INNOVATIVE TECHNIQUES FOR THE FINITE ELEMENT ANALYSIS AND OPTIMISATION OF COMPOSITE STRUCTURES

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Abstract

Current methods for the conceptual design of composite control surfaces focus on the analysis of the structure to meet specific design loads. The final design is usually obtained by trial and error, rather than utilising the optimisation routines of finite element (FE) software. However, while optimisation routines produce an analytical optimum, this often does not correlate well with a manufacturable optimum.

By utilising new methodologies and techniques to achieve the optimum design of a composite structure, FE analysis can be more fully employed in the design process. Investigation of cost effective and reliable methods for the optimisation and analysis of these structures and the detailed modelling aspects associated with the FE analysis of a control surface are discussed. Discussion focuses on the design of rib and spar reinforced composite control surfaces, but is not limited to these structures.

The outcome of this research was the investigation of many innovative FE analysis techniques to produce an optimum design. Results showed that by utilising some novel and simple techniques it is possible to further improve the design and optimisation process, such that the result is a shorter design cycle and improved optimum. These techniques are simple to employ at the preliminary design stage, without complicating the design process.

1 Introduction

The design of composite aerospace structures by finite element (FE) methods is a well-established field, with a great deal of knowledge already gained from previous investigations [1]. This paper expands on this knowledge, by discussing innovative techniques for the analysis of these structures.

The aim of this research work was to investigate design and manufacturing technologies applied to the manufacture of composite control surfaces for large commercial transport aircraft. The primary focus was the creation of a design methodology that would reduce design cycle time and produce an optimum manufacturable design [2-4]. An investigation into current and emerging manufacturing techniques for the construction of composite control surfaces was also made.

Today most composite structures are designed through a combination of classical and analytical approaches, with optimisation routines only utilised at critical design points. New design methodologies are now beginning to emerge as optimisation routines improve and computing power increases. This has helped to considerably improve the conceptual design cycle time

FE packages such as Ansys and Nastran are regularly utilised for the design of composite structures within the aerospace industry. A large amount of preliminary design work has already been successfully completed utilising the Ansys FE package to produce optimum designs of rib and spar reinforced composite structures [5]. Ansys is a parametric FE package that is particularly useful in the conceptual design stage due its ability to easily perform topology, shape and sizing optimisation.

Even with the large reduction in computational time, optimisation routines are currently not intelligent enough to select lay-up sequences, spar positions or manufacturing cost based on anything other than an analytical optimum. A realistic constraint on the manufacturability of a structure is often impossible or impractical to impose during the optimisation process. Designers must therefore be reliant on their own engineering judgment to produce the final manufacturable optimum, which is often more constrained by cost rather than weight or any other design constraint.

Composite aerospace structures can be manufactured using a large variety of methods. Recently, the trend has been to move away from the traditional hand lay-up pre-preg design and towards designs incorporating manufacturing technologies such as Resin Transfer Moulding (RTM) and Resin Film Infusion (RFI) [6]. The structural arrangement of composite aerospace structures are also changing as the use of ribs, spars and stringers traditionally associated with an aluminium design are more widely adopted. This style of design lends itself to the optimisation process, since ribs, spars and stringers can easily be added, moved or extended depending on the result of an optimisation analysis.

2 Design Requirements

2.1 Geometry

The starting point for the design of a composite control surface is usually a pre-defined Outer Mould Line (OML) with specified hinge and actuator locations. The OML of the control surface is set by the aerodynamic and mating surfaces, while the hinge and actuator locations are determined by the main structural connection points. An example of a control surface OML used as the starting point for a conceptual design can be seen in Fig. 1. This OML is representative of a rudder with eight hinges and three actuators.

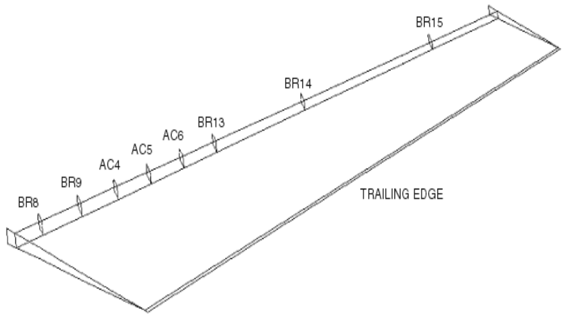

Fig. 1. Example of a control surface OML.

The methodology discussed will focus on a co-cured rib and spar dominated design. For this type of design the objective will be to find the minimum number of ribs, spars or pad-ups required within this design space while meeting all design constraints. Since every additional rib, spar and skin pad-up will increase manufacturing complexity and therefore cost.

2.2 Loading

To simulate actual loads on the control surface, loading is generally separated into two distinct conditions. This includes aerodynamic loads, often simulated by applying a triangular chordwise pressure distribution with a maximum value at the hinge line and tapering to zero at the trailing edge. The triangular chordwise pressure distribution for a rudder control surface is shown in Fig. 2. The shape of this distribution can of course vary significantly, depending on the type of control surface and the load case applied. During the preliminary design stage, the values for this distribution are often generated from previous experience or a supplied maximum hinge moment.

The second loading case is due to sympathetic bending of the control surface, caused by a combination of the aerodynamic and inertia loads on the attachment structure.

The deflection values are usually generated from an allowable mid-span or tip deflection constraint, or by imposing a direct surface strain level on the structure. Shown in Fig. 3 is the spanwise displacement profile for a rudder control surface.

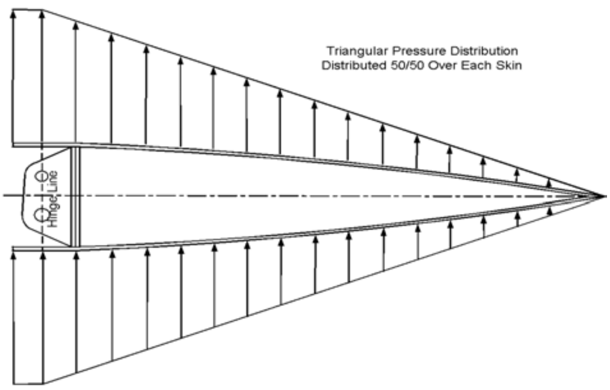

Fig. 2. Typical aerodynamic pressure distribution.

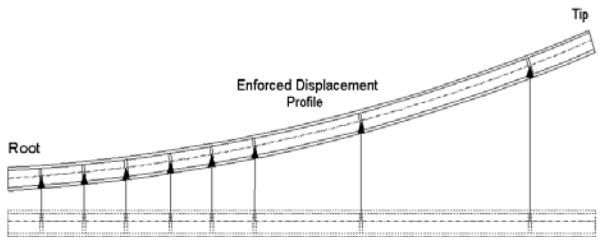

Fig. 3. Typical enforced displacement profile.

2.3 Constraints

Typically for a control surface, there are seven critical design constraints that drive the conceptual design, they are as follows:

- Mass
- Buckling
- Maximum Tip Deflection
- General Surface Waviness
- Strength
- Cost
- Manufacturability

The first five constraints have a measurable value that can be used within the optimisation process. The last two are more difficult to incorporate into the optimisation process, although attempts are currently being made to do this.

The buckling constraint specifies that no buckling should occur on a surface before a specified load. This value is generally Limit Load (LL) or 1.3 LL, depending on the thickness of the buckling region. This constraint is the main driver for the number and location of the ribs and spars and the skin thicknesses.

Maximum tip deflection is a stiffness constraint designed to minimise any adverse aerodynamic and aeroelastic issues during the detailed design phase. The maximum tip deflection can be a design driver for rib and spar placement and skin thicknesses.

The general surface waviness (or slope) of an aerodynamic surface is constrained to a specified value at the cruise condition. The surface waviness will generally drive the skin thickness in regions where buckling is not critical.

The value for maximum slope is calculated by finding the out-of-plane displacements along the free stream direction. At the preliminary design stage the mean outer skin profile can be found by fitting a cubic equation to the actual outer skin profile, as shown in Fig. 4. The slope is determined by calculating the wave amplitude and half-wavelength, then applying Eqn 1.

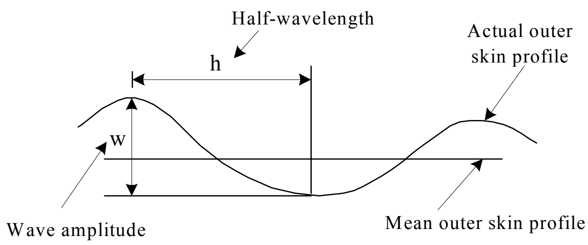

Fig. 4. Calculation of surface waviness.

$$slope = \frac{w}{h} \tag{1}$$

The strength criterion specifies that failure of the composite material is not permitted before Ultimate Load (1.5 LL). The strength constraint is usually critical at the hinge and actuator locations and often drives the skin pad-up thickness and ply stacking sequence in these regions. The failure indices for the composite should be calculated using the maximum strain criterion.

Cost is usually the critical design constraint when considering a composite structure. There are currently only simplistic methods available for the optimisation of cost parameters within FE routines. The easiest way this can be performed is by investigating various design concepts to minimise the number of spars and ribs and still meet all design constraints.

Manufacturing constraints should also be considered early in the design process, since they are a critical cost driver for the final design. While there is currently no way to directly optimise for manufacturability. The designer should always keep in mind the affect that design changes can have on this constraint.

3 Design Methodology

Utilising the parametric optimisation capabilities of the Ansys FE package a methodology can be developed that enables the designer to quickly produce a design concept. Starting from the supplied geometry, loads and constraints, a topological optimisation is performed on the design space. Once the initial structural configuration has been selected from the topological optimisation results, parametric optimisation takes places, where structural locations and sizes are determined. Looping of this parametric optimisation process occurs, until all design constraints have been met and the final design concept is ready for a detailed analysis. A block diagram of this design methodology can be seen in Fig. 5.

The optimisation process is computationally expensive, so to reduce computation time the composite material is represented using equivalent isotropic material properties. The equivalent material properties are determined by creating a lay-up representative of the average thickness and sequence from similar control surface designs. This technique significantly reduces design cycle time and still achieves a satisfactory optimum during the topological and parametric design phases.

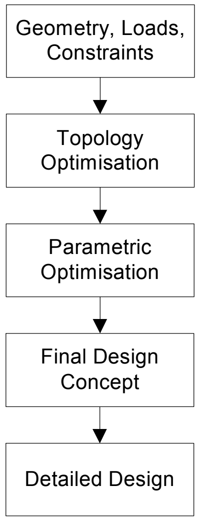

Fig. 5. Design methodology.

Other simplification also occurs in the FE model by neglecting rib and spar flanges, ply offsets and pad-up transition regions. Modelling of the hinge and actuator flanges is accomplished by creating duplicate elements at the attachments regions along the front spar, then equivalencing the nodes.

3.1 Topology Optimisation

The first step in the design cycle is the creation of a topological model where a large number of ribs and spars are placed in the design space. The material thicknesses for this model should be such that they are representative of similar control surfaces. A topology optimisation is performed on this model to determine the critical load paths within the structure. The optimisation is based on a specified volume reduction for the minimum total strain energy. An example of the topological optimisation results for a rudder is shown in Fig. 6.

The selection of the number and location of the ribs and spars should be based on a combination of the topological optimisation results and the designer's knowledge. At the early stage of the design, it is advisable to minimise the number of ribs and spars to reduce design and manufacturing complexity.

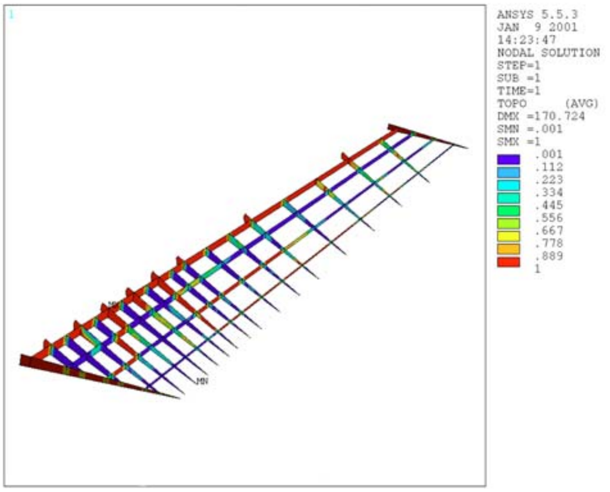

Fig. 6. Topology optimisation results.

3.2 Parametric Optimisation

Once the preliminary structure has been chosen from the topology optimisation results, the parametric design phase begins. Using the bucking constraint, the model is parameterised and optimisation performed to determine the optimum locations for the ribs and spars. The benefits of using an FE package such as Ansys for this procedure is its ability to easily move geometry around the design space and quickly converge on the optimum. An FE package such as Nastran does not have the ability for large geometrical changes during shape optimisation, since a linkage is not maintained between the geometry and elements.

One important factor to note when using Ansys for parametric optimisation is to limit the number of variables to 20 [7]. This can be achieved by variable linking and progressive optimisation runs.

Thickness optimisation is then performed on the model still using buckling as a constraint with the objective to minimise the structural mass. The thickness results from the optimisation run must then be rounded to the nearest value divisible by the ply thickness. An example of the critical buckling eigenvector plot for a rudder is shown in Fig. 7.

Once compliance with the mass and buckling constraints has been achieved the general surface waviness should be checked. A chordwise section is cut at various locations along the span. Selection of the spanwise location to determine the slope is a manual process, but generally the maximum slope will occur at the location of maximum variation in displacement between the leading and trailing edges.

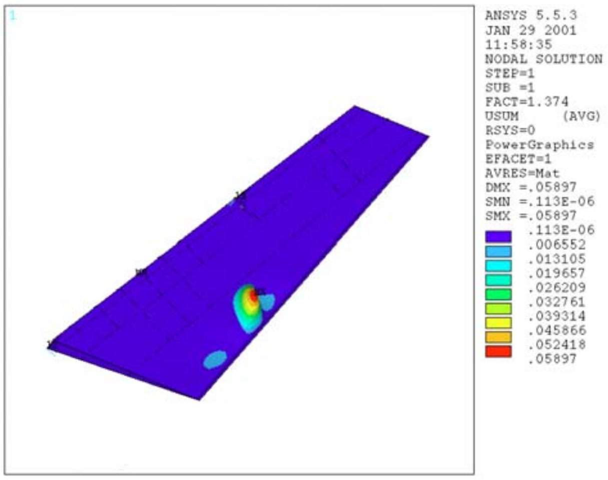

Fig. 7. Critical buckling eigenvalue.

While the slope is usually calculated along the free stream direction, for the purposes of a preliminary design and to assist in mesh generation, a location perpendicular to the front spar is often a better location to use. This approach will usually yield a more critical value for the maximum slope due to a reduction in the value of the half-wavelength.

To simplify calculation of the slope and allow its incorporation into a parametric optimisation routine, a user-designed subroutine was created using Ansys Parametric Design Language (APDL). This routine finds the value for maximum slope along selected lines on the aerodynamic surfaces.

When analysing the surface waviness, a geometric non-linear analysis should be preformed at the specified design load. An example of the displacement plot at the cruise condition and location of maximum slope is shown in Fig. 8. A plot of the out-of-plane displacement at this location and the corresponding mean outer skin profile is shown in Fig. 9.

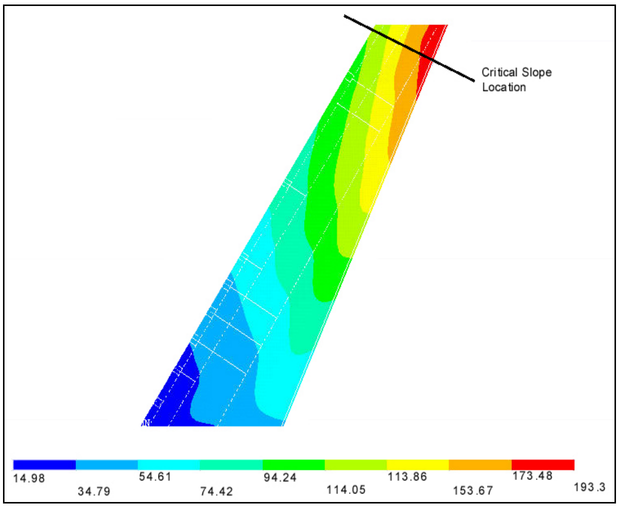

Fig. 8. Out-of-plane displacement plot at the cruise condition.

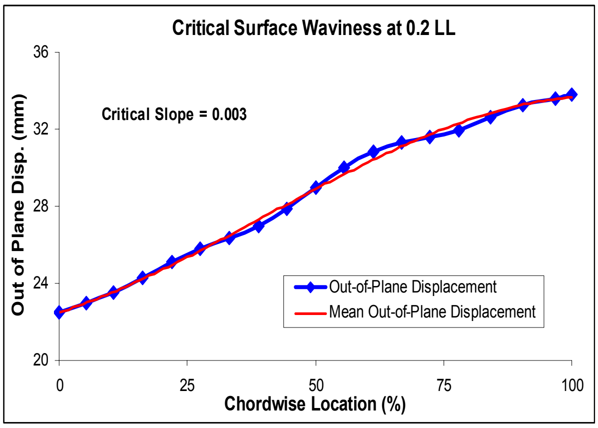

Fig. 9. Plot of the out-of-plane displacement at the critical location

Further parametric optimisation can be performed on the hinge and actuator elements to determine lug, web and flange thicknesses. This helps give a more accurate value of the structural mass and will more accurately predict the constraint forces at the hinge and actuator connections for their sizing.

To check the structural strength of the control surface, the maximum strains are determined for the equivalent isotropic model. If the strain values calculated are below the allowable strain values for the composite material it is safe to assume that structural integrity will be achieved.

At this stage, the design should be reviewed for compliance with the mass target and manufacturability requirements. If the design does not meet the mass target regions of localised skin pad-up should be introduced. These regions should be gradually increased until the mass target is met. If the mass target cannot still be met, then additional ribs, spars or stringers should be added to the design concept. This process will involve looping through the parametric optimisation process to create a design concept of increasing complexity. An example of the design changes for an aileron to meet the mass target is shown in Fig. 10.

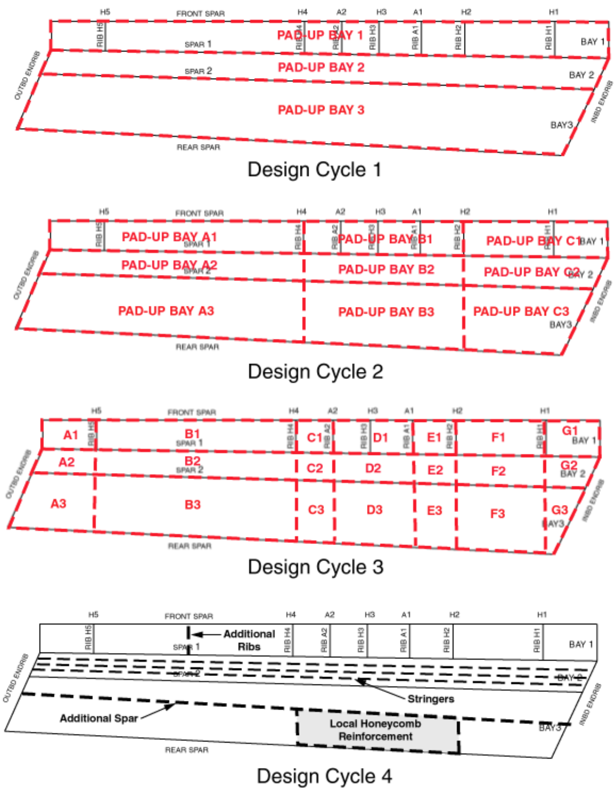

Fig. 10. Example of the design cycle for an aileron.

Once a structure has been designed to meet all constraints, the equivalent isotropic model is replaced by a composite material model. The ply sequence is tailored to suit manufacturing constraints and the failure indices calculated for the structure. All design constraints are then rechecked using this model.

A user-designed subroutine using APDL was created to input failure allowables and view results. A plot of the failure indices for a rudder is shown in Fig. 11.

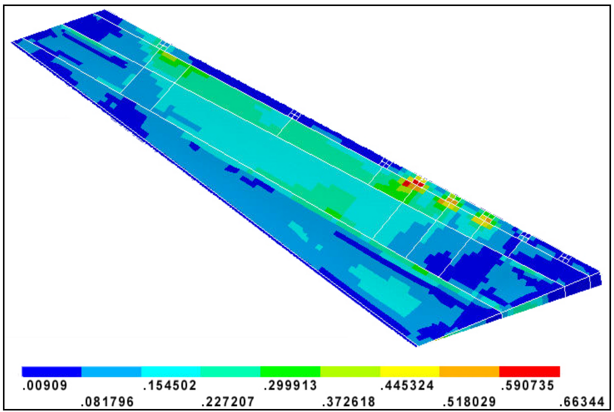

Fig. 11. Failure indices plot.

3.3 Detailed Design

At this point the conceptual design process is completed and you now need to move into the detailed design phase. Analysis can continue using Ansys, or the model can be imported for use with Nastran. This will depend on the designer's preference.

During the detailed design process, further changes will be made to the FE model, including the following:

- Modelling of the rib and spar flanges
- Incorporation of non-structural components such as nose ribs
- Modelling of the ply drop-off clearance from the rib and spar flanges
- Modelling the length of the ply-drop off region
- Accurately modelling the hinge and actuator fastener connections
- Updating the hinge and actuator lugs after detailed sizing
- Analysis of cut-outs in critical regions

If all design constraints were met during the conceptual design phase, further optimisation of the design will be minimised. This can result in the detailed design phase being considerably shortened.

4 Manufacturability

It is extremely important to bring manufacturability into the design process from the moment an initial structural configuration is chosen. The number of ribs, spars and amount of skin pad-ups each have a major contribution to the final cost and manufacturability of the component. At the start of the parametric optimisation process, a minimalist approach should be taken by limiting the pad-up area, number of ribs and spars, and rib extensions. The designer should be particularly aware of enclosed bays, where mandrel extraction could be an issue.

To accurately explore issues of manufacturability, it is important to translate the conceptual design to the CAD environment, as shown in Fig. 12 [8]. The designer can then visualise the effect of rib and spar placement and pad-up transition. This also facilitates communication with manufacturing personnel so any problems with the design can be quickly rectified.

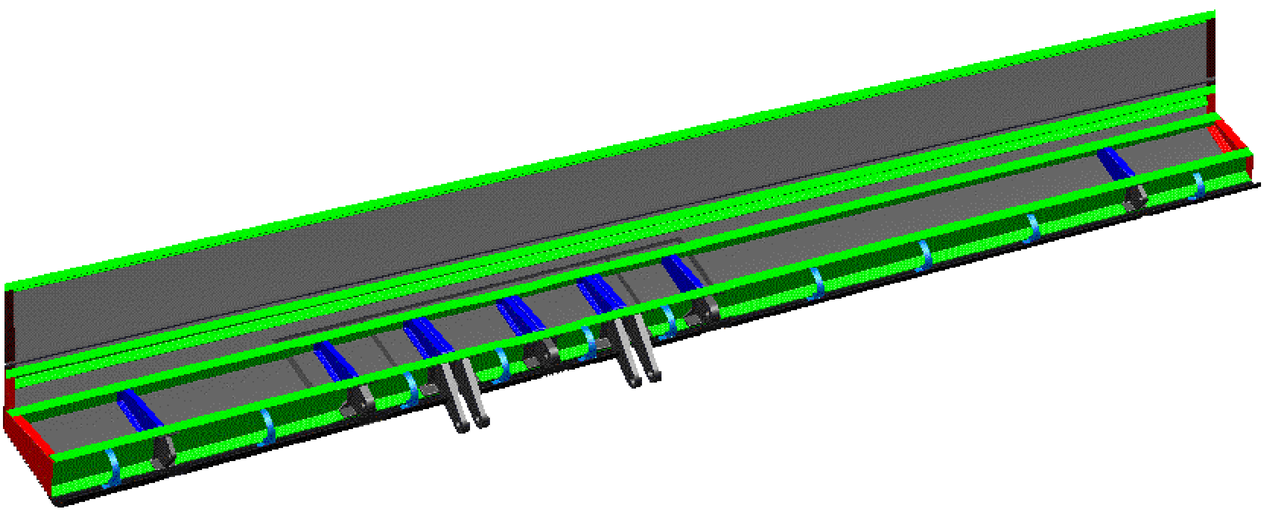

Fig. 12. CAD drawing of a control surface (top skin removed).

5 Validation

The design methodologies discussed have been validated through the design and structural testing of a composite spoiler demonstrator.

A spoiler representative of a large commercial transport aircraft was manufactured using a co-cured rib and spar design [9]. The initial design concepts were analysed and evaluated using Ansys, with a detailed analysis performed with Nastran.

Manufacturing studies were performed and the RFI technique utilised for manufacture. Metal mandrels were used for lay-up and compaction. Manufacturing trials were also undertaken to prove manufacturing concepts before production of the test article.

A test rig was designed and manufactured to impart the critical static load case for the spoiler demonstrator (see Fig. 13 and Fig. 14). Loading was accomplished through the use of screw jacks at the hinges to impart wing bending and a whiffletree arrangement was used to simulate the aerodynamic loads.

Testing was performed for the limit load, buckling load and ultimate load cases. Results from the test showed that the test article met all design constraints for buckling and failure beyond ultimate load.

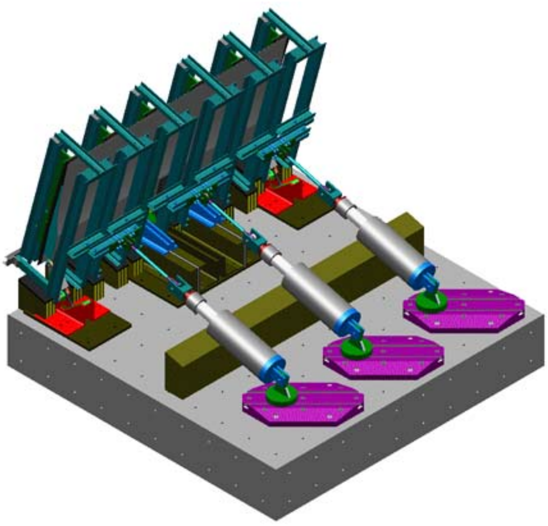

Fig. 13. CAD model of the spoiler and test rig.

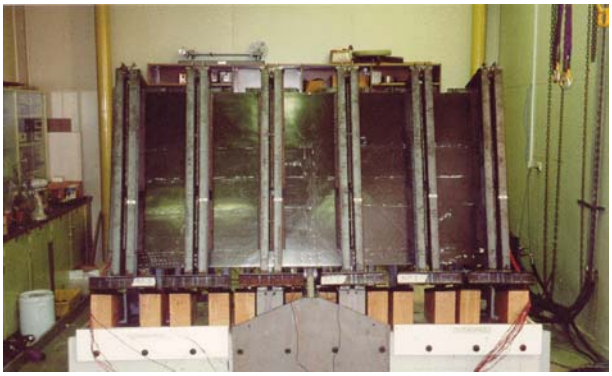

Fig. 14. Spoiler test article placed in test rig ready to be tested.

6 Discussion

Research has been undertaken into the application of FE optimisation packages such as Ansys for the conceptual design of composite structures. This FE package has been shown to have many benefits in the preliminary design of structures. Ansys has been used to produce a number of conceptual designs for rib and spar dominated composite control surfaces and has proven successful in developing a cost and weight competitive structure.

The outcome of this project was the development of a design methodology for the fast and efficient design of composite control surfaces. This methodology was validated by the manufacture and static testing beyond ultimate load of a large transport aircraft spoiler. Results from this test showed that by using this design methodology a lighter, cheaper and structurally more efficient design was possible. This methodology employed the parametric capabilities of the Ansys FE package to create optimum designs through a procedure whereby topological optimisation and parametric optimisation are performed on the structure.

Nastran is regarded as the industry standard when it comes to the FE analysis of aerospace structures. However, Nastran has some noticeable shortcomings, particularly when it comes to shape optimisation. Due to the non-parametric nature of the optimisation process, maintaining the structure's geometric profile is difficult to achieve. The use of Ansys in the conceptual design phase allows the designer to fully explore the design space by maintaining a link between mesh and geometry. Topological optimisation coupled with Ansys's parametric capabilities enables the selection of a structural configuration that meets all design constraints. The simplification of the FE model to improve design cycle time by approximating material properties and structural arrangements was shown to not significantly affect the final detail results.

The use of this methodology for the design of rib and spar arrangements allows the designer to explore various design concepts with regard to manufacturability requirements. Translation of the conceptual design into the CAD environment is of great benefit for detecting manufacturing problems before modelling the design details.

7 Conclusion

Preliminary design techniques for the optimum design of composite structures have been presented. It has been shown that by utilising suitable FE tools the design cycle time can be significantly reduced, while achieving a manufacturable design that is close to optimum. The parametric capabilities of the Ansys FE package have been utilised to achieve this. These capabilities allow the designer to fully explore the design space, and quickly perform trade studies on design variations. The inclusion of user-subroutines to quickly calculate the slope and failure indices, assisted in shortening the design cycle time even further.

The design methodology has been validated by the exploration of various control surface designs and the detailed design, manufacture and testing of a spoiler demonstrator.

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