# Strain-based Damage Assessment for Accurate Residual Strength Prediction of Impacted Composite Laminates

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### Abstract

A method for predicting the residual strength of damaged carbon-fibre composites using full-field strain data measured with digital image correlation has been developed and applied to laminates containing barely visible impact damage (BVID). Carbon-fibre coupons containing impact damage were manufactured and then inspected using the novel strain-based damage assessment technique and an ultrasonic technique commonly applied in industry. Predictions of residual strength, with quantified uncertainties, were generated for both the strain-based and ultrasonic measurements using robust Bayesian linear regression. The accuracy of strain-based predictions were found to be significantly higher than those generated using ultrasonic measurements, with the predictions for one set of coupons being over three times more accurate when using the strain-based technique. The use of such a damage assessment technique, capable of accurately predicting the residual strength of a damaged composite structure, could reduce the number of repairs required to ensure the safety of that structure.

## Keywords

Residual strength prediction, Image decomposition, Composite materials, Impact damage, Strain-based damage assessment

## Introduction

Damage in composite structures can cause substantial reductions in the load-bearing strength of the structure. In particular, impact damage can reduce the compressive strength of laminates with almost no visible indication of the damage on the surface [1]. Hence, composite structures are designed assuming that barely visible damage is already present, so that its actual presence will not compromise the performance of the structure. In addition to this, composite structures are assessed at intervals to ensure that damage in the structure is not going to propagate and result in failure during operation. These assessment techniques can take many forms depending on the material and damage that is being looked for and the importance of the information they provide can vary considerably. Rytter [2] categorised the information obtained from damage assessments into four levels, which are described as follows [3]:

* Level 1: Damage detection
* Level 2: Level 1 plus location identification
* Level 3: Level 2 plus extent definition
* Level 4: Level 3 plus remnant life prediction

For composite structures, there are substantial costs associated with repairs, hence it would be beneficial for assessment techniques to provide Level 4 information. This could help to reduce the number of repairs to those that are essential for the structure to be safely operated. Ultrasound and thermography are amongst the most common techniques currently employed to assess aerospace composites [4], and provide Level 3 information in the form of the size and shape of damage. From this data, the residual strength of the structure can be inferred but predictions based on these measurements have high levels of uncertainty because the effect of the damage on the structural integrity is not completely characterised [5]. In general, the loss of structural integrity involves the failure of materials due to the breaking of bonds as a result of deformation; and, deformation is usually characterised in terms of strain fields. Hence, the changes in deformation or strain fields induced by damage should be treated as Level 4 information in Rytter’s classification, because they provide the most appropriate input parameters for predicting the change in structural integrity, or residual strength [3]. Thus, employing strain fields to assess the effect of damage in composites is likely to lead to more reliable predictions of the residual strength or life; and in turn, this is likely to reduce premature or unnecessary repairs and save resources.

A number of non-contact techniques have previously been used to measure deformation and strain fields in damaged composites. For instance, deflectometry has been used to measure changes in surface slope induced by impact damage in composites [6]. While more direct measurements of in-plane strain fields have been made using both digital image correlation (DIC) [7, 8] and thermoelastic stress analysis [9]. However, an inherent drawback of full-field measurement techniques is the generation of large quantities of data containing substantial levels of redundant information. Patki and Patterson [7] used the technique of image decomposition to reduce the dimensionality of data-rich strain fields, captured using DIC, to a small number of shape descriptors. The shape descriptors were used to make comparisons between glass-fibre composite coupons containing impact damage and a virgin coupon, in a similar manner to that used for damage assessments in structural health monitoring [10]. The amount by which the strain field changed from the virgin state was thus quantified and shown to correlate with the kinetic energy of the impactor. This paper extends this process by applying it to different material systems and directly quantifying the residual strength of a damaged laminate. Robust Bayesian linear regression is used to obtain statistically conservative estimates of the residual strength of a damaged laminate. Quantitative comparisons are made between the accuracy of predictions made using traditional ultrasonic assessments and the novel strain-based methodology.

This paper is organised as follows. In Section 2 the experimental procedure for manufacturing the coupons, performing ultrasonic inspections and measuring residual strength are presented. Section 3 details the process of measuring full-field strain data and how the strain-based damage assessments were conducted. The experimental results are presented in Section 4, with a discussion of results in Section 5, and concluding remarks in Section 6.

## Experimental Method

Two different material systems and layups were chosen to explore the accuracy of strain-based residual strength predictions. Twenty quasi-isotropic coupons were produced using RP507UT210 prepreg (PRF, UK) with a [02/902/452/-452]S layup. The laminates measured 90 by 240 mm and were cured using a hot press (APV-3530, Meyer, Germany) at a temperature of 130 ⁰C for 45 minutes, as recommended by the manufacturer. The press was heated to this temperature at a rate of 10 ⁰C/min and the laminate kept under a constant pressure of 2.5 bar whilst it was heated, cured and then naturally cooled. A second set of coupons with a cross-ply layup were also produced to demonstrate that the techniques were material independent. Due to the lack of availability of material, it was only possible to manufacture eight crossply specimens; however, this was sufficient to estimate the uncertainty in the predictions. Cross-ply coupons with a [02/902/02/902/02/90]S layup were manufactured using M10R-UD-150 prepreg (Hexcel, USA) and cured with an identical method to that used for the quasi-isotropic coupons. When removed from the hot press the crossply and quasi-isotropic coupons had nominal thicknesses of 2.90 and 3.02 mm respectively.

Barely visible impact damage (BVID) was created in the laminates using a drop-weight impact tower. A 20 mm hemispherical tup of mass 2.67 kg was used to produce damage without forming cracks on the impacted surface of the coupon. The impact energy was controlled by varying the height from which the impactor was released. Once released, the impactor was guided by rails towards the coupons with negligible frictional losses. The potential energy of the impactor was calculated based on its mass and height and it was assumed that this potential energy was equal to the kinetic energy of the impactor just prior to impact. The only damage visible after impact was a shallow indentation that varied in depth from 0.05 to 0.2 mm, with higher impact energies resulting in deeper indentations. The laminates were then cut into 220 mm by 40 mm coupons using a wet diamond saw (Versatile 103450, Vitrex, USA) with the impact location used as the centre of the coupons and the 0⁰ plies running in the x-direction as shown in Fig. 1. A wet diamond saw was used to ensure the cut edges were free from delaminations that may have caused premature failure.

The spatial distribution of the delaminations produced by the impacts were measured using pulse-echo ultrasound. The process used to produce time-of-flight C-scans is explained in [11]. Time-of-flight C-scans are images that show the position and depth of damage within a laminate. After the ultrasonic inspection, the strain-based damage assessment explained in Section 3 was performed. Since the strain-based damage assessment required a load to be applied to each coupon, a further ultrasonic inspection was performed after the strain-based assessment was complete to check that the damage had not propagated. The delaminations in one quasi-isotropic coupon, which was impacted with an energy of 15J, had propagated and hence, data for this coupon was not included in any further analysis.

After both damage inspections, each coupon was loaded to failure using a four-point bend setup. The measurement of residual strength in bending was chosen because loading the coupons to failure in tension or compression would require very high loads. A servo-hydraulic load frame (8501, Instron, USA) with a four-point bending rig, consisting of a support span and load span of 160 mm and 80 mm respectively, was used to load the coupons. The coupons were placed in the bending rig such that the impacted surface was in tension; and thus, the large delaminations close to the rear surface, were in compression. The load frame was then operated under displacement control to monotonically load the coupons to failure at a rate of 0.8 mm/min. A coupon was considered to have failed when its stiffness was reduced to 50% of its original value. The ultimate bending moments were recorded and used as the residual strength for the coupons.

## Strain-Based Damage Assessment

Each coupon was loaded in the same four-point bend configuration described at the end of Section 2 and the induced surface strain measured with stereoscopic DIC. To perform DIC, a speckle pattern was first applied to a 50 mm long section at the middle of each coupon on the surface that was impacted, a photograph of a speckled coupon is shown in Fig. 1. A white base coat (Matt White, PlastiKote, USA) was first applied and black speckles (Pro Paint Acrylic Black Matt, CRC, USA) sprayed over the base coat resulting in high-contrast speckles with a typical diameter of 0.25 mm. The impacted surface was chosen for the strain-based inspection because aerospace structures are normally inspected on the most accessible surface, which is also likely to be the surface that experiences impacts. A stereoscopic DIC system (Q-400, Dantec Dynamics, Germany) was used to capture displacement fields on the surface of the loaded coupons. The DIC system consisted of two cameras positioned 200 mm apart on either side of the support span facing the loaded coupon with a stereo angle of 65⁰, the experimental setup is shown in Fig. 2. A facet size of 25 pixels and grid spacing of 5 pixels was used to evaluate displacement vectors in a dense grid. Strain was calculated from the displacement field using local polynomial smoothing [12] whereby a quadratic surface was fitted, using the method of least-squares, to a square subset of the displacement field with 21 displacement vectors across its width. The gradient at the centre of the fitted quadratic surface was then used to calculate the strain at the centre of the subset. The x-direction strain fields, where x is the length direction of the coupon, were used for the strain-based damage assessments.

The uncertainty of the DIC system was estimated by measuring the strain on the surface of an aluminium coupon of similar size and speckle pattern quality as the composite coupons. A 1.5 Nm bending moment was applied to the aluminium coupon to induce strain. A resistance strain gauge bonded to the compressive side of the aluminium coupon was used to determine the magnitude of the uniform surface-strain field. DIC measurements were performed on the tensile side and the root mean square error between the strain field measured using DIC and the strain gauge was calculated. The root mean square error of the DIC measurement system was found to be 44 μϵ.

Each coupon was loaded to the same displacement by vertically moving the loading span 6 mm towards the support span, where a displacement of 0 mm would indicate all four noses of the four-point bend rig were in contact but not inducing a bending moment in the coupon. The application of a common displacement instead of bending moment ensured that variations in the stiffness of the undamaged material does not affect the damage assessment; and, that only variations in redistribution of the strain due to the damage are measured [9]. Each coupon was loaded 6 times and the strain field captured each time. The common displacement resulted in a mean bending moment applied to the crossply and quasi-isotropic coupons of 20.36 Nm and 21.38 Nm respectively. The bending moment was calculated using the compressive load measured by the load frame and the dimensions of the bending rig.

The strain fields contained large quantities of data, much of it redundant, and thus the dimensionality of the fields were reduced prior to performing the damage assessment. Once each strain field was captured, a 25 mm wide square area of the strain field was selected with the centre defined by the surface dimple caused by the impactor. The width of this square area was chosen to be approximately the same as the y-direction width of the largest region of damage detected using ultrasound. If the area of strain data used for assessments was substantially larger than the damage, only a small portion of the strain-field would be affected by the damage, limiting the sensitivity of the technique. The square area of strain data was dimensionally reduced using the technique of image decomposition [13]. Image decomposition is the process by which an image consisting of a large number of pixels can be represented by a comparatively small number of shape descriptors. Orthonormal discrete Tchebichef polynomials [14] were used to describe each strain field and hence, to provide these shape descriptors. The same set of Tchebichef polynomials were used for the decomposition of both the crossply and quasi-isotropic strain fields. The shape descriptors corresponding to Tchebichef polynomials up to an order of 24 were calculated for each strain field, , and collated into a feature vector, , with 325 dimensions. A reconstruction of the original strain field, , was produced from the feature vector and the reconstruction error assessed using the root mean squared residual:

(1)

A large number of shape descriptors were initially calculated to ensure that the reconstruction error was substantially smaller than the measurement uncertainty of the DIC system. The feature vectors were then filtered by a similar technique used in [15] whereby the shape descriptors below a threshold were set to zero. The value of the threshold was chosen such that the root mean squared residual of the reconstruction after filtering was equal to the measurement uncertainty. An example of this filtering process and its results is shown in Fig. 3. After filtering, the feature vectors typically had around 30 non-zero shape descriptors compared to 10,000 pixels in the original strain fields. The feature vectors still had 325 dimensions after filtering and the shape descriptors in each vector were associated with the same Tchebichef polynomials.

The severity of the damage was assessed by making a direct comparison between the feature vectors representing the damaged coupons and those representing the virgin coupons using a dissimilarity metric. Several dissimilarity metrics for comparing strain feature vectors have previously been explored [7] and the Pearson correlation coefficient suggested as the most effective. However, if any of the shape descriptors are of a substantially higher magnitude than the others, then the Pearson correlation coefficient is typically very close to unity. Since the value of the first shape descriptor is always equal to the mean value of the strain field, and a load bearing structure typically experiences a high mean strain, the Pearson correlation will be high regardless of the amount of damage present in the structure. Another metric considered in [7] is the Euclidean distance; but, when this is used to compare feature vectors that contain many terms, the Euclidean distance suffers from an effect called concentration [16], where the distances between all the feature vectors become roughly equal, and thus damage severity measures become meaningless. The Manhattan distance, sometimes called the city-block distance, is less sensitive to concentration and thus, is a better metric for assessing the extent to which the strain field has been affected by the damage. The Manhattan distance was calculated as [16]:

(2)

where is the number of shape descriptors in the feature vectors and representing the strain fields in the damaged and virgin coupons, respectively. As the strain field was captured six times for each coupon, including the virgin coupons, the Manhattan distance for each damaged coupon was evaluated 36 times and the mean value recorded as the strain-based damage severity for that coupon. It was assumed that if the damage was likely to propagate, then the strain field on the surface of the damaged coupon would be expected to be substantially different to the strain field on the virgin coupon.

## Results

Examples of ultrasound time-of-flight C-scans captured for the crossply and quasi-isotropic coupons are shown at the top of Figs. 4 and 5 respectively. The projected area of the damage visible in the time-of-flight C-scans were recorded and this measurement used as the ultrasound-based damage severity. The strain field on the impacted surface, when the four-point bend rig was at a 6 mm displacement, is shown at the bottom of Figs. 4 and 5 with the area of the strain field used for damage assessment shown by the white dashed rectangle. A characteristic pattern is visible in the strain field at the damage location, consisting of a high strain area in the centre with low strain areas to its left and right. The variation in the magnitude of this strain pattern as the impact energy increased can be seen in Fig. 6.

For the strain-based damage assessment to be performed, data from a virgin coupon was required as a reference. For the crossply coupons, only one virgin coupon was available and this was used for comparison with the damaged crossply coupons. For the quasi-isotropic coupons, there were data from six virgin coupons and thus, the most suitable had to be selected as the reference strain field against which to compare the damaged coupons. Some variability was observed in the failure load for the six virgin quasi-isotropic coupons, as shown in Table 1. The ultimate bending moments for the six coupons had a mean of 52.95 Nm and standard deviation of 4.96 Nm; however, it was clear that the failure load for coupon RC4 was substantially lower than for the other five coupons. The maximum normed residual technique, a method of identifying outliers described in [17], was used and confirmed that RC4 was an outlier, and thus unsuitable for use as the reference coupon. The mean and standard deviation of the five virgin quasi-isotropic coupons, excluding RC4, were found to be 54.95 Nm and 1.01 Nm respectively and no further outliers were identified. Coupon RC1 had a failure load closest to the mean and, hence, it was chosen as the reference coupon for the quasi-isotropic coupons. All coupons failed due to the delamination of the bottom 0⁰ ply. This delamination was across the entire width and length of the coupon between the two load noses of the bending rig. For the impacted coupons, the bottom delaminations caused by the impact first buckled, before rapidly propagating. This failure progression has been observed in a previous study on delaminations in similar laminates [18].

The residual strength, damage area and Manhattan distances for the crossply and quasi-isotropic coupons are listed in Table 2 and Table 3 respectively. Robust Bayesian linear regression [11, 19] was used to fit a predictive function for the residual strength to the measured damage severities. Two regression models were constructed for each batch of coupons; in one, the regression model made predictions based on the damage area measured using ultrasound; and, the other model used the Manhattan distance from the strain-based damage assessment. The damage area measured using ultrasound has previously been shown to be the most effective ultrasound metric for use in residual strength predictions [11]. The construction of the two regression models per batch of coupons allowed a direct comparison of the predictions generated from the ultrasound and strain data. Robust Bayesian linear regression was chosen because it is capable of generating uncertainty bounds for predictions, referred to as credible intervals, and is able to account for outliers that may be present in the data. The regression models were based on a line-of-best-fit, where the probability distribution of the residuals (the distance between the data and the line) was a Student’s t-distribution. The t-distribution has a “normality” parameter, 1, such that as tends to infinity, the t-distribution tends to a normal distribution. Conversely, the smaller the value of , the heavier the tails of the t-distribution. This allows it to account for outliers. Since the normality of the t-distribution is automatically adjusted during the fitting process, the model is able to adjust its behaviour to the severity of any outliers in the data. Points that were outliers and thus located far from the line-of-best-fit caused the normality of the t-distribution to be low and thus had only a minimal effect on the position and gradient of the regression line. This feature of robust Bayesian regression ensures that the position of the line-of-best-fit is always accurate; whilst the credible interval around the line allows for the possibility of outliers. The model was fitted to the data using Gibbs sampling performed with the software JAGS [20]. A detailed discussion of how the robust Bayesian regression model was created and fitted to the data and how it can be used for predicting the residual strength of damaged composites is given in [11]. The measurements and the fitted regression models for the damage assessments are shown in Fig. 7. These regression models could be used to generate predictions of the residual strength of damaged components made from an identical laminate found to contain impact damage. The credible interval around the line-of-best-fit, shown as the grey region on the graphs in Fig. 7, indicates the range of most probable residual strength values that could be exhibited by a laminate with a measured damage severity. The probability that the true residual strength would be contained in the credible interval is 95% and thus the lower bound of the interval could be used as a conservative estimate of residual strength with only a 2.5% chance that the residual strength would be lower.

To make quantitative comparisons between the predictive capabilities of the models based on ultrasonic and strain-based damage assessments, it was necessary to calculate their average prediction uncertainty. This was achieved by calculating the leave-one-out-cross-validation (LOOCV) performance metric [21], which can be used to measure the predictive power of a regression model. This performance metric was calculated by fitting the regression model to the data times, where was the number of damaged coupons that were assessed, and leaving out the data from one damaged coupon each time. Then each time, the fitted model was used to predict the residual strength of the coupon that was left out for that iteration. The numerical difference between the predicted and measured residual strengths of the left-out coupon were recorded as the prediction error for that coupon, , and the LOOCV performance metric calculated from these errors as:

(3)

The best performing damage assessment technique would have the lowest value of the LOOCV performance metric, because it is a measure of the average prediction uncertainty. The performance metrics for the ultrasound and strain-based damage predictions are shown in Table 4.

## Discussion

The ultrasound time-of-flight C-scans of the damage in both the crossply and quasi-isotropic coupons have been used to measure the projected damage area caused by the drop-weight impactor. There is more noise evident in the C-scans of the damage in the cross-ply than the quasi-isotropic laminates. This noise is likely caused by areas of fibre-breakage that are more likely in the cross-ply material and which, unlike delaminations, cause the ultrasound energy to scatter rather than be reflected back to the probe. The strain-field is not adversely affected by different failure modes and thus the noise in the data is uniform regardless of the damage present. A characteristic pattern can be observed in the strain data for impacted laminates, shown in Figs. 4 and 5. This characteristic pattern becomes more visible as the energy of impact increases, this can be seen in Fig. 6. At sub-critical loads, the shape of this pattern does not change, regardless of the load applied. The Manhattan distances between feature vectors representing the strain fields in the damaged coupons and the reference virgin coupon were then calculated and used as the strain-based measure of damage severity. The Manhattan distances for all of the strain fields, including those shown in Fig. 6, are listed in Table 3. When the Manhattan distance was plotted against the residual strength of the damaged coupons, as show in the right-hand column of Fig. 7, a strong linear correlation was observed. A linear correlation was also observed for the ultrasound-based damage severity measurements; but, the spread of data points around the line-of-best-fit was much wider, and thus, predictions based on this ultrasound data would be less accurate.

The predictive power of the strain and ultrasound-based regression models were assessed using the LOOCV performance metric, which estimates the average prediction uncertainty of each of the regression models. When the LOOCV metrics were calculated for the crossply coupons the average prediction uncertainty was found to be approximately three times larger for ultrasound-based predictions than the corresponding uncertainty for strain-based predictions. This indicates that the strain-based methodology represents a substantial improvement in ability to assess the severity of damage compared to ultrasonic measurements. Thus, if the strain-based damage assessment was used in place of an ultrasound-based method then a reduction in the number of components being unnecessarily repaired or replaced could be expected. Although, for other defect types ultrasound or thermography may still be the most appropriate inspection technique. When comparisons are made between the ultrasound and strain-based LOOCV metrics for the quasi-isotropic coupons, a similar decrease in uncertainty is evident; however, the LOOCV metric for ultrasound-based predictions is 1.32 times more than for the strain-based predictions. This difference in performance may be due to the distribution of delaminations in the two different laminates, but still represents a significant increase in the accuracy of predictions.

In a first step to elucidate the new methodology for strain-based damage assessment, laminates with a nominally planar surface have been employed; however, surface strains can be measured on three-dimensional surfaces using stereoscopic digital image correlation [22]. In this study, uniaxial bending loads were applied to induce appropriate strains; however more complex multiaxial loads [23] or service loads could be used. For example, DIC has been used to conduct full-field measurements of wing deformations during flight tests of a full-scale aircraft [24]. Nevertheless, the requirement to induce strain is likely to be the most significant hurdle for the application of this new methodology, as the induced strain must exceed the minimum resolution of the measurement system. For an elastic material, the magnitude of the strain-field varies linearly with the applied load, thus the value of the shape descriptors representing that strain field also have a linear relationship with load [25]. The Manhattan distance between two feature vectors therefore scales with the load used to induce the strain fields that the feature vectors represent. And, the ability for the strain-based damage assessment to measure small values of Manhattan distance is related to the measurement uncertainty of the DIC system. The DIC system used in this paper was found to have a measurement uncertainty of 44 μϵ. A lower strain measurement uncertainty of 29 μϵ has been achieved using a similar measurement system [26] and a DIC system from a different manufacturer was found to have a measurement uncertainty of 30 μϵ [15]. The higher uncertainty of the DIC system used in this paper is likely due to the high stereo angle of the cameras, resulting in a reduction in the accuracy of in-plane measurements [12]. Damage that causes the strain field to vary with a Manhattan distance close to the measurement uncertainty would be indistinguishable from an undamaged coupon. This is not necessarily a significant problem for structural assessments, as such damage would not be expected to reduce the residual strength of the composite. For instance, if one of the crossply coupons contained a through-width delamination, then the bending moment at which the delamination propagates, , and the amount the strain field is affected by the delamination, , can be estimated using a simple one-dimensional model, which is described in Appendix A. Hence, the propagation bending moment can be calculated for a range of different sized delaminations and plotted against the change in the strain field, as shown in Fig. 8. The vertical line in Fig. 8 indicates the smallest measurable strain difference between a virgin and damaged specimen, which was set to the 95% confidence interval for strain measurement using the DIC system, equal to four times the system measurement uncertainty. Therefore, Fig. 8 shows that a delamination that does not result in a measurable change to the strain-field, i.e. to the left of the vertical dashed line, would not be expected to propagate and does not reduce the residual strength of the coupon. Consequently, if the difference in the strain-field between the virgin and damaged states is less than the measurement resolution of the DIC system, the damage can be ignored.

The prediction of residual strength requires a separate empirical model for each type of composite laminate and for each type of loading, both when the prediction is based on strain damage and on ultrasound measurements, because the nature of the loading on the component will affect its residual strength [27].

For ultrasonic assessments, the size of detectable damage is closely linked with the resolution of the assessment technique, but the size of damage does not indicate the risk associated with the presence of that damage. For instance, a small delamination in a highly-stressed area of a structure would likely cause a greater reduction in residual strength than a large delamination in a low-stressed area, but the ultrasound inspection is more likely to detect the large delamination. This could lead to damage being missed that could significantly reduce the strength of a structure whilst large defects, that may be insignificant, are detected. With a strain-based inspection, there is a correlation between how the damage affects the residual strength and how much it changes the strain-field. Therefore, undetectable damage would not be expected to affect the residual strength and can be safely ignored. The required measurement uncertainty for a strain-based assessment can be defined by considering the minimum residual strength of the damaged structure. This means that for a strain-based inspection the required measurement resolution is simple to define, and may lead to fewer situations where critical damage is missed.

## Conclusions

A novel method of assessing damaged composites with measurements of the resulting strain field has been used to make predictions of the residual strength of crossply and quasi-isotropic carbon fibre composite coupons with barely visible impact damage (BVID). A large number of coupons were manufactured and a known level of impact damage applied using a drop-weight impact tower. The coupons were then loaded in bending to induce strain and full-field strain data captured using digital image correlation. The dimensionality of the strain fields was reduced using image decomposition resulting in feature vectors that represent the strain on the surface of each coupon. The damage was quantified by numerically comparing the feature vector for each damaged coupon with the feature vector for a virgin coupon, which resulted in a strain-based measure of damage severity that was found to linearly correlate with the residual strength of the damaged coupons. An ultrasound-based damage assessment was also performed on the coupons allowing for a direct comparison between the new methodology and an established inspection technique.

Robust Bayesian regression was used to fit a linear function to the measures of damage severity and the residual strengths of the coupons. The uncertainty in the predictions made using the strain-based methodology were one-third and three-quarters of the uncertainty in predictions based on ultrasound measurements for the crossply and quasi-isotropic coupons respectively. This indicates that the strain-based predictions significantly outperformed the ultrasound predictions. Since ultrasound only measures the size and shape of damage, not all of the required information is available to accurately predict the residual strength of a damaged composite. For strain-based assessments, there is a direct connection between the strain field in proximity to the damage and the mechanisms driving damage propagation and thus the predictions of residual strength are likely to be more accurate.

Strain-based assessments of damaged composite structures could lead to predictions of remnant properties that are substantially more accurate than those made using traditional inspection techniques, which in turn could reduce the costs of both manufacturing and operating composite aerospace structures.

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## Appendix A. One-dimensional Model of a Delamination Propagating

If one of the crossply coupons contained a through-width delamination and was loaded in bending, then the bending moment at which the delamination would propagate, , can be estimated in terms of the delamination length, , using a simple one-dimensional model based on buckling [28, 29]. In the model, the strain energy release rate, , is related to the axial strains in the material at the delamination when buckling occurs, , and when propagation occurs, , by:

(A.1)

where is the elastic modulus of the laminate calculated from data in [30], is the ratio of ply thickness to laminate thickness and is the laminate thickness. , the axial strain at which the material below the delamination would buckle, is given by [29]:

(A.2)

and, , the axial strain at the delamination when propagation occurs, can be calculated by assuming simple bending and based on [29]:

(A.3)

where is the coupon width and is the bending moment at which propagation occurs. The parameters for Eqs. (A.1), (A.2) and (A.3) are defined in Table A.1, with the material properties taken from [30] and dimensions based on the crossply specimens tested in this paper. The bending moment at which the delamination starts to propagate can then be calculated by finding the roots to the quadratic in equation (A.1).

By using Eqs. (A.1), (A.2) and (A.3), the bending moment at which propagation occurs can be obtained for any length of delamination. However, to demonstrate that insignificant damage has only a minimal effect on the strain field, the propagation bending moment needs to be related to how much the strain field is affected by the delamination. Thus, the amount of change to the strain-field in the inspected square area, at an applied inspection bending moment, = 20Nm, was estimated. To achieve this, it was assumed that the delaminated 0⁰ ply does not contribute to the stiffness of the specimen, resulting in a reduced modulus of elasticity, , due to the missing ply, and a reduction in the specimen thickness. The strain on the specimen surface at a delaminated location can then be calculated using simple bending as:

(A.4)

which would be higher than the surface strain at a virgin location, given by:

(A.5)

The amount the mean surface strain has changed from a virgin specimen can then be calculated using the strains given by Eqs. (A.4) and (A.5) and the size of the delamination relative to the size of the inspected area, . The strain difference, , between a virgin and a damaged specimen can therefore be calculated as:

(A.6)

The difference between the mean surface strain on a virgin specimen and on the delaminated specimen, , can then be compared with the bending moment at which propagation occurs, .

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Fig. 1. A coupon with speckle pattern applied at the location where the impact was applied showing dimensions and the coordinate system used for the DIC and ultrasound measurements.

Fig. 2. Coupon under four-point bend load with the cameras used for DIC attached to the top half of the rig facing the impacted surface of the coupon.

Fig. 3. The first 120 of the 325 shape descriptors in a feature vector describing the strain field on a loaded coupon with impact damage (left) with the filter thresholds indicated by dashed lines. All 325 shape descriptors were used for the unfiltered reconstruction (top right) but only 29 shape descriptors, shaded in the bar chart, were required after filtering (bottom right).

Fig. 4. Ultrasound time-of-flight C-scan of the delaminations formed by a 12J impact on a crossply laminate (top) and the corresponding surface strain field (bottom) with the 25 mm square region used for image decomposition shown in white.

Fig. 5. Ultrasound time-of-flight C-scan of the delaminations formed by a 12J impact on a quasi-isotropic laminate (top) and the corresponding surface strain field (bottom) with the 25 mm square region used for image decomposition shown in white.

Fig. 6. Strain fields observed in crossply coupons with increasing impact energies of 0J (this is the reference strain field), 5J, 8J and 10J (reading left-to-right from top-left).

Fig. 7. Regression models relating damage severity measurements to the residual strength of damaged crossply composites (top) and damaged quasi-isotropic laminates (bottom) using the ultrasound-based damage severity (left) and strain-based damage severity (right).

Fig. 8. Estimated bending moment at which a delamination will propagate and the detectability of the delamination.

Table 1. Ultimate bending moments for the six virgin quasi-isotropic coupons.

|  |  |
| --- | --- |
| **Coupon Identifier** | **Ultimate Bending Moment (Nm)** |
| RC1 | 55.1 |
| RC2 | 53.9 |
| RC3 | 55.2 |
| RC4 | 43.0 |
| RC5 | 56.4 |
| RC6 | 54.1 |

Table 2. The impact energy, damage area measured using ultrasound, Manhattan distance and ultimate bending moment for the crossply coupons.

|  |  |  |  |
| --- | --- | --- | --- |
| **Impact Energy (J)** | **Damage Area (mm)** | **Manhattan Distance, , (μϵ)** | **Ultimate Bending Moment (Nm)** |
| 0 | 0 | – | 52.4 |
| 4 | 4 | 210 | 50.0 |
| 5 | 218 | 451 | 40.3 |
| 6 | 200 | 395 | 44.4 |
| 7 | 301 | 574 | 35.6 |
| 8 | 261 | 433 | 40.4 |
| 10 | 349 | 592 | 35.8 |
| 12 | 406 | 526 | 38.3 |

Table 3. The impact energy, damage area measured using ultrasound, Manhattan distance and ultimate bending moment for the quasi-isotropic coupons.

|  |  |  |  |
| --- | --- | --- | --- |
| **Impact Energy (J)** | **Damage Area (mm)** | **Manhattan Distance, , (μϵ)** | **Ultimate Bending Moment (Nm)** |
| 0 | 0 | – | 55.1 |
| 0 | 0 | 193 | 53.9 |
| 0 | 0 | 267 | 55.2 |
| 0 | 0 | 256 | 43.0 |
| 0 | 0 | 136 | 56.4 |
| 0 | 0 | 233 | 54.1 |
| 4 | 12 | 278 | 55.8 |
| 5 | 113 | 274 | 45.7 |
| 6 | 203 | 247 | 56.2 |
| 7 | 232 | 258 | 49.9 |
| 8 | 247 | 263 | 55.3 |
| 9 | 304 | 393 | 39.1 |
| 10 | 382 | 356 | 43.2 |
| 11 | 404 | 393 | 43.8 |
| 12 | 438 | 467 | 33.2 |
| 12 | 453 | 394 | 32.2 |
| 13 | 491 | 504 | 31.4 |
| 14 | 515 | 491 | 30.2 |
| 15 | 542 | 508 | 30.8 |

Table 4. The LOOCV performance metrics for the ultrasound-based predictions and the strain-based predictions of residual strength for crossply and quasi-isotropic laminates.

|  |  |  |
| --- | --- | --- |
|  | **LOOCV of Ultrasound-based Predictions (Nm)** | **LOOCV of Strain-based Predictions (Nm)** |
| **Crossply Coupons** | 2.96 | 0.97 |
| **Quasi-isotropic Coupons** | 5.84 | 4.43 |

Table A.1. Parameters used for predicting the propagation loads for a through thickness laminate.

|  |  |
| --- | --- |
| **Parameter** | **Value** |
|  | 550 N/m [30] |
|  | 76.7 GPa [30] |
|  | 71.2 GPa |
|  |  |
|  | 3 mm |
|  | 40 mm |
|  | 25 mm |



Fig. 1. A coupon with speckle pattern applied at the location where the impact was applied showing dimensions and the coordinate system used for the DIC and ultrasound measurements.



Fig. 2. Coupon under four-point bend load with the cameras used for DIC attached to the top half of the rig facing the impacted surface of the coupon.



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Fig. 7. Regression models relating damage severity measurements to the residual strength of damaged crossply composites (top) and damaged quasi-isotropic laminates (bottom) using the ultrasound-based damage severity (left) and strain-based damage severity (right).



Fig. 8. The moment, , to cause propagation of a delamination (solid line) as a function of the strain difference, , relative to a virgin specimen, developed around the delamination when an inspection moment of 20Nm is applied (dotted line). The graph indicates the inspection moment will not induce propagation and the minimum measurable strain difference (dashed line) corresponds to a delamination that will only propagate due to a moment larger than the ultimate moment of the virgin specimen (chain line).

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