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Development of Design Guidelines for Postbuckling Composite Aerospace Structures

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Abstract

Postbuckling composite structures have significant potential for increasing the efficiency in aircraft designs, but to date their application has been limited. This is due in part to a lack of understanding of composite damage mechanism, and an inability to account for these in a reliable manner as part of design. In response, this paper presents guidelines for designing and analysing postbuckling structures accounting for damage. These have been drawn from an extensive range of experimental and numerical results from fuselage-representative panels, structures and coupons, in both intact and debonded configurations. Due to the complexity of the problem, the guidelines are not simple design rules, but are presented as the key observations and recommendations from all results. These are given in various categories: damage mechanisms, damage criticality, design variability, analysis sensitivity, interlaminar crack growth, the building block approach and analysis techniques. The guidelines have been drawn from the participation of the Cooperative Research Centre for Advanced Composite Structures within the European Commission Sixth Framework Research Project COCOMAT.

Keywords: Composite structures, postbuckling design, design guidelines, damage modelling.

Introduction

Fibre-reinforced composite materials are being increasingly used in the design of aerospace structures due to their high specific strength and stiffness, amongst other properties. Postbuckling structures, which are designed to operate safely at loads in excess of buckling, have been used in metallic aircraft for decades, leading to more efficient structures. However, to date, the application of postbuckling design with composites has been limited, due in part to concerns related to both the durability of composite structures and the accuracy of design tools. As a result, there is considerable potential for improvements in structural efficiency and design safety from improved predictions of failure in postbuckling designs.

This topic was addressed by the recently completed European Commission Sixth Framework Project COCOMAT (Improved MATerial Exploitation at Safe Design of COmposite Airframe Structures by Accurate Simulation of COllapse) [1-2]. The focus of COCOMAT was to develop degradation models capable of capturing the critical damage mechanisms, leading to improved design tools for postbuckling composite structures. The four-year project involved a comprehensive experimental test program that covered a range of length scales including material characterisation specimens, validation specimens of a two-dimensional or substructure nature, and multi-stiffener curved panels representative of fuselage designs.

From the COCOMAT project, a significant database of experience and results was obtained relating to the performance of composite stiffened structures in postbuckling applications, and the capabilities of analysis tools to capture the critical damage mechanisms. These results have been used in the development of guidelines for design and analysis of postbuckling composite structures, particularly in consideration of damage. This paper presents design and analysis guidelines drawn from the participation of the Cooperative Research Centre for Advanced Composite Structures (CRC-ACS) in the COCOMAT project. The incorporation of damage introduces significant complexity, such that simple design rules were not found to be suitable. Instead, the guidelines presented are the key observations and recommendations that are considered critical to account for damage in postbuckling composite aerospace structures.

Design and Analysis Guidelines

Design and analysis guidelines are presented below in the following categories: damage mechanisms, damage criticality, design variability, analysis sensitivity, interlaminar crack growth, the building block approach and analysis techniques.

It should be noted that these guidelines have been drawn exclusively from the analysis and validation procedures of CRC-ACS within the COCOMAT project. This included analysis of three multi-stiffener curved panel designs (D1 [3-5], D2 [5-6] and D6 [7]) and two single-stiffener curved panel designs (D1 and D2) [8]. All of these panels were analysed in intact and debonded configurations, and were loaded only in compression until collapse. They also all used the same material, though in two different thicknesses and with both co-cured and secondary bonded skin-stiffener construction.

The guidelines were also drawn from CRC-ACS analysis and validation using two-dimensional skin-stiffener sections under postbuckling deformations [5,9-11], as well as fracture mechanics characterisation specimens such as the double cantilever beam (DCB) [12], end notched flexure (ENF) [13] and mixed-mode bending (MMB) tests [13].

A summary of all specimens that have been investigated is given in Figure 1, and the reader is referred to the publications listed above for further detail on the experimental and numerical results. In addition to these specimens, some aspects of the guidelines were drawn from experience in a benchmarking exercise [14].

Damage Mechanisms

For composite stiffened structures in compression, structural collapse is triggered by two key damage mechanisms: fibre fracture in the stiffeners and the initiation of interlaminar damage at or around the skin-stiffener interface. These were the dominant mechanisms leading to rapid and often catastrophic failure in experimental testing, and numerical analyses in which these aspects were captured gave very good predictions of the experimental collapse load.

Crack growth from a pre-existing interlaminar damage region is an important damage mechanism to capture, as pre-damaged structures can show an ultimate load higher than the load to initiate crack growth. Furthermore, crack growth from a pre-damage region typically showed a preliminary stage of only small crack growth initially, followed by steady crack growth at a higher load. This demonstrates that for pre-damage regions, the propagation of damage is more critical than simply the initiation of crack growth.
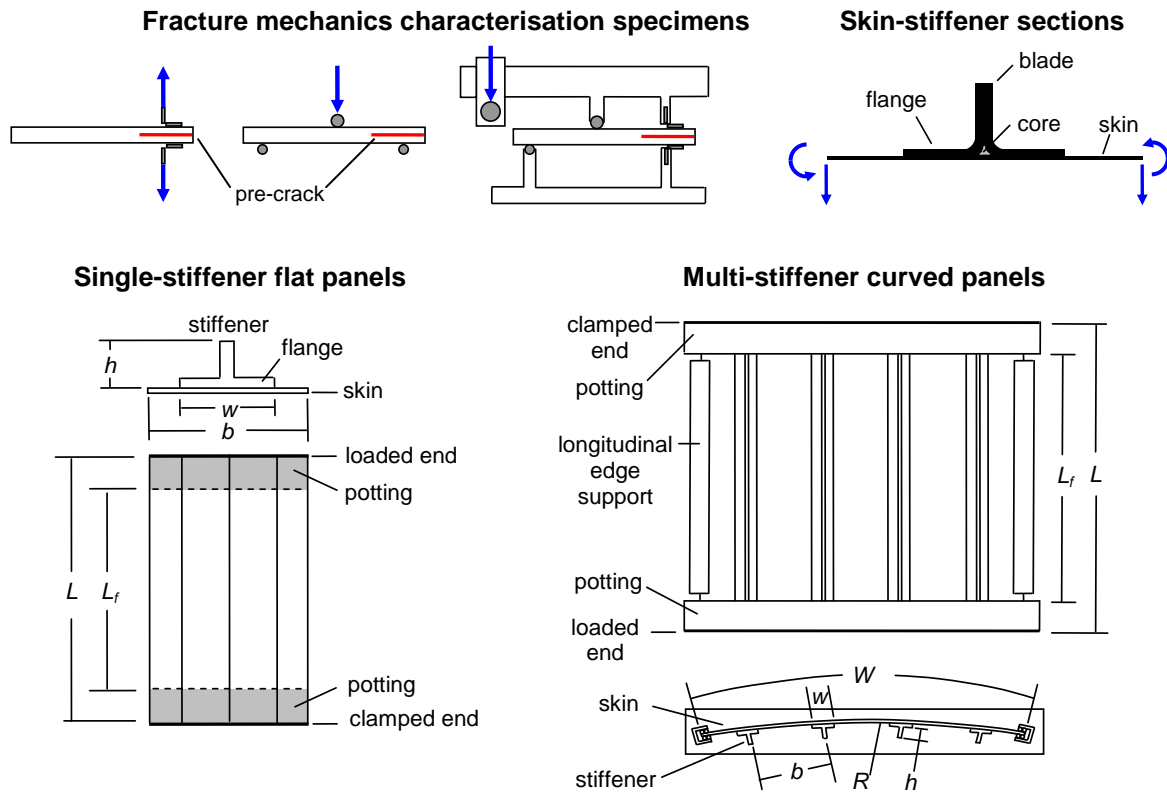
Fracture mechanics characterisation specimens

Skin-stiffener sections

Single-stiffener flat panels

Multi-stiffener curved panels

Figure 1: Summary of specimens investigated

Matrix cracking is not a critical damage mechanism, but should be captured where possible as the local load distribution can have important effects, particularly in affecting the postbuckling deformations.

Damage Criticality

For all damage mechanisms, the postbuckling mode shape is the most critical factor affecting damage initiation, development and criticality. This is further complicated by the possibility for mode shape changes throughout the postbuckling region, and the difficulties associated with capturing the correct postbuckling shape in analysis.

As a result of this dependence on mode shape, it is difficult to predict the critical locations for the different damage mechanisms without performing a full postbuckling analysis. This means that design parameters such as the critical stiffener, location under the stiffener, stiffener size (debonded area) and shape need to be determined for each structure. Furthermore, these critical design parameters would change with changes in postbuckling mode shape.

For pre-existing interlaminar damage at the skin-stiffener interface, the presence of the damage at the edge of the stiffener flange is a key factor for criticality. From this, full-width damage extending to both flange edges is more critical than damage extending only to one flange edge, and damage located only under the stiffener and not running out to a flange edge. This is illustrated in Figure 2.

For impact of stiffened structures, the critical locations for compression loading are those that correspond to locations of maximum compressive strain in the stiffeners.
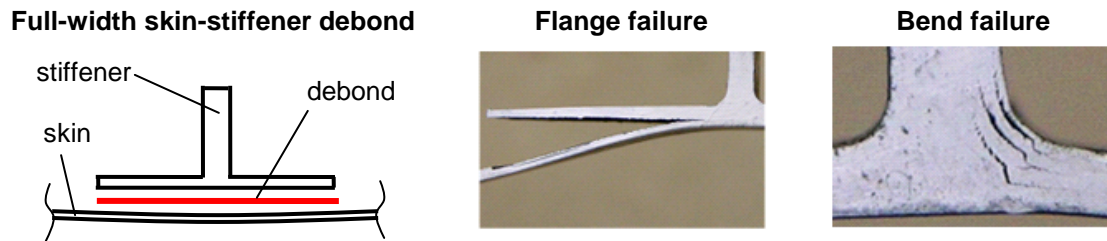
Full-width skin-stiffener debond   **Flange failure**   **Bend failure**

Figure 2: Critical damage types

For the initiation of interlaminar damage at intact skin-stiffener sections:

- The peeling of the skin away from the flange is critical, such that the critical locations correspond to locations of maximum deflection of the skin away from the flange, and not simply to maximum deflection anywhere in the panel (see Figure 2).
- Failure in the bend of the skin-stiffener joint can also be critical for certain loads and panel geometries, particularly when failure at the flange edge is suppressed through ply drop-offs or resin overflow (see Figure 2).
- Locations involving displacement away from the centre of curvature, that is, those that involve a "push" type load on the stiffener and increase the radius of curvature of the skin, are not critical.

Design Variability

Postbuckling stiffened structures undergoing damage up to collapse are sensitive to a range of parameters, including: imperfections in the geometry, load or boundary conditions, manufacturing variability such as ply misalignment or variations in bond quality, and the unpredictable nature of buckling and postbuckling problems with regards to mode shape development.

In a design context, this variability must be accounted for as part of the solution process. This means that for any design solution, it is critical to understand whether variances in the design parameters within expected tolerances affect the performance of the design. This is to ensure that the design solution continues to provide the required performance in real manufacturing and loading scenarios.

The parameter of Robustness has been proposed as a measure of design variability [15-17]. A structure is considered robust when its performance is tolerant to variations in geometry, boundary conditions and material properties. Robustness is determined by performing a stochastic analysis of a design, and combining the Influence (based on ordinal rank) and Sensitivity into a Robust Index for that design. A Robust Index for an entire structure can be determined by combining all the Influence and Sensitivity parameters into a matrix form and factorising to extract the Robust Index for the structure.

Robustness has shown to be a useful measure in two ways. Firstly it can be used to measure the sensitivities of a particular design with respect to variance of its inputs. Robustness has also shown to be a useful measure in design studies comparing the sensitivities of multiple designs. The Robustness methodology seeks to find the variables causing the variations and not the actual mean or scatter of the results.

One key aspect that should be accounted for wherever possible is geometric imperfections. These can occur as a result of part curing and general manufacturing variability, and correspond to deviations of the real part from the nominal geometry. An example of this is shown in Figure 3. In a design context, geometric imperfections are generally not known *a priori*, but should be incorporated where possible due to their critical nature.

- One approach for this is to apply a first analysis step that attempts to model the curing process. This was shown to be capable of reproducing the types of imperfection patterns seen in real structures. It was also demonstrated that introducing imperfection patterns from curing analyses into the model produced more realistic analysis results compared to the nominal model.
- Another approach within a design process would be to apply previous experience on geometric imperfections from similar structures.
- The application of eigenvalues to model imperfections, although commonly reported in literature, was found not to be useful, and had little effect on the structural behaviour, particularly in postbuckling.
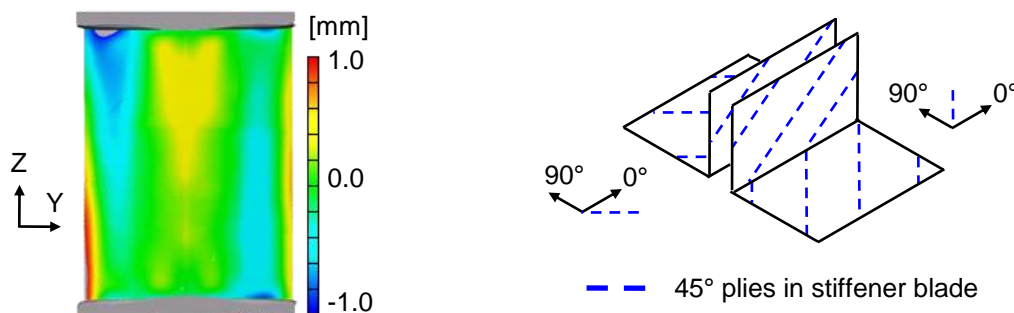

Figure 3: Left: Geometric imperfections. Right: Asymmetry in the skin-stiffener layup

Another key aspect that should be accounted for where possible is the existence of material imperfections. Variations occur in material properties through such causes as ply misalignment, void and defect content or general manufacturing variability. The typical scatter in material properties can be determined from material characterisation tests. The maxima and minima of this scatter should then be incorporated into the design and analysis process to determine its influence on the performance of the structure.

Analysis Sensitivity

The analysis of composite stiffened structures in postbuckling is also sensitive to a wide range of analysis parameters. This is due to the large degree of nonlinearity and the sensitive nature of the designs themselves. As such, it is critical to ensure that a high level of model and analysis accuracy is maintained at all times. Areas in which high accuracy is required include:

- The incorporation of asymmetric stiffener flanges, which are created by laying the stiffener plies on top of opposite facing tools, as shown in Figure 3.
- The definition of the skin-stiffener interface, such that the modelling accurately captures the displacement and bending behaviour. It has been found that accurate results are found by offsetting the laminate so that the shell layers are defined at the connecting surfaces (and as such are nominally coincident), as shown in Figure 4.
- High precision analysis parameters – small convergence tolerances (e.g. 1×10^{-3} for load residuals), and the most accurate stiffness update method (update every iteration).
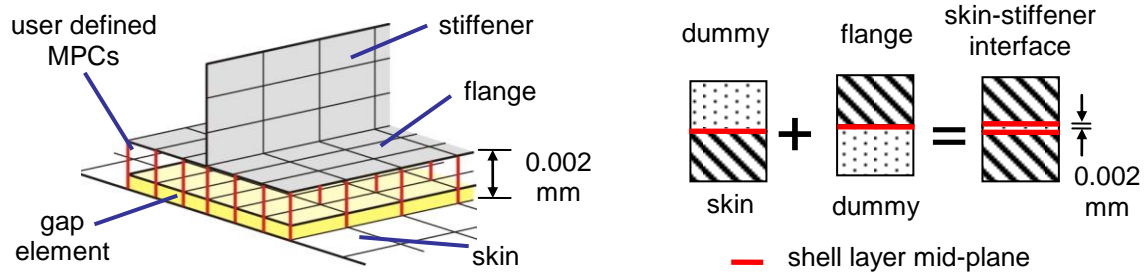
Figure 4: Skin-stiffener interface modelling

Aspects that in general require parametric studies in order to ensure accuracy include:

- Mesh density and mesh configuration, particularly the use of transition meshes between fine and coarse mesh regions. For capturing postbuckling behaviour in general, a regular and consistent mesh is beneficial, with at least three to four elements in the key structural features (stiffener blade, flange, skin) to represent buckling patterns.
- Damping: both global (structural level) and local (damage level).
- The use of explicit analysis techniques to model quasi-static loading, particularly in setting appropriate loading rates and mass scaling.

Although results indicated that some aspects may not be critical or significant for every model, (such as the asymmetric flange definition), in general the small additional effort is more than offset by reducing the possibility that the model parameters could influence the postbuckling deformation and damage definition.

Interlaminar Crack Growth

For an interlaminar crack in stiffened structures, a reasonable assumption in design is that all crack growth will occur at the skin-stiffener interface. Although in real crack growth processes the interlaminar crack can migrate through-the-thickness to other interfaces, this is not able to be accurately predicted or characterised from an analysis point of view. Assuming all crack growth occurs at the skin-stiffener interface is a compromise between the most likely, most critical, and most practical location for analysis, due to the following reasons.

- Skin-stiffener debonding is a likely and critical damage type, so that using the skin-stiffener interface to model crack growth allows direct control of the properties of this crucial connection.
- Through-thickness crack migration requires additional energy and typically only occurs to interfaces within the vicinity of the skin-stiffener interface. Modelling a single damage location at the skin-stiffener interface is therefore a worst case scenario that still adequately represents the structural behaviour of most other crack growth scenarios.
- Accurate and representative material properties is an unavoidable issue for crack growth analysis regardless of interface, as is discussed further in a later section.

Interlaminar crack growth in stiffened structures is in general always a mixed-mode phenomenon. This is due to a combination of factors including the complex deformation patterns and loading, size of the debonded area, orientation of the crack front and asymmetric sublaminates.

As a result, a mixed-mode failure criterion is required, as is some understanding of the mixed-mode behaviour in crack growth for the particular interface at which growth is occurring. The B-K criterion was found to be suitable, and though differed only slightly from a Power Law criterion, appeared to be more realistic at higher proportions of mode II component.

For design and analysis of crack growth, the following fracture mechanics assumptions can be applied, in the absence of detailed experimental data:

- $G_{III\,c} = G_{II\,c}$
- G_{II} can be replaced by $G_{shear} = G_{II} + G_{III}$ in mixed-mode equations

The Virtual Crack Closure Technique (VCCT) has been shown to be suitable for the design and analysis of composite postbuckling structures containing a pre-existing interlaminar damage region. To do this requires methods for handling arbitrary mesh size and crack front, which are available in literature (see, for example Ref. 18). The VCCT can be used to detect the initiation of crack growth, and has been incorporated into an approach to represent crack propagation. The application of VCCT in a crack propagation analysis should incorporate an assessment of the continuing validity of assuming self-similar crack growth, as this has been found to be dependent on the propagation method.

Where possible, the design and analysis of structures containing interlaminar pre-damage should incorporate crack growth modelling, as opposed to simply predicting the initiation of crack growth. It was repeatedly shown that the first instance of crack growth in a postbuckling stiffened panel did not lead immediately to stable and continuous crack growth, due to the phenomenon of sub-critical cracking. Furthermore, structures undergoing stable crack growth are still able to show increasing load capacity with increasing crack length, depending on the relative severity of the damaged area. As a result of both of these considerations, the collapse load of a structure undergoing crack growth is significantly higher than that predicted using only the first instance of cracking.

It should be remembered that whilst the analysis of interlaminar crack growth will tend to predict stable crack growth, crack growth in real structures is more likely to occur in a stop-start manner. This is due in part to the unpredictable nature of interlaminar crack growth, and of the irregularities and micromechanical features not captured in the modelling. In spite of this, it has been shown that in general, the predicted crack growth lengths can agree well with experimental results.

Building Block Approach

The use of a building block approach (BBA) to investigate specimens of increasing complexity is valuable in identifying and isolating key damage mechanisms and assessing their behaviour at different length scales. The building block approach should apply as much commonality in specimen design as possible, to ensure behaviour is transferable at different length scales. This includes specimen geometry, material, loading and boundary conditions.

- Characterisations specimens such as strength and fracture mechanics tests are vital to quantifying the material behaviour. These tests are also able to be easily modified to provide critical information on more realistic specimen aspects not strictly covered in test standards, such as quasi-isotropic laminates and adhesive bonding.

- Two-dimensional specimens such as skin-stiffener sections were shown to provide important information on the criticality of design parameters including geometry, loading, stiffener type, manufacturing method, and analysis parameters such as strength, boundary condition and model definition.
- Single-stiffener specimens are valuable in terms of providing insight into the development and interaction of damage on a small scale structural level, and are particularly valuable for validation of numerical models.

Although investigation of specimens at different length scales is highly valuable, the damage behaviour of composite materials does not always translate directly between length scales. Specifically, damage mechanisms that are evident or critical at one scale, such as at the material characterisation level, may not be critical or may involve additional complexities at other scales. This phenomenon is known as the scale effect [19], and the inability of current analysis methods to take this into account is largely responsible for the large amount of experimental testing and associated high cost of the BBA within industry.

Analysis Techniques

The application of an eigenvalue analysis as a design tool for postbuckling fuselage structures has been shown to have limited value. Whilst useful in the design of some structures as a rapid sizing tool, eigenvalue analysis was found to give nonsensical or non-applicable results for both the mode shape and buckling load of the panels investigated.

The global-local analysis technique was shown to be a suitable and efficient method for the combination of a large structural model of 2D shell elements with detailed 3D models. The technique is particularly suited to rapid analysis of multiple local locations, where the coordinates of the local model can easily be modified to run a series of analyses based on a single global result file. The global-local approach applied is illustrated in Figure 5.
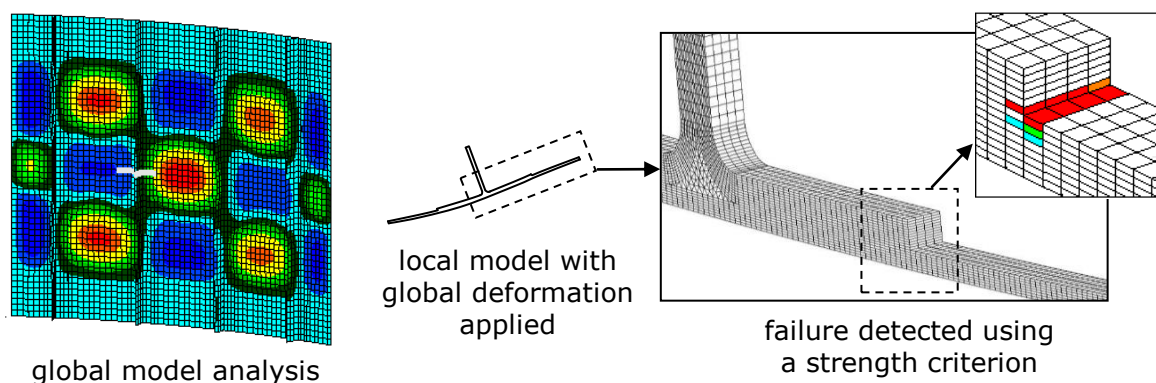

global model analysis   local model with global deformation applied   failure detected using a strength criterion

Figure 5: Global-local analysis for interlaminar damage intiation prediction

Strength-based failure techniques were shown to be suitable for damage prediction and as part of damage modelling approaches. However, for predicting failure at stress concentrations, such as flange edges, the mesh size will control the prediction of failure initiation. This effect can be mitigated by using a "matched mesh" approach, in which an appropriate mesh size is calibrated using experimental results. The use of small validation specimens has been shown to be beneficial in this regard.

In terms of comparing different analysis codes in the benchmarking exercise, it is difficult to be conclusive due to the limited nature of the comparison, and the fact that damage modelling was not considered. Furthermore, the composite damage models available in some codes have significantly improved since the benchmarking exercise in Ref. 14 was performed.

- For the implicit codes considered, MSC.Nastran (Nastran), MSC.Marc (Marc) and Abaqus/Standard (Abaqus), the nonlinear solution algorithms were similar, and were all shown to be suitable for postbuckling problems. Of these, Abaqus appeared to have a slight advantage, in that it included the capacity to implement structural damping (not available in Nastran), and showed the most robust solution algorithm (the Marc solver was more computationally expensive for some problems considered).
- Comparing the explicit solver LS-Dyna with the implicit codes, it was seen that both solver types could be used to achieve suitable results. However, it was clear that the assumptions and limitations of both solver types were quite different, and that an understanding of these is required in order to ensure accurate results are obtained.

Discussion

The issue of accurate and representative material properties is critical for any analysis, particularly those involving damage modelling based on strength and fracture mechanics data. For strength properties, some small variation in values obtained from characterisation is typical, despite the fact that the test standards for strength are well established. This was clearly seen in COCOMAT, where properties obtained for the same material tested in different laboratories varied significantly in some instances, and showed variation between properties previously characterised for the same material in POSICOSS. This variation should be incorporated into design and analysis studies, as previously discussed.

For fracture mechanics properties, the issue of material properties is more complex, for a number of reasons. Firstly, the interface that is measured in standardised characterisation methods is between two unidirectional plies, whilst in real structures crack growth typically occurs between dissimilar plies, and can also involve an adhesive layer. Some fracture mechanics parameters are also not as well understood or not currently capable of being characterised, such as single or mixed-mode properties involving mode III, and properties between dissimilar plies. Furthermore, there are complexities in crack growth that are difficult to incorporate into the model, such as "jumping" of the crack through the laminate, fibre bridging across the crack interface, the "stop-start" nature of experimental crack growth, the effect of residual thermal stresses, and the influence of the bounding ply orientations. As a result, interlaminar crack growth modelling and fracture toughness properties may be only able to be incorporated in an average sense, with appropriate parameters needing to be determined from experimental testing of representative structures at different scales.

One aspect that remains important in the analysis of postbuckling composite structures is the computation time. For CRC-ACS analysis within COCOMAT, run times for large postbuckling structures were dependent on the extent of crack growth and fibre fracture, and ranged from 40 minutes to more than a week for models where these factors were significant. In general, this order of computation time fits in with the aims of the developed approach to form part of a necessarily "slow" analysis tool suitable for aircraft certification. However, it must remembered that the accurate analysis of crack growth and ply failure will always be computationally expensive, and that experience is required apply the degradation models within practical design and analysis procedures.

Conclusion

Design and analysis guidelines were presented for postbuckling composite stiffened fuselage structures. As simple design rules are not suitable given the complexity of the problem, the guidelines are principles and key concepts to assist with designing aerospace postbuckling structures in consideration of damage. Analysis guidelines were also presented that are specifically related to performing an accurate analysis, and detail key parameters and modelling strategies. All guidelines were drawn from CRC-ACS experience in COCOMAT, and covered a number of different aspects: damage mechanisms, damage criticality, design variability, analysis sensitivity, interlaminar crack growth, the building block approach, analysis techniques and analysis guidelines. The issues of material properties and analysis time were also discussed in terms of CRC-ACS experience in COCOMAT.

Acknowledgments

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