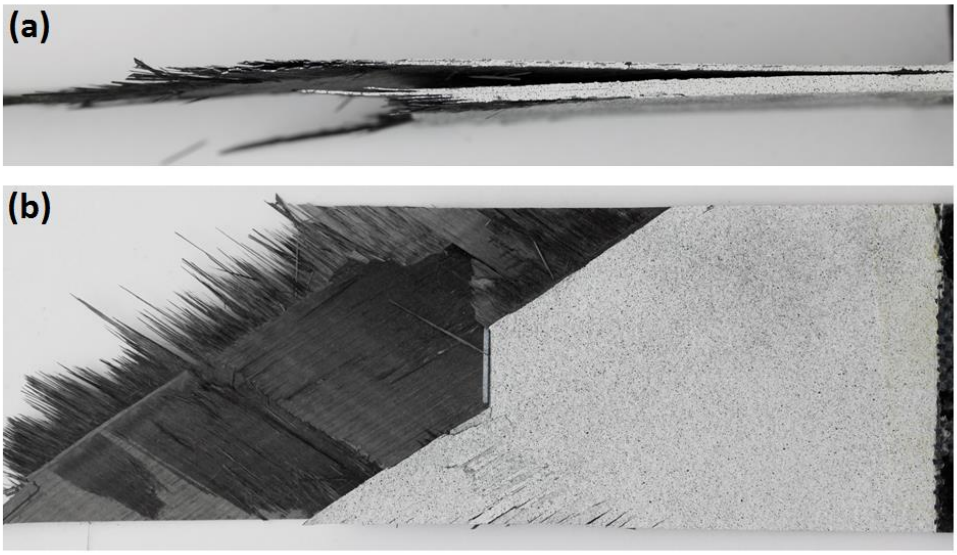

Figure 6: (a) Side view and (b) front view of a ±35 specimen with a 75% depth notch after failure

While uniaxial tensile testing is not truly representative of pressure vessel loading, the identification of damage mechanisms associated with partial-depth notches in this work becomes significant when composite toroidal vessels are considered. As stated earlier, no standard currently exists to define composite flaw tolerance requirements which is problematic due to the rate of change of hoop-to-axial stress ratio around the cross-section of circular toroidal vessels [2] (which is typically fixed at 2:1 in cylindrical vessels). Damage mechanisms associated with partial-depth notches could therefore vary significantly depending on where they are located on the toroid so a thorough understanding of notched angle-ply composite behaviour is required. This knowledge can also be used to optimise inlet/outlet valve location in order to fully exploit the variable ratio of hoop-to-axial stress in toroidal CPVs.

6 CONCLUSIONS

The notched performance of uniaxially-loaded angle-ply specimens with partial-depth notches has been experimentally analysed. It was observed that delamination develops from the base of partial-depth notches, causing gross specimen failure to eventually occur in un-notched sub-laminates under the notch. This damage progression re-distributed stresses throughout the specimens which resulted in low strength knockdowns. The identification of partial-depth notch damage modes in this work is vitally important for the on-going development of a damage tolerant CPV design methodology and accompanying numerical model for CFT design qualification testing which will be addressed in a follow-on study.

ACKNOWLEDGEMENTS

This original research is proudly supported by RMIT University and the Commonwealth of Australia, through the AA2020CRC.

REFERENCES

[1] *ISO 11439:2013 : Gas cylinders -- High pressure cylinders for the on-board storage of natural gas as a fuel for automotive vehicles*. Geneva, Switzerland: International Standards Organisation (ISO), 2013.

[2] C. P. Fowler, A. C. Orifici, and C. H. Wang, "A review of toroidal composite pressure vessel optimisation and damage tolerant design for high pressure gaseous fuel storage," *International Journal of Hydrogen Energy,* vol. 41(47), pp. 22067-22089, 2016.

[3] C. Soutis and P. T. Curtis, "Prediction of the post-impact compressive strength of CFRP laminated composites," *Composites Science and Technology,* vol. 56(6), pp. 677-684, 1996.

[4] *ANSI/CSA NGV2-2000. Basic Requirements for Compressed Natural Gas Vehicle (NGV) Fuel Containers*. Cleveland, OH, U.S.A.: American National Standards Institute (ANSI)/CSA International, 2000.

[5] Y. S. Kim, L. H. Kim, and J. S. Park, "The effect of composite damage on fatigue life of the high pressure vessel for natural gas vehicles," *Composite Structures,* vol. 93(11), pp. 2963-2968, 2011.

[6] J. Makinson and N. L. Newhouse, "Flaw testing of fiber reinforced composite pressure vessels," *Journal of Pressure Vessel Technology,* vol. 136(4), pp. 041409-1 - 041409-5, 2014.

[7] U. D. o. Defense, *The Composite Materials Handbook-MIL 17: Guidelines for Characterization of Structural Materials* vol. 1: CRC Press, 1999.

[8] S. Villalonga, B. Gentilleau, and D. Halm, "Preface to the special section on "OSIRHYS IV project: Type IV hydrogen high pressure storage vessel simulation and optimization"," *International Journal of Hydrogen Energy,* vol. 40(38), pp. 13146-13147, 2015.

[9] J. P. Berro Ramirez, D. Halm, J. C. Grandidier, S. Villalonga, and F. Nony, "Experimental study of the thermomechanical behavior of wound notched structures," *International Journal of Hydrogen Energy,* vol. 40(38), pp. 13148-13159, 2015.

[10] B. Gentilleau, S. Villalonga, F. Nony, and H. Galiano, "A probabilistic damage behavior law for composite material dedicated to composite pressure vessel," *International Journal of Hydrogen Energy,* vol. 40(38), pp. 13160-13164, 2015.

[11] J. P. Berro Ramirez, D. Halm, J. C. Grandidier, and S. Villalonga, "A fixed directions damage model for composite materials dedicated to hyperbaric type IV hydrogen storage vessel – Part I: Model formulation and identification," *International Journal of Hydrogen Energy,* vol. 40(38), pp. 13165-13173, 2015.

[12] J. P. Berro Ramirez, D. Halm, J. C. Grandidier, and S. Villalonga, "A fixed directions damage model for composite materials dedicated to hyperbaric type IV hydrogen storage vessel – Part II: Validation on notched structures," *International Journal of Hydrogen Energy,* vol. 40(38), pp. 13174-13182, 2015.

[13] L. Zu, "Stability of fiber trajectories for winding toroidal pressure vessels," *Composite Structures,* vol. 94(5), pp. 1855-1860, 2012.

[14] L. Zu, S. Koussios, and A. Beukers, "Design of filament-wound circular toroidal hydrogen storage vessels based on non-geodesic fiber trajectories," *International Journal of Hydrogen Energy,* vol. 35(2), pp. 660-670, 2010.

[15] L. Zu, S. Koussios, and A. Beukers, "A novel design solution for improving the performance of composite toroidal hydrogen storage tanks," *International Journal of Hydrogen Energy,* vol. 37(19), pp. 14343-14350, 2012.

[16] L. Zu, S. Koussios, and A. Beukers, "Minimum weight design of helically and hoop wound toroidal hydrogen storage tanks with variable slippage coefficients," *Polymer Composites,* vol. 33(12), pp. 2218-2227, 2012.

[17] L. Zu, D. H. Zhang, Y. Q. Xu, and D. J. Xiao, "Integral design and simulation of composite toroidal hydrogen storage tanks," *International Journal of Hydrogen Energy,* vol. 37(1), pp. 1027-1036, 2012.

[18] *D3039/D3039M-08: Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials*. PA, U.S.A.: ASTM International, 2008.

[19] *D5766/D5766M-11: Standard Test Method for Open-Hole Tensile Strength of Polymer Matrix Composite Laminates*. PA, U.S.A.: ASTM International, 2011.

[20] L. Parnas and N. Katirci, "Design of fiber-reinforced composite pressure vessels under various loading conditions," *Composite Structures,* vol. 58(1), pp. 83-95, 2002.

[21] S. Adali, E. B. Summers, and V. E. Verijenko, "Optimisation of laminated cylindrical pressure vessels under strength criterion," *Composite Structures,* vol. 25(1-4), pp. 305-312, 1993.

[22] E. M. C. Jones, M. N. Silberstein, S. R. White, and N. R. Sottos, "In situ measurements of strains in composite battery electrodes during electrochemical cycling," *Experimental Mechanics,* vol. 54(pp. 971-985, 2014.

[23] E. M. C. Jones. (2013, 28 Jan). *Improved digital image correlation*. Available: http://www.mathworks.com/matlabcentral/fileexchange/43073-improved-digital-image-correlation--dic-

[24] C. P. Fowler, M. W. Joosten, A. C. Orifici, and C. H. Wang, "Experimental and numerical investigation into the progressive failure of notched angle-ply composites," presented at the 2016 Advanced Composites Innovation Conference, Melbourne, Australia, 2016.

[25] C. P. Fowler, M. W. Joosten, A. C. Orifici, and C. H. Wang, "Progressive failure of notched angle-ply laminates for damage tolerant composite pressure vessel design," in *10th Asian-Australasian Conference on Composite Materials (ACCM-10),* ed. Busan, Korea, 2016.

[26] F. Sket, A. Enfedaque, C. D. Lopez, C. Gonzalez, J. Molina-Aldareguia, and J. LLorca, "X-ray computed tomography analysis of damage evolution in open hole carbon fiber-reinforced laminates subjected to in-plane shear," *Composites Science and Technology,* vol. 133(pp. 40-50, 2016.