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Title: *The effect of out-of-plane waviness asymmetry on laminate strength*

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ABSTRACT

The study of defects and their influence on the performance of composite structures is well documented. However, simplifications are often made regarding the morphology of these defects. As part of the CerTest project, a database of composite features and defects is being built, for which an assessment must be made of what information is relevant. This study looks specifically at out-of-plane waviness and seeks to investigate whether the commonly used severity metrics (e.g. maximum angle) are sufficient to characterize such defects when considering more complex morphologies. To assess this, previously developed numerical methods are used to investigate the tensile and compressive strength of cross-ply and quasi-isotropic laminates. These laminates are seeded with asymmetrical out-of-plane waviness. The numerical results demonstrate that for reliable prediction of the strength reduction caused by out-of-plane waviness, the asymmetry is an important consideration with relative reductions from symmetric to asymmetric wrinkle of up to 50% found within the wrinkles evaluated in this study.

INTRODUCTION

Composite materials, while offering various advantages, have long struggled with variability in quality and occurrence of defects [1,2]. As such the literature is full of investigations to better understand the source of this variability and these defects [3], with wrinkling, also known as out-of-plane waviness, receiving a fair amount of attention as documented in the recent review by Thor et at. [4]. With the rise in popularity and advancement of numerical tools [5], attention has now also shifted to better leveraging the embodied knowledge to streamline the virtual validation of performance (*e.g.* CerTest [6]). Within the CerTest programme specifically, one key activity is focused on establishing a database collating the information from the scientific literature. To this end it is important to establish which characteristics (*i.e.*

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metrics) are relevant when quantifying and/or describing the defects. These characteristics are important both for allowing trends to be identified across different datasets as well as in translating defects into Finite Element Models for analysis of the structural performance of the part containing the defect. In the following sections a brief overview is provided of the morphology of wrinkles, the focus of this current study, comparing occurrence in realistic parts against instances created and studied in the literature.

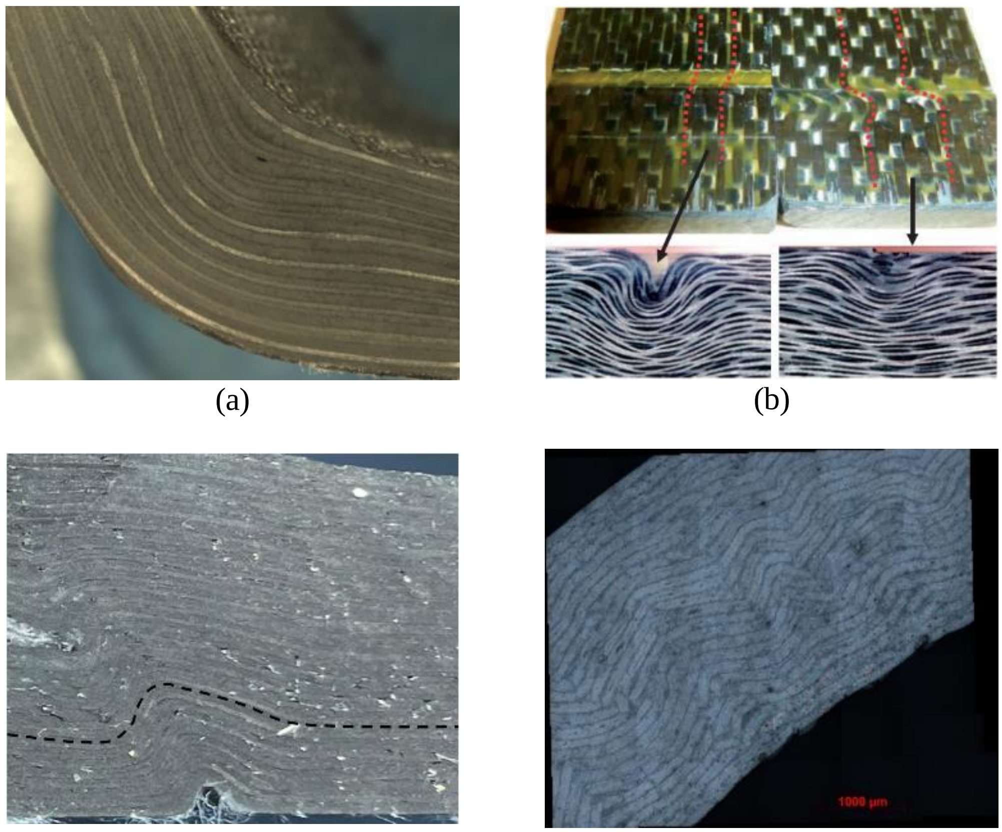
Wrinkles in Realistic Parts

Due to the variability inherent in both the raw materials and the processes used to manufacture composites components, the defect states generated are also highly variable. A selection of images of wrinkling patterns are presented in Figure 1, demonstrating the wide variety and complexity of defect morphologies even when primarily focused on only one defect type. Specifically notable are combination of multiple defects as observable in Figure 1 (a) - (c). In Figure 1 (a), taken from the recent study by Netzel *et al.* [7] looking into the influence of environmental variable on the defect formation in corner pieces, a fairly simple wrinkle pattern can be observed in combination with a singular void. Far more complex states are shown in Figure 1 (b), where both wrinkling and in-plane waviness combine with resin pockets. This image is taken from the study of Weber *et al.* [8] who looked at the influence of various process parameters on the generation of defects in a c-section. The image shown here provides a comparison between the defect states obtained when curing without a caul plate (left) *vs.* curing with a caul plate (right). Finally, Figure 1 (c) shows an asymmetric wrinkle pattern observed near the foot of an omega stringer (dashed line added to improve visibility) and Figure 1 (d) shows the continuous and spatially varying wrinkling observed in a curved panel. Together they highlight the inherent difficulty associated with establishing a single characterization framework to adequately capture the ways in which these defect states are similar and the ways in which they are different. The chosen metrics, whether quantitative or qualitative or both, must allow adequate recreation of the variability in morphologies observed, capturing those features most influential in the performance impact of the wrinkle, while ideally being as minimal as possible to avoid need for excessive data extraction and storage.

Wrinkles in the Literature

Turning to the literature it is clear, as observed also by Thor et al. in their recent review [4], that there are generally only two metrics used when characterising wrinkles. The aspect ratio is the most commonly used, while the maximum angle has become generally considered to be the most impactful from a performance standpoint. Previous numerical studies investigating the performance of laminates containing wrinkles have almost exclusively used the maximum angle [9,10] or some form of aspect ratio [11], with some notable exceptions including the work of Bender *et al.* on wrinkling in the trailing edge of wind-turbine blade sections where an average waviness angle was used [12], and the work by Xie *et al.* who investigated the influence of various geometrical parameters but was still using a continuous cosine or sine function [13]. Similarly, studies investigating the formation of wrinkles, including those experimental specimens were produced for which more complex morphologies could be observed (e.g. Netzel *et al.* [7]), still only extracted either height or width separately [8,14–16], the aspect ratio

[7], the maximum angle [17,18], or a spatial distribution of angles [19]. A notable exception to these experimental studies is the work by Hayman *et al.* who included the height, width, and maximum angle in the characterisation of wrinkles in their study on sandwich panels [20]. While this overview is not exhaustive, it demonstrates the general trend in the literature to use a singular metric for characterising and hence studying wrinkle defects in composite parts.



(a) (b) (c) (d)

Figure 1. Selection of wrinkling morphologies including (a) single roughly sinusoidal wrinkles [7], (b) single complex asymmetric wrinkles combined with in-plane waviness and resin pockets [8], (c) single asymmetric winkles with external valley, (d) continuous variable wrinkles.

Contrasting the variety of wrinkling patterns in Figure 1 against the morphologies studied the literature, a clear gap emerges which calls into question this common use of the aspect ratio or maximum angle to solely characterise a winkle pattern. To establish whether the additional features present in some of the realistic examples are relevant to include as metrics in a defects database, the influence on performance must be evaluated. Simply because a certain variation occurs, does not automatically mean it is significant. Only variations and features that can be observed in real components and can be shown to have a meaningful influence on the performance of said parts, are relevant for consideration in the database. In this study, the influence of asymmetry of the wrinkle pattern is investigated relative to the tensile and compressive strength of cross-ply and quasi-isotropic laminates for a selection of baseline wrinkle patterns and levels of asymmetry.

NUMERICAL METHODOLOGY

To carry out the investigations on wrinkle pattern asymmetry, a reliable simulation technique is required. The benefit of numerical studies is that a significant parametric study can be carried out at significantly lower costs, both in terms of time and capital. In this section the approach used in this study and the extend of the parametric space that was explored are outlined.

Representative Volume Element Approach

The numerical results presented in this study are generated on the basis of Representative Volume Elements (RVEs). The use of RVE methods is common in the study of the influence of variations and defects on properties of composite materials and laminates [21–23]. In this study, a meso-scale model representing a unit cell of a composite laminate containing wrinkling is used, see Figure 2. These models, where each laminae in the stacking sequence is represented by a layer of solid hex elements connected to neighbouring layers using cohesive zone elements, were developed in a previous work as part of a multi-scale modelling approach for simulating the performance of large composite structures [23]. The RVE model analysis, run in ABAQUS, uses custom progressive failure material models which provide accurate predictions on the damage initiation and ultimate failure of the unit cell. This failure load of the unit cell can be evaluated for different wrinkle morphologies to investigate the effect changes in the wrinkle have on the ultimate performance of a laminate with the chosen stacking sequence. The full field results from each RVE simulation are submitted to a computational homogenisation module, which generates homogenised stress-strain curves that are then used to detect the onset and progression of failure.

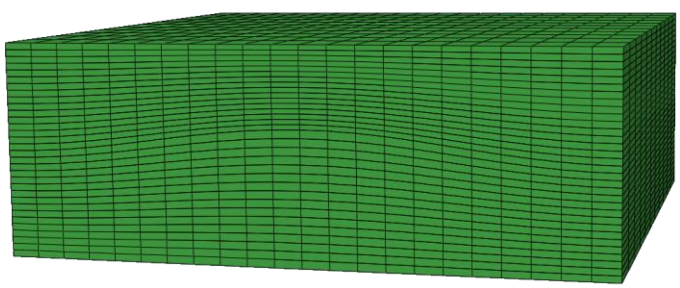


Figure 2. Example of an RVE mesh containing a mild wrinkle pattern.

Wrinkling is introduced into the unit cell by first generating a pristine mesh of perfect rectangular prism elements, and then defining a mesh deformation that shifts the nodes of the mesh in order to produce the desired wrinkled pattern. With this technique it is possible parametrically introduce any wrinkling morphology for which a shape function exists.

Introducing Asymmetry

The previous studies using the RVE models to determine the influence of wrinkling on performance, seeded the wrinkling morphology with a cosine function using the wrinkle amplitude as the driving parameter. In this study, as interest lies in evaluating asymmetric wrinkling patterns, a modified definition of the nodal displacement function is required. The new approach still uses a cosine function, but splits the unit cell domain into 4 regions. Combined with parameters that shift the edges of these regions to be shifted, this produces a first order continuous function capable of generating asymmetric wrinkle patterns. The nodal displacement, as a function of the initial nodal positions, is

$$dz = \begin{cases} \frac{A}{4}\left[1 + cos\left(\pi * \frac{x-\alpha_x}{l-\alpha_x}\right)\right]\left[cos\left(\pi\frac{z-\alpha_z}{\frac{t}{2}-\alpha_z}\right)+1\right], x \geq \alpha_x, z \geq \alpha\_z \\ \frac{A}{4}\left[1 - cos\left(\pi * \frac{x-\alpha_x}{l-\alpha_x}\right)\right]\left[cos\left(\pi\frac{z-\alpha_z}{\frac{t}{2}-\alpha_z}\right)+1\right], x < \alpha_x, z \geq \alpha\_z \\ \frac{A}{4}\left[1 - cos\left(\pi * \frac{x-\alpha_x}{l-\alpha_x}\right)\right]\left[cos\left(\pi\frac{z+\frac{t}{2}}{\alpha_z+\frac{t}{2}}\right)-1\right], x < \alpha_x, z < \alpha\_z \\ \frac{A}{4}\left[1 + cos\left(\pi * \frac{x-\alpha_x}{l-\alpha_x}\right)\right]\left[cos\left(\pi\frac{z+\frac{t}{2}}{\alpha_z+\frac{t}{2}}\right)-1\right], x \geq \alpha_x, z < \alpha\_z \end{cases} \tag{1}$$

where A is the amplitude of the wrinkle, α_x is the horizontal asymmetry offset, α_z is the vertical asymmetry offset, l is half-length of the wrinkle volume and t is the thickness of the unit cell. For clarity the key dimensions are illustrated in Figure 3 where the wrinkled shape of maximally offset line is shown in red. The nodal displacement function above is only dependent on the x and z locations as the wrinkle design is 2D with the unit cell representing an extruded wrinkle with no variation in y. Furthermore the function contains an additional cosine function dependent on the original z coordinate of the node to introduce a decay in the nodal displacement, which creates a smoother variation in ply thickness resulting from the shifting of the nodes.

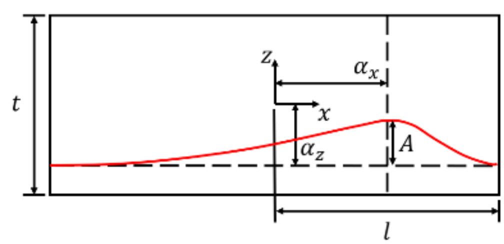


Figure 3. 2D schematic with key parameters for nodal displacement function which splits unit cell cross-section into four quadrants. The maximum amplitude, A, is achieved at the node originally at (α_x, α_z).

It is worth noting here, as indirectly indicating in Figure 3, that in the current work the aspect ratio will be twice as large as in other works. This is because the amplitude of the wrinkle is taken here to be the largest perpendicular distance between the "pristine" path of the fibres, *i.e.* the path the fibres would have if there were no wrinkling present, and the actual fibre path given the wrinkle. Hence for the cosine function used to map the wrinkle path, the amplitude of the function is actually $A/2$. This choice to define the amplitude this way is made to reflect that the amplitude is a description of the observed morphology which ought to be independent of shape function used to map it.

Numerical Test Matrix

In order to get a broader understanding of the possible relevance of the wrinkle asymmetry feature, the numerical test cases were run for both a cross-ply laminate (CP) and a quasi-isotropic laminate (QI) in both tensions and compression loading cases. The CP laminate had a lay-up of $[90_2/0_2]_{4s}$ while the QI had a lay-up of $[90_2/0_2/45_2/-45_2]_{2s}$, with both laminates having a total of 32 plies. The material is IM7/8552, using the material models developed previously [9,10,23].

For each of the 4 scenarios, 80 datapoints were generated by altering the amplitude of the wrinkle, in the range of 0.05 mm and 2 mm, as well as the horizontal asymmetry offset, α_x, in the range of 0 mm and 3.5 mm. For all datapoints the vertical asymmetry offset, α_z, was set to -1.8 mm to create similar wrinkle patterns as seen in Figure 1 (c), which are both horizontally asymmetric as well as offset towards the bottom surface of the laminate. This offsets also enables larger amplitudes without requiring an increase in laminate thickness, achieved by mimicking the natural process of ply thinning (through squeezing) of plies going over the wrinkle.

In all cases, the unit cell in was a cube of 11 mm x 11 mm x 4 mm, meshed using 22 elements in the x-direction, 11 elements in the y-direction and 63 elements in the z direction (1 element per ply and 1 element per inter-ply region).

RESULTS

The numerical predictions of laminate strength can be seen plotted in Figure 4 to Figure 7. In these datasets, the maximum angle acts as a metric of asymmetry. As the maximum angle increases, relative to its lowest value for a given aspect ratio, this indicates an increase in asymmetry. Due to the limitations of the mesh resolution, only for smaller aspect ratios, only a very small maximum angle can be achieved. This is why at lower aspect ratios the ranges of angles is also limited.

Beginning with Figure 4, which provides the results for a QI laminate under tension, there is a visible influence of both the changing aspect ratio and the increasing asymmetry captured by the increasing maximum angle at a fixed aspect ratio. The strongest effect stems from the changing aspect ratio, but some further drop in tensile strength occurs with increasing asymmetry, especially in the range of intermediate aspect ratio values. Notable at an aspect ratio of 0.1, the ultimate tensile strength drops from around 540 MPa to 400 MPa, a relative drop of roughly 26 % due to the introduction of asymmetry, indicating the accuracy of using solely the aspect ratio as a metric of wrinkling. Similarly it is possible to use this data to evaluate the use of solely the maximum angle. Within the datapoints generated for each case there are two points which both share the maximum angle of roughly 27°, achieved with different levels of asymmetry. At low asymmetry the ultimate tensile strength with this angle is 620 MPa, while at high asymmetry the ultimate tensile load with this angle is only 310 MPa, representing a relative drop of 50 %.

Similar trends can also be observed in Figure 5, which documents the response of the QI laminate under compression. In this instance the ultimate load is entirely driven by the aspect ratio with the exception of the aspect ratio of 0.03, where the ultimate compressive strength drops from -620 MPa at no asymmetry to -570 MPa at maximum asymmetry attempted here, representing a relative drop of around 8 %. For all other aspect ratios the maximum difference between compressive strength of the symmetric and any level of asymmetry was less than 2 %. Comparing the two instances of a maximum angle of 27°, however, a change is observed from -500 mPa to -340 MPa, or a 32 % drop.

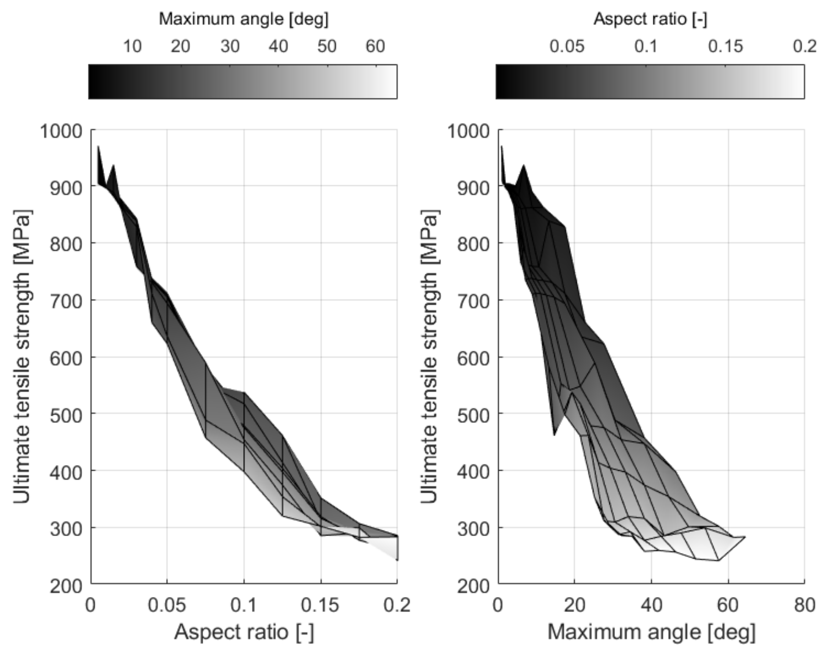


Figure 4. Ultimate tensile strength as a function of wrinkle aspect ratio (left) and maximum deviation angle (right) for the quasi-isotropic laminate.

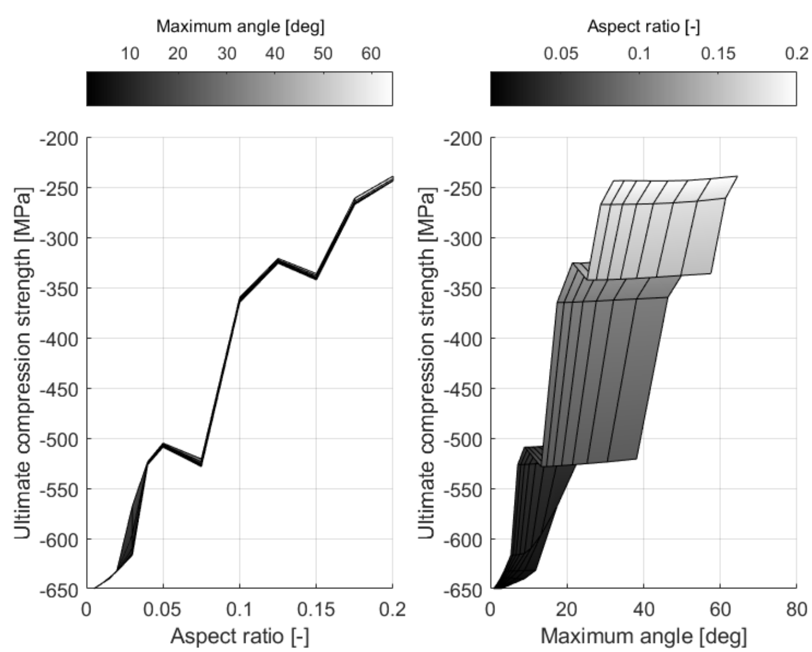


Figure 5. Ultimate compression strength as a function of wrinkle aspect ratio (left) and maximum deviation angle (right) for the quasi-isotropic laminate.

Moving on to the cross-ply laminate, the tensile response is shown in Figure 6, where very similar patterns can again be observed as was true for the QI laminate. Generally speaking the QI and CP laminates showing very similar trends, through the CP laminate generally had higher load carrying capacity across the board, which is to be expected as it contained more fibres orientated in the primary loading direction. For comparison the same points evaluated for the QI laminate can be reviewed. At a constant aspect ratio of 0.1, a symmetric wrinkle results in an ultimate tensile strength of roughly 530 MPa, while at the maximum asymmetry attempted for this aspect ratio the ultimate tensile strength drops to 400 MPa equivalent to a relative decrease of 24 %. This is fairly close to the 26 % drop observed for the QI laminate. At a constant maximum angle of 27°, the ultimate tensile strength drops from 690 MPa at low asymmetry to 330 MPa at high asymmetry. This represents a relative drop of 53 %, a little higher than the 50 % drop seen between the same datapoints for the QI laminate.

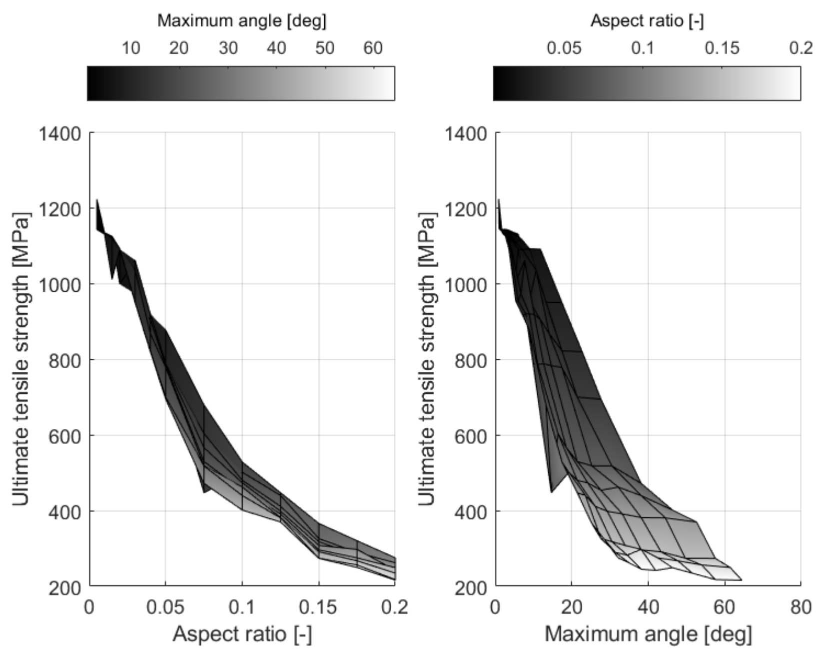


Figure 6. Ultimate tensile strength as a function of wrinkle aspect ratio (left) and maximum deviation angle (right) for the cross-ply laminate.

Finally, the ultimate scenario of a cross-ply laminate in compression is captured in Figure 7. Here the same overall behaviour is observed as with the QI laminate, with the difference being that the influence of asymmetry is here seen at an aspect ratio of 0.02, as opposed to 0.03, and that for the higher aspect ratios of 0.1 and 0.15 the CP data also shows some influence of asymmetry. At the aspect ratio of 0.02, the ultimate compressive strength changes from -790 MPa to -750 MPa, a drop of roughly 6 %. When evaluating at the constant angle of 27°, a change from -610 MPa to -380 MPa is observed, which is a relative drop of 38 %.

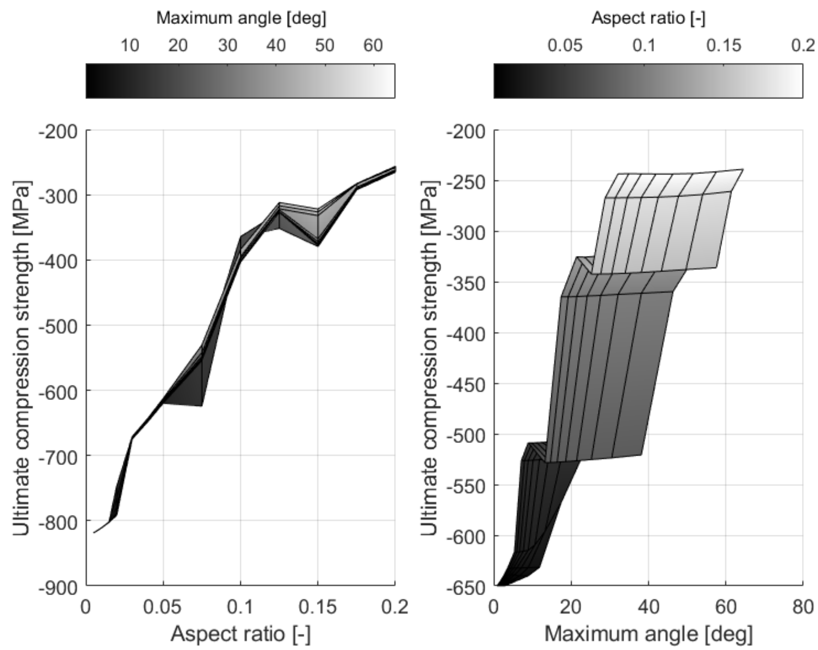


Figure 7. Ultimate compression strength as a function of wrinkle aspect ratio (left) and maximum deviation angle (right) for the cross-ply laminate.

DISCUSSION

The results obtained from the models in this study indicate strongly that a measure of asymmetry in wrinkles is needed. This is based on the observed influence the asymmetry has on the strength of a wrinkle containing laminate. When considering tensile loading the models suggested that for both the QI and the CP laminate use of either the aspect ratio or the maximum angle are poor correlators to strength. Within the data generated, the ultimate tensile strength varied relatively by 26 % for the QI laminate and by 24 % for the CP laminate at a constant aspect ratio of 0.01 when comparing the symmetric and most asymmetric wrinkles with that aspect ratio. The maximum angle performed even worse as a correlator to strength, with a relative drop of 50 % for the QI laminate and a relative drop of 53 % for the CP laminate when reviewing wrinkles with a maximum angle of 27.64 °.

The compression results generally showed less of an influence in asymmetry, this did not change the poor correlation between maximum angle and ultimate strength. On the other hand, the low influence of asymmetry does indicate that, for these subsets of the data, the use of aspect ratio as the sole characteristic of the wrinkle would lead to minimal errors in predictions of the ultimate load. The trends, which were similar for both laminates, as a whole do negate the ability for the sole use of either the aspect ratio or the maximum angle to adequately describe wrinkle patterns containing asymmetry.

From the understanding that wrinkles reduce the performance of laminates primarily through generating elevated through thickness stresses which result in early onset delamination, the observed trends make sense. Two wrinkle morphologies with the same maximum angles but different aspect ratios will have the same raised through thickness stress in one half of the wave, but a different level of through thickness stress in the other half. This can be observed in FIGURE X, where the two through thickness shear components are shown for two wrinkle patterns which both have a maximum angle of 25°. The symmetric and asymmetric case both develop similar stresses on the side that has the same angles (on the right side of the RVE's in this instance) but in the asymmetric case that other side with a lower maximum angle shows lower stresses. As the asymmetry increases, the increased stress region from one half of the wave not only decreases in intensity by also moves further way from the other half, reducing the overall stress amplification in the wrinkle. On the other hand, two wrinkles with the same aspect ratio but different maximum angles will see different maximum stresses caused by their steepest side and hence a different reduction in performance.

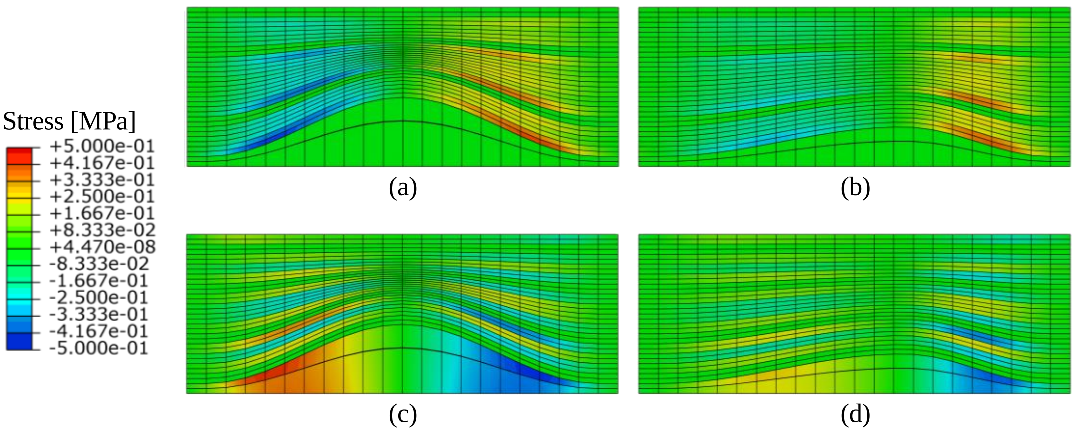


Figure 8. Examples of through thickness shear stresses in the 13 direction (a,b) and the 23 direction (c,d) for both a symmetric wave (a,c) and an asymmetric wave (b,d) with maximum angle of 25° during initial loading of RVE under compression, showing the reduced through thickness stress due to asymmetry.

With this insight, there is now the need for experimental validation. Test specimens are needed to verify, at least for a subset of the datapoints, that the models have accurately predicted the behavioural trends of the actual laminates. For this, samples could be manufactured following the method of cutting and moving strips of material as employed previously by Wang *et al.* [24] in their study of wrinkles. This method is versatile and controllable enough to produce the required symmetric and asymmetric wrinkle patterns.

The knowledge that asymmetry is a key feature in the morphology of wrinkles also indicates that for future studies which characterize wrinkles should enhance the metrics used. The current data supports the potential use of combining maximum angle with aspect ratio, which would allow existing image processing techniques used to extract these values to be used over having to develop novel algorithms for extracting different metrics of the asymmetry.

CONCLUSION

This work set out to investigate the influence of previously unstudied features of realistic wrinkle patterns. Specially the work focused on evaluating the tensile and compressive load carrying capacity of laminates containing asymmetric wrinkles. This asymmetry was observed in images of defects taken from real composite parts, but is not a geometry feature captured in the data present in the literature.

Numerical data was generated with the use of a Representative Volume Element, as implemented in ABAQUS and using material models for accurate prediction of the onset and propagation of failure. A modified nodal displacement function was introduced to allow the pristine mesh (representative of a laminate without wrinkling) to be transformed to contain wrinkling patterns with a variety of asymmetrical features. Both a quasi-isotropic and a cross-ply laminate were investigated for a variety of aspect ratios and levels of asymmetry.

From the data it could be concluded that when considering asymmetric wrinkle morphologies, neither aspect ratio nor maximum angle adequately capture the performance penalty incurred by the presence of the wrinkle. Of the two, aspect ratios fair the best, with variations (comparing the asymmetric to the symmetric) within 10 % for both QI and CP laminates when considering compression and only around 25 % variation when considering tension. The use of maximum angle as a sole metric is more questionable as for both laminates variations were seen in excess of 50 % under tensile loading and in excess of 30 % under compression.

The suggestion to combine both metric appears viable, but would require further investigation for different laminates and more complex loading conditions. Finally, the work is in need of experimental validation to confirm the overall trends identified numerically, for which a viable manufacturing technique was identified.

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