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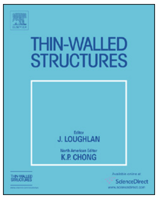

Full length article

Buckling detection of an omega-stiffened aircraft composite panel using distributed fibre optic sensors

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ABSTRACT

A novel approach to detect and locate buckling from distributed optical sensors is proposed in this paper by means of a second derivative analysis of the strain measurements. This methodology demonstrates that non-linear events are prone to significant changes in the full-field strain shape obtained using a dense distributed optical network, whose measurements were processed earlier using a Savitzy-Golay filter. Moreover, these non-linear events can be identified without needing to know the load step value.

A buckling test was conducted in a stiffened composite panel representative of a cockpit fuselage skin stiffened by two omega stiffeners plus two fastened metallic frames. A distributed fibre optic network was bonded to the flat panel side in a crooked configuration. The panel was also instrumented using conventional back-to-back strain gauge rosettes and a high-speed-camera to establish a qualitative comparison with the distributed strain contour map.

Through the proposed methodology, the detection and location of the global and local buckling were successfully conducted.

1. Introduction

The challenge of reducing the weight in aircraft structures has been nearly settled through the application of composite materials [1–3]. Nowadays, most innovative commercial aircrafts, such as the A350, are made up of 50% composite materials in its structure and components. Additionally, the use of lightweight composites in military aircraft has been even more significant, in some cases reaching an 80% of the airframe. This includes the primary structure components such as the vertical and horizontal stabilizer, fuselage sections, or wing panel [4]. The use of composites not only allows a lightening of the structures owing to their high specific properties, but also the development of an efficient design, reducing the number of structural parts and creating new design concepts.

Thus, in the quest to enhance the strength-to-weight ratio, stiffened composite panels have been a breakthrough in the area of structural configurations [5]. This type of panel configuration is widely used to improve the load bearing, increasing the stiffness and panel stability without adding more additional weight. However, one of the most important drawbacks related to stiffened panels lies in the fact that they are prone to buckling failure because the panel skin is generally thinner, allowing for a lighter structure. Furthermore, this failure is highly likely to occur under an in-plane shear load, causing diagonal tension on the panel skin between the stiffeners and half buckling waves, which create a specific angle with the stiffener axis [6]. The onset of high shear loads in a stiffened panel may incur not only the appearance of global and local buckling, but also damage, such as delamination or stiffener de-bonding [7–9]. Thereby, the stringer debonding is one the most critical mechanism of failure causes by out-of-plane displacement after buckling onset [10,11]. Furthermore, the influence of large notch damages under compressive loads in an omega stiffened panels has been already deeply analysed by numerical approaches [12,13]. These investigations conclude that the presence of inter-laminar damages is prone to anticipate the buckling phenomenon as well as the fibre failure propagation.

Then, to ensure the in-service safety and stability, stiffened panels are usually tested under a diagonal compressive load, which rapidly induces non-linear behaviour in the panel skin owing to a non-pure shear loading. Therefore, an outstanding part of such a panel design is to analyse the buckling response under critical shear loads.

Thus far, back-to-back strain gauge rosettes are the most common strain sensor used to detect the initiation of buckling at a single location

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(where the sensor is positioned). By comparing two rosette readouts bonded on opposites sides of the structure skin at the same location, buckling can be predicted when the slopes of their load-strain curve change their direction [14]. The main problem related to a strain gauge sensor is that they can only perform a single point measurement because it is inefficient and cumbersome to apply several strain gauges to monitor the full-field strain across the structure. Furthermore, the wires of these sensors will increase the weight of the structure. Non-contact optical techniques, such as a digital image correlation (DIC) [15,16], are usually employed to identify buckling patterns and the full-field deformation of the structure with very high accuracy and precision. However, the cameras used to acquire the images need to be carefully placed and calibrated before testing, are focused in a specific area. This has led to the application of this technology to be restricted mainly to laboratory testing. Other fringe projection techniques, such as a shadow Moiré technique, is able to measure the out-of-plane displacement and buckling wave evolution [14,17]. Despite being a good technique to measure the displacement of large structures, it has low measurement accuracy and resolution, which is a requirement in the aeronautical field.

In this experiment, a recent and thriving technique is proposed for analysing the full-field strain to detect, locate, and characterize the buckling initiation in stiffened panels, namely, distributed fibre optic sensors (DFOS) based on Rayleigh scattering. DFOS have opened up new possibilities for structural test monitoring, not only for civil engineering structures [18–20], but also for aircraft structures [21,22]. There are three key techniques to performing a distributed measurement (strain and/or temperature) dependant on the light scattering measurements in the fibre-optic used: Raman, Brillouin, and Rayleigh techniques [23,24]. While a Raman technique is mostly used to monitor the temperature over tens of kilometres, such as oil pipes [25,26], the Brillouin and Rayleigh techniques are able to obtain distributed measurements of both the strain and temperature within a shorter range with better resolution and accuracy. However, Rayleigh scattering can achieve a resolution of millimetres at over 70 m with very high accuracy.

The scope of this experiment involves a novel methodology to detect and locate the local and global buckling in a stiffened composite panel by means of a second derivative analysis of a distributed strain measurement. These signals were acquired using an optical backscatter reflectometer (OBR), which is one of the most promising technologies for structural test monitoring [27,28].

2. Distributed strain measurements

The distributed strain measurements presented in this paper were acquired using the OBR-4600 system from Luna Innovations [23,29,30]. This system enables measurements of the Rayleigh scattering caused by random fluctuations in the refractive index during the manufacturing process of optical fibre [29]. OBR is an optical frequency domain reflectometer (OFDR) that uses swept-wavelength interferometry by means of a tuneable laser (TLS) to interrogate the device under test (DUT), i.e. optical fibre, with a very high spatial resolution (~ 5 mm) and accuracy (~ 1 με). A functioning schema of an OBR is illustrated in Fig. 1 [31,32].

The distributed strain measurement of the complex reflection over a finite bandwidth is given by the vector sum of the two orthogonal polarization states ('s′ and 'p′). Once the complex reflection coefficient is obtained in the frequency domain, the reflectivity as a function of the fibre length is obtained through a fast Fourier transform [31,33]. The reflected spectrum then experiences a shift when a segment of the DUT is strained or heated. To determine this spectral shift, a cross-correlation should be performed between the two fibre states, the reference and loaded states (Fig. 2). The spectral shift is linearly dependant on the temperature (ΔT) and strain ($\Delta\varepsilon$) changes at each segment, as shown in Eq. (1), where K_T and K_ε are the temperature and strain coefficients, $\Delta\lambda$ and $\Delta\nu$ are the wavelength and frequency shift, and λ_0 and ν_0 are the centre wavelength and frequency of the distributed measurement, respectively.

$$\frac{\Delta\lambda}{\lambda_0} = -\frac{\Delta\upsilon}{\upsilon_0} = K_T\Delta T + K_\varepsilon\Delta\varepsilon \tag{1}$$

Finally, the distributed measurement can be accomplished when the overall shifts are calculated by performing a cross-correlation for each segment along the DUT (i.e. the optical fibre line placed on the structure). In some cases, the signal reflectivity becomes attenuated because of fibre optic loops and transverse stresses, and thus, in such a case, the calculation of the spectral shift might turn out to be cumbersome.

Prior to acquiring the distributed measurement from an OBR, a set of signal conditioning parameters (SCP) must be selected based on the sensing network features and experimental setup requirements. The distributed strain measurement is affected by the SCP selection in terms of the accuracy and resolution. These parameters are the gauge or sensor length, the spacing between consecutive sensors, and the measurement range. On the one hand, the shorter the length used, the smaller the number of data points that will be included in the spectral shift calculation, and therefore the signal might become unstable and noisy. On the other hand, the calculation of the spectral shift might be obtained with a longer sensor length, and consequently, a greater number of points will be used to obtain the spectral shift. In such a case, when the structure is experiencing areas with a small overload, the strain field becomes quite variable over short distances. Hence, if the sensor gauge length is too long, these overload areas (potential failure points) might be missed and remain undetected. Consequently, a good combination of SCP ensures a better temperature or strain accuracy and resolution in the resultant distributed measurement.

3. Experimental setup

The structural test was conducted using a specimen of a stiffened composite panel representative of cockpit fuselage skin for a regional aircraft. This panel was designed, manufactured, and tested by Airbus as part of the Clean Sky programme, of which Polytechnic University of Madrid (UPM) took part through a buckling analysis based on a distributed sensing network for strain monitoring.

3.1. Specimen description

First, the panel configuration is shown in Fig. 3 (left). The panel skin was made of carbon/epoxy unidirectional tape, prepreg AS4/8552, and stiffened using two carbon/epoxy unidirectional tape prepreg AGP280/8552 omega stiffeners (S1 and S2), plus two fastened metallic frames (F1 and F2) made of aluminium. The manufacturing of the panel skin was made by automated fibre placement, whereas the two stiffeners were joined by two secondary bonding. The nominal width and length were 600 mm 1655 mm, respectively. The total panel skin thickness was 2.3 mm, and for omega stiffeners was 1 mm.

3.2. Sensor instrumentation and equipment

The specimen was held in a rig such that the line connecting two of its four corners was perpendicular to the floor, also having the same direction as the applied load. A designed shear frame was manufactured to carry out this test, which mainly consists of interface plates, frame bar assemblies, and load bolt assemblies. For buckling analysis, a diagonal compressive load was introduced to the panel linearly from -20 to -160 kN at load step increments of -20 kN, and from -160 to -195 kN by load step increments of -5 kN. The room temperature remained constant without significance changes during the entire experimental test.

The test was conducted on an MTS testing machine (250 t). Strain monitoring for the buckling test was carried out through conventional