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Experimental and numerical estimation of buckling load on unstiffened cylindrical shells using a vibration correlation technique

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ABSTRACT

Nondestructive methods, to calculate the buckling load of imperfection sensitive thin-walled structures, are one of the most important techniques for the validation of new structures and numerical models of large scale aerospace structures. The vibration correlation technique (VCT) allows determining the buckling load for several types of structures without reaching the instability point, but this technique is still under development for thin-walled plates and shells.

This paper presents and discusses an experimental and numerical validation of a novel approach, using the vibration correlation technique, for the prediction of realistic buckling loads on unstiffened cylindrical shells loaded in compression. From the experimental point of view, a batch of three composite laminated cylindrical shells are fabricated and loaded in compression up to buckling. An unsymmetric laminate is adopted in order to increase the sensitivity of the test structure to initial geometric imperfections. In order to characterize a relationship with the applied load, the first natural frequency of vibration and mode shape is measured during testing using a 3D laser scanner. The proposed vibration correlation technique allows one to predict the experimental buckling load with a very good approximation, without actually reaching the instability point. Furthermore, a series of numerical models, including non-linear effects such as initial geometric and thickness imperfection, are carried-out in order to characterize the variation of the natural frequencies of vibration with the applied load and compare the results with the experiment findings. Additional experimental tests are currently under development to further validate the proposed approach for metallic and balanced composite structures.

1. Introduction

The concept of relating vibration characteristics to buckling loads was considered at the beginning of the 20th century for Somerfeld [1], but only in the 50s some experimental investigations were conducted by Chu [2], Lurie [3] and Meier [4], among others. A very detailed review of the theory, application, experimental setup and results of the vibration correlation technique (VCT) approach on different structures can be found in Singer et al. [5 (Chapter 15)].

For a better understanding of the applications of VCT on plates and shells it is important to classify the method according to its use: 1) determination of actual boundary conditions for numerical calculation purposes; 2) direct estimation of buckling load. This paper will deal with the direct determination of the buckling load on cylindrical shells.

There is not full understanding of how to apply the VCT for unstiffened cylindrical shells, commonly used in space applications for launcher structures. This type of structure is usually associated with a high imperfection sensitivity, which requires the application of empirical guidelines in order to calculate the design buckling load, currently leading to conservative estimations (Degenhardt et al. [7]). Skukis et al. [8] presented a preliminary assessment correlating the vibration modes with the buckling load of stainless steel cylinders. If a relationship between the buckling load and the variation of the natural frequencies of vibration exists, it is possible to use the VCT as a non-destructive technique for estimating the real knock-down factor of space structures. Moreover, for this type of structures there is a remarkable influence of the boundary conditions on the buckling load (see Zimmermann [9] and Hühne et al. [10]), where the VCT could be

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used for a better characterization of the actual boundary conditions, providing reliable data for numerical simulation, such as finite element models (see Hilburger et al. [11], Degenhardt et al. [12], and Degenhardt et al. [7]).

Recent efforts to improve the work done so far on the VCT field are presented by Jansen et al. [13], where new semi-analytical tools are introduced to extend the existing semi-empirical VCT for shells, considering both the non-linear effect of the static state and the nonlinear effect of the geometric imperfections.

The current manuscript will present and discuss an experimental and numerical validation of a new VCT approach presented by Arbelo et al. [14]. This approach is based on the observations made by Souza et al. [15]. The original approach proposed by Souza is a linear fit between $(1-p)^2$ versus $(1-f^4)$, where $p=(P/P_{cr})$, $f=(f_m/f_0)$; P is the applied axial load, P_{cr} is the critical buckling load for a perfect shell, f_m is the measured frequency at P load and f_0 is the natural frequency of the unloaded shell. Souza states that the value of $(1-p)^2$ corresponding to $(1-f^4)=1$ would represent the square of the drop of the load carrying capacity (ξ^2), due to the initial imperfections. However, if this approach is applied on unstiffened cylindrical shells the results will be negative values of the drop of the load carrying capacity (ξ^2), which does not have a physical meaning (see Arbelo et al. [14]).

Instead of plotting $(1-p)^2$ versus $(1-f^4)$, Arbelo proposed to plot $(1-p)^2$ versus $(1-f^2)$ and represented the points by a second order fitting curve. Moreover, the minimum value of $(1-p)^2$ obtained using this approximation represents the square of the drop of the load carrying capacity (ξ^2), for unstiffened cylindrical shells, due to the initial imperfections. Then, the buckling load can be estimate by Eq. (1):

$$P_{imperfect} = P_{cr}\left(1-\sqrt{\xi^2}\right) \tag{1}$$

Focused on the validation of the new VCT approach, this manuscript presents a series of experimental test, conducted on 500 mm diameter cylinders, fabricated with composite materials, in order to identify the range of applicability of the VCT for unstiffened cylindrical shells. The applied load and the first natural frequency of vibration and mode shape are measured and correlated. The results are compared with numerical simulations including initial geometric and thickness imperfection. After an initial finite element assessment for the design of the test structures, an unsymmetric laminate setup is adopted in order to increase the sensitivity of the test structure to initial geometric imperfections (see Zimmermann [16]), increasing the loss of load carrying capacity, which is more difficult to predict using standard experimental tests or conventional finite element approaches.

2. Experimental test: materials and methods

2.1. Test specimen: overview

Three identical unstiffened cylindrical shells (named R07, R08 & R09) are fabricated by hand-layup using 6 plies of unidirectional (UD) carbon fiber Unipreg 100 g/m^2. The geometry and lay-up are presented in Table 1. The material properties were measured according to the ASTM D3039 [17], D3410 [18] and D3518 [19] standards for tension, compression and shear respectively and the results are presented in Table 2; where E_i^j is the elastic modulus along the fiber direction ($i=1$) or matrix direction ($i=2$) in tension ($j=T$) or compression ($j=C$). G_{12} is the shear modulus and ν_{12} is the Poisson ratio. S_i^j is the maximum strength along the fiber direction ($i=1$) or matrix direction ($i=2$) in tension ($j=T$) or compression ($j=C$). S_{12} is the shear strength. t is the ply thickness.

Table 1
Geometric parameters for R07 to R09 cylinders.

Length [mm]	500 ± 1
Radius [mm]	250 ± 1
Thickness [mm]	0.6264 ± 0.11
Lay-up [in-out]	$[0_2°/(\pm45º)_2]\pm1º$

Table 2
Material properties of UD prepreg Unipreg 100 g/m^2.

$\mathbf{E_1^T}$	116.44 ± 8.71	GPa
$\mathbf{E_1^C}$	91.65 ± 7.58	GPa
$\mathbf{E_2^T}$	6.73 ± 0.23	GPa
$\mathbf{E_2^C}$	6.39 ± 0.81	GPa
$\boldsymbol{G_{12}}$	3.63 ± 0.2	GPa
$\boldsymbol{\nu_{12}}$	0.34 ± 0.04	
$\mathbf{S_1^T}$	1771.82 ± 177.88	MPa
$\mathbf{S_1^C}$	478.22 ± 17.3	MPa
$\mathbf{S_2^T}$	40.48 ± 2.67	MPa
$\mathbf{S_2^C}$	122.87 ± 7.48	MPa
$\boldsymbol{S_{12}}$	61.53 ± 0.67	MPa
$\boldsymbol{t}$	0.1044 ± 0.0015	mm

After fabrication, the top and bottom edges are trimmed and clamped using a resin potting and metallic rings. The final radius over thickness (R/t) ratio is about 400.

2.2. Characterization of initial thickness imperfection using ultrasonic scan

In order to characterize the thickness imperfection inherent of the material and fabrication process, an ultrasonic scan is performed on each test specimen. The obtained thickness imperfection distribution is used afterwards to improve the correlation of the finite element models, since the buckling mechanism can be trigged by local imperfections along the shell. Furthermore, imperfections like gaps or overlaps between plies (due to the fabrication process) can be quantified using ultrasonic scanning. Fig. 1 shows the results of the thickness imperfection for each cylinder. A 10 MHz probe is used to perform the thickness measuring, which provides a good balance between resolution and thickness range.

2.3. Characterization of initial geometric imperfection using laser scan (inner surface)

A laser scan (Panasonic® HL-G1 sensor) is used to measure the initial geometric imperfection on the inner surface of each cylinder. The laser scan is controlled using an in-house software and the acquired data is exported in real time to a plain text file for further analysis and postprocessing. The best-fit-cylinder algorithm is applied afterwards over the raw data to eliminate the rigid body motion modes from the measurements. The results are presented in Fig. 2, where it can be seen as approximately 12 half-waves distributed along the circumference of the inner surface. The maximum amplitude observed from the measurements is less than 0.2% of the cylinder diameter.

It must be noticed that the geometric imperfection of the first 50 mm from both top and bottom edges is not measured due to hardware limitations of the laser scan system, and in this region the imperfection data is extrapolated from the closest cross-section containing measured data.