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Effect of structural dynamic characteristics on fatigue and damage tolerance of aerospace grade composite materials

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ABSTRACT

In aircraft structural integrity analysis, the damage tolerance and fatigue life is investigated against a cyclic loading spectrum. The particular spectrum includes the stress/loading levels counted during a flight of certain duration. The occurrences of load factors may include higher gravitational acceleration 'g' levels. While maintaining a certain g level occurrence at higher angle of attack, wing structure vibrates with the amplitudes of its natural frequencies. The cyclic stress amplitudes of vibration depend upon the natural frequencies of vibrating structure, i.e. lower frequency gives higher amplitudes and vice versa.

To improve the dynamic stability, modal parameters of simple carbon fibre sandwich panels have been adjusted by tailoring the fibre orientation angles and stacking sequence. In this way, the effect of change in structural dynamic characteristics on fatigue life of this simplified structure has been demonstrated. The research methodology followed in this work consists of two phases. In the first phase, aero-elastically tailored design was finalized using FEM based modal analysis and unsteady aerodynamic analysis simulations followed by experimental modal analysis. In the second phase, fatigue and damage tolerance behaviour of material was investigated using different fracture mechanics based techniques. ASTM's standard practices were adopted to determine material allowable and fracture properties. Simulation work was performed after proper calibration and correlation of finite element model with experimentally determined static and dynamic behaviour of panels.

It has been observed that the applicable cyclic loading spectra, as major input parameter of fatigue analysis, largely depend upon the natural frequencies, damping and the stiffness of the structure. The results and discussions of the whole exercise may be beneficial while carrying out aero-elastic tailoring of composite aircraft wing. This research work has also a positive contribution towards multidisciplinary structural design optimization of aerospace vehicles.

1. Introduction

General Aircraft Structural Integrity Program (ASIP) activities include: static & fatigue aspects, environmental degradation and structural life assessments. Additionally, damage tolerance analysis is often required to prevent the failure of structure as a result of fatigue cracks [1]. The objective of the damage tolerant design requirement is to demonstrate adequate residual strength in the presence of flaws for specified periods of service usage. Fatigue and Damage Tolerance (F&DT) analysis gives the service life of critical load bearing structural members by taking into account the material properties, initial crack/damage level and the applicable cyclic loading spectrum. Commercially available Damage Tolerance Analysis (DTA) software codes are based upon different material models from which NASGRO is considered the latest model in metals. This material model incorporates crack growth rate data of material at different stress ratios [2,3]. Whereas, in case of composite structures, there are many analytical models under consideration to analyse damage, however the validation of newly developed models is still a challenge. Currently, some phenomenological and micro level theories are being used to predict onset of damage. Besides material failure criteria, there are many other things of consideration when dealing with composites, such as the inclusion of thermal stresses in structure, moisture effects, in plane shear strength and non-linear behaviour of the material [4]. One of the most important parameters to be considered in aerospace structures is the aerodynamic vibrational loads that depend upon structural dynamic characteristics [5]. In certain cases of aircraft's critical structural location, the applicable loading spectrum can't be measured directly by installing accelerometers. One of the limitations may be the inaccessibility of high stress concentration area.

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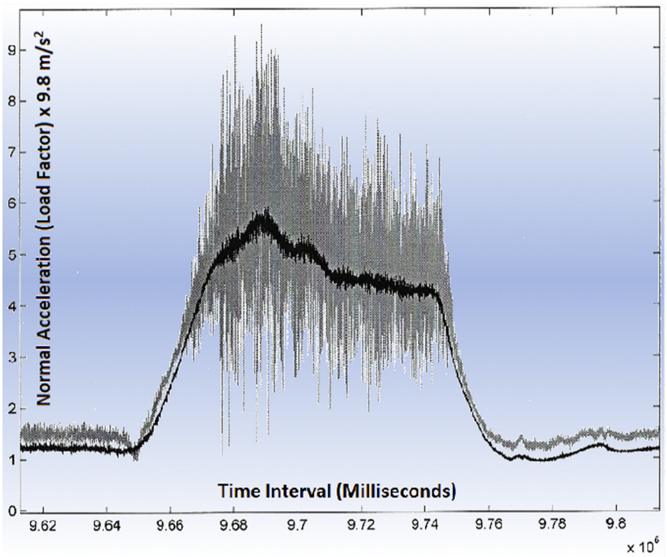

Fig. 1. Aircraft normal acceleration data comparison (CG & wing tip).

Secondly, the flight testing for fatigue loads calculation is also an expensive activity. In this way, the fatigue spectrum for different critical structural locations is generally generated by using the easily available N-z acceleration data of the sensor installed at centre of gravity (CG). If it is required to carry out F&DT analysis on a critical member at the root of an aircraft wing, the cyclic loading spectrum for this particular member will be governed by the N-z acceleration occurrences count of aircraft and the vibrations of the wing. In this way, any change in natural frequencies of the wing should be considered while declaring the fatigue life. In Fig. 1, time domain data of 02 accelerometers mounted on wing tip and centre of gravity have been presented. As compared to fuselage, the wing vibrates with higher amplitudes while maintaining an occurrence of 5 g level.

Keeping in view the close relationship among structural dynamics, static strength and fatigue life of both the metals and composite parts of the aircraft, the effort has been carried out to establish a relationship among these parameters for multidisciplinary design optimization. Failure index of composite part against ply material failure and delamination propagation has been investigated using latest fracture mechanics based techniques such as: progressive failure analysis, cohesive zone modelling and virtual crack closure technique.

2. Research methodology

In this research, the pattern of engineering work is in line with the standard practices of aerospace industry. However, the investigations have not been performed on proper aircraft wing. A simplest design of carbon fibre sandwich panels along with an aluminium attachment has been used for the proof of concept, as shown in Fig. 2 this approach is adopted to reduce the overall design space of work. Such problems become complicated when the output of each parameter does not only depend on the independent design variables, but often on each other as well. Multidisciplinary design optimization studies are usually conducted to achieve a better agreement among the parameters under consideration [6,7].

The overall methodology adopted in this work comprises of two phases. In first phase aero-elastically improved design of panels was finalized using finite element based numerical simulations followed by the experimental validation and correlation of results.

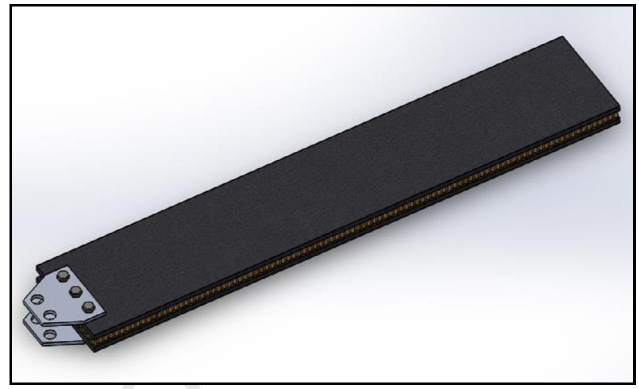

Fig. 2. 3D model of specimen under investigation.

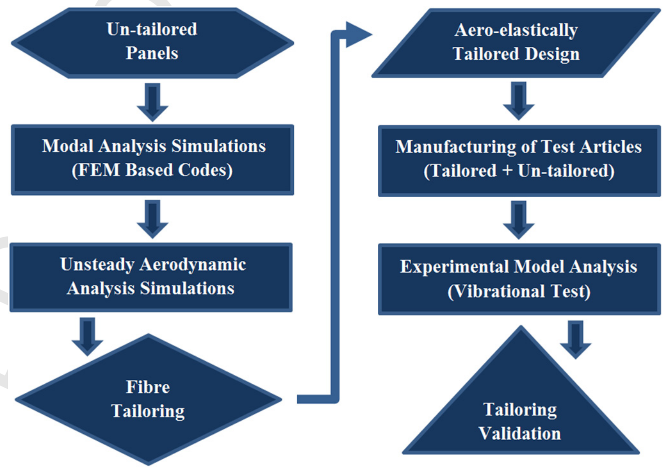

Fig. 3. Activities flow chart of phase-I.

Dynamic stability was improved by setting up a certain orientation of carbon fibres.

For this purpose two sets of tailored and un-tailored composite panels were manufactured and went under extensive experimentation. Structural dynamic characteristics such as natural frequency, damping, generalized stiffness and generalized mass against each vibrational mode of panels were the input parameters to unsteady aerodynamic analysis. This analysis was performed to prove a positive change in aerodynamic stability of panels. Flutter speed was calculated for both the tailored and un-tailored panels. Flow chart of engineering activities adopted in first phase is shown in Fig. 3. Output of first phase is an experimentally verified aero-elastic design with altered structural dynamic characteristics.

In second phase, where the tailored and un-tailored test articles are available, the static and fatigue strength of both the designs was investigated. The objective of this phase was to investigate the effect of altered dynamic characteristics on structural integrity and fatigue life. Software based simulations for progressive damage analyses were carried out under applicable cyclic loading conditions for both the designs. For updating and fine tuning the FEM model, static response of both designs was also correlated with experimental results. Basic strength parameters and fracture properties of composites were experimentally determined in laboratory using genetic material coupons. Fig. 4 shows the activities flow chart adopted in phase-II.

3. Modelling & simulations

An appropriate size of test articles was selected to demonstrate the whole exercise for the proof of concept. The overall dimension

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