NUMERICAL SIMULATION OF THE STRUCTURAL BEHAVIOUR OF ORTOTHROPICALLY STIFFENED AIRCRAFT PANELS UNDER SHORT TIME DURATION LOADING

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Abstract

This paper studies the structural behaviour by numerical simulation of ortothropically stiffened aircraft panels subjected to dynamic loading. Focus is placed on a stringer-frame stiffened circular aircraft fuselage panel loaded by different duration load pulses.

The simulation of the behaviour under a static load through buckling and the post-buckling regime is presented. The panel's own dynamic characteristics are presented followed by the application of different time pulses. The results are compared to the base line static behaviour. Finally, a summary, conclusions and recommendations for future research are presented.

1 Introduction

Lightweight aircraft structures, when it would come to a failure, are characterized by failing under instability due to their thin cross sections. Well designed fuselage structures typically display a considerable load carrying capacity after buckling onset during the post-buckling regime until failure occurs.

Extensive physical testing [1-4] has clarified much of this behaviour together with considerable development of numerical and analytical methods [5-6]. Practically all this work is based on the assumption that the load is applied slowly, i.e. static conditions, however, for the largest magnitude loads in a real aircraft, this is seldom the case. Indeed, the largest loads are dynamic and typically of very short time duration.

The currently adopted approach of aircraft sizing originates from an era without possibilities to treat nonlinear structural dynamics analytically, while significant progress has been achieved during the last 20 years in numerical methods, nonlinear material and structural models, computational dynamics and computer hardware. In combination, the progress in these areas may potentially result in considerably more efficient design tools for aircraft structures and even lighter aircraft structures. Consequently, nowadays, concerning new design criteria and requirements, aircraft industry begins to focus particular attention on the sizing load determination.

Figure 1 shows a typical scenario of dimensioning criteria on a long-range aircraft fuselage structure [7]. Criteria like emergency braking are also to be considered for the upper fuselage. These dimensioning criteria may be re-considered applying dynamic loads.

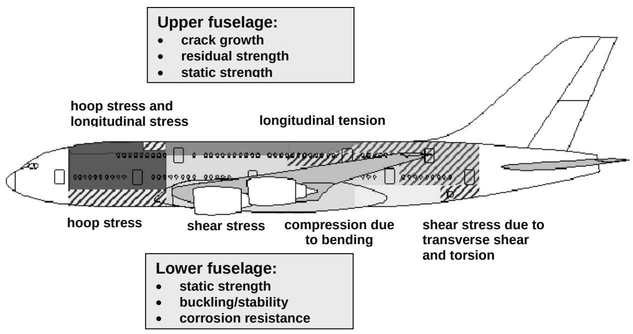


Fig. 1. Dimensioning criteria for a long-range aircraft fuselage

Today, detailed time history loads exist for aircraft as well as detailed structural models. The combination of detailed load histories and a detailed structural model may potentially offer an advantageous approach by which more optimized aircraft structures could be designed.

In this study, the attention is focused on buckling phenomena under dynamic loading [8]. Only few studies can be found in literature on this subject, and they involve cylindrical shells [9-12] and flat panels [13].

In particular, this paper studies the structural behaviour by numerical simulation of ortothropically stiffened aircraft panels subjected to dynamic loading.

2 Aircraft fuselage panel

A stringer-frame stiffened circular aircraft fuselage panel made of aluminium, as shown in Figure 2, is considered. The panel is 2540 *mm* long and 900 *mm* wide.

It is stiffened with stringers in the longitudinal (fuselage axial-) direction and frames along the fuselage circumferential direction. The skin, frames and stringers are joined together by riveted clips.

The skin has a thickness of 2 *mm*, while the stringers and the frames have a thickness of 1.6 *mm* and 3.2 *mm*, respectively.

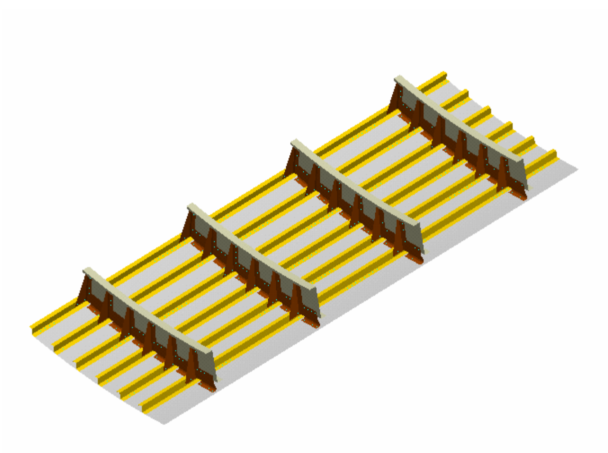


Fig. 2. Stringer-frame stiffened circular panel of aircraft fuselage

3 Finite element model

The numerical model is shown in Figure 3. It consists of about 38000 elements. The skin, the stringers and the frames consist of four-node- and three-node doubly curved shell elements, while the rivets are modelled with two-node linear beams.

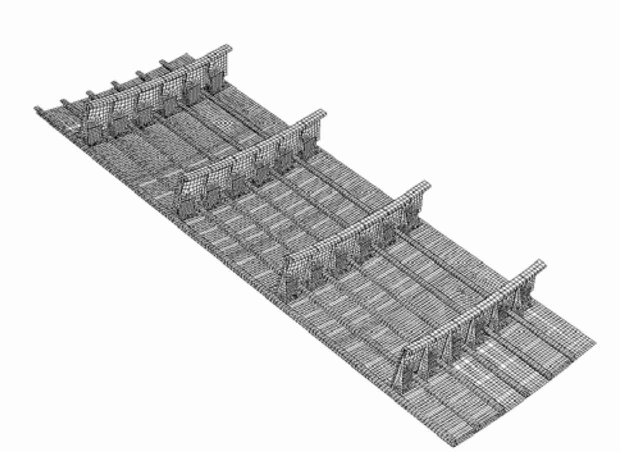


Fig. 3. Finite element model

4 Analysis under static loading

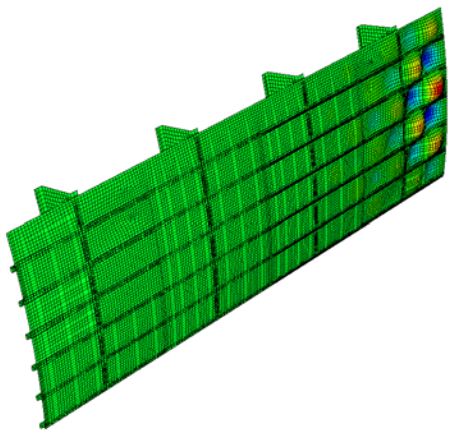
The simulation of the behaviour under a static load through buckling and the post-buckling regime is presented.

The finite element analyses [14] are performed by eigenvalue analysis using ABAQUS/Standard and by a slow dynamic analysis using ABAQUS/Explicit [15].

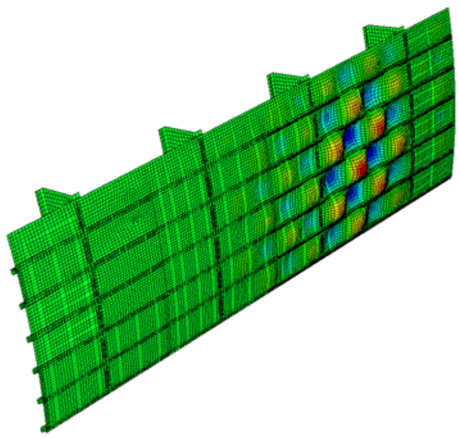
During the analyses, loaded nodes are free to move only in the load direction. The opposite edge of the panel is fully clamped, while longitudinal edges are simply supported. The panel is loaded in pure longitudinal compression.

At first, the static buckling is investigated by eigenvalue analysis using ABAQUS/ Standard. The first three eigenvalues are investigated and their respective critical buckling loads are calculated.

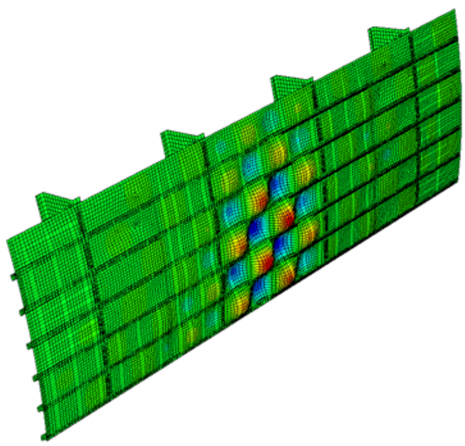
The first buckling load results equal to 130.54 *kN*. The three eigenvectors are reported in Figure 4, with an amplitude scale factor equal to 10.



First eigenvector



Second eigenvector



Third eigenvector

Fig. 4. First three eigenvectors of an eigenvalue analysis (ABAQUS/Standard)

Then, the finite element code ABAQUS/Explicit is used to perform dynamic analysis, employing a Lagrangian formulation and integrating the equations of motion in time explicitly by means of central differences. It can be used also for static analysis simulating the dynamics of a slow compression test.

The dynamic response is calculated for axial compression, uniformly applied as a nodal time dependent displacement.

The accuracy of the dynamic analyses results highly depends on the displacement velocity, as the equations of equilibrium governing the dynamic phenomena consider inertial forces. Good results are obtained by maintaining the displacement velocity equal to 10 *mm/s*, so that the inertia effects are negligible and the difference between the buckling load values obtained by the eigenvalue analyses and the ones obtained by the dynamic analyses, equal to 140.3 *kN*, are less than 7.5%.

The dynamic analysis allows investigation of the deformed shape evolution from the pre-buckling to the post-buckling field, and is able to follow the curve of the compression reaction load versus the imposed displacement even in the post-buckling field.

The load-shortening curve is reported in Figure 5, while Figures 6 and 7 show the deformed shape evolution with an amplitude scale factor equal to 10, according to two different panel views, so to highlight the post-buckling deformation.

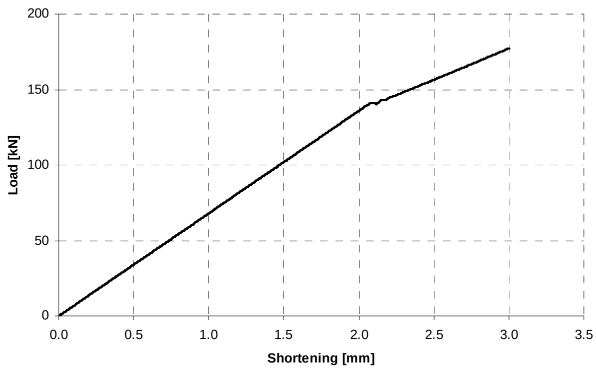
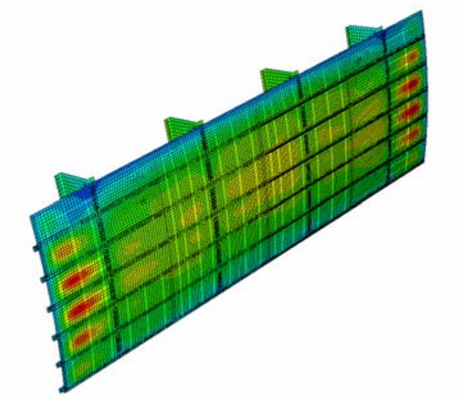
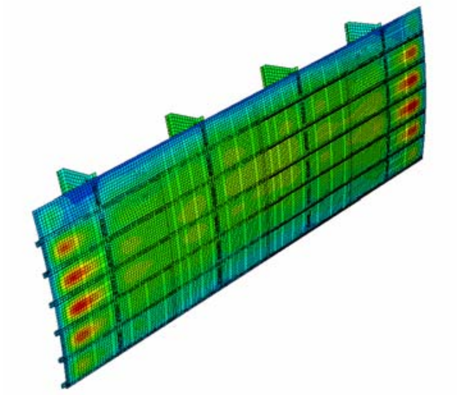


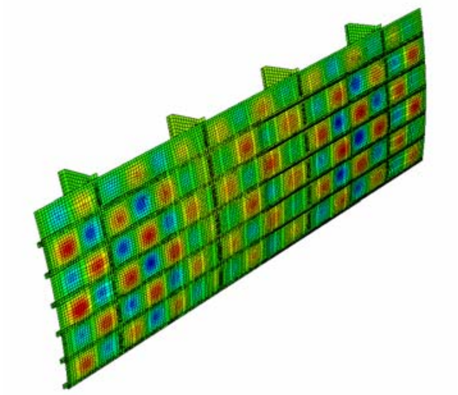
Fig. 5. Load-shortening curve of the slow dynamic analysis (ABAQUS/Explicit)



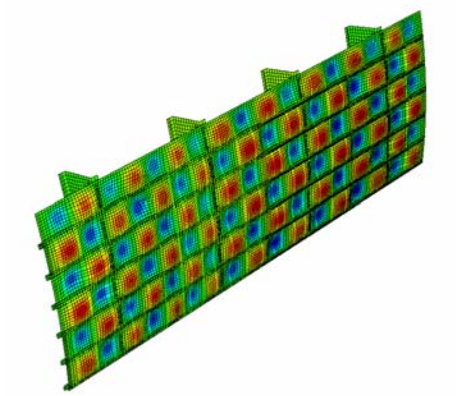
Shortening = 0.43 *mm*



Shortening = 1.28 *mm*

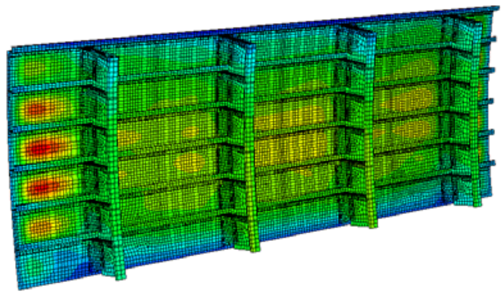


Shortening = 2.14 *mm*

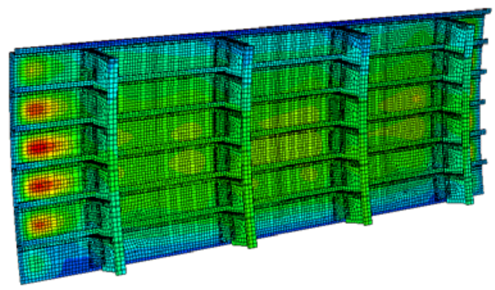


Shortening = 3 *mm*

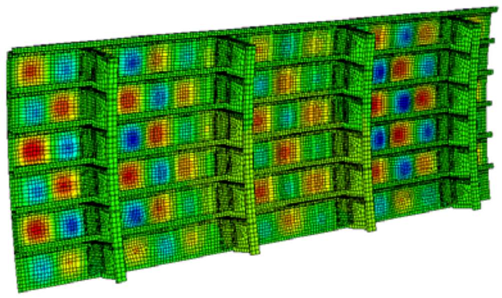
Fig. 6. Slow dynamic analysis (ABAQUS/Explicit)



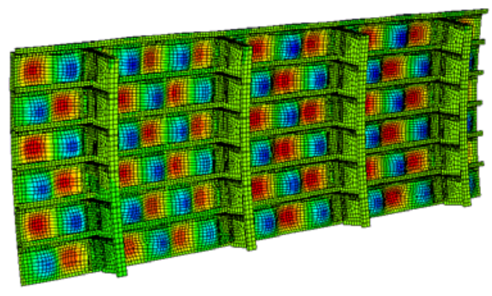
Shortening = 0.43 *mm*



Shortening = 1.28 *mm*



Shortening = 2.14 *mm*



Shortening = 3 *mm*

Fig. 7. Slow dynamic analysis (ABAQUS/Explicit)

5 Analysis under short time duration loading

The panel's own dynamic characteristics are presented followed by the application of different short time duration loadings. The results are compared to the baseline static behaviour and are placed in relation to the panel dynamic properties.

The critical conditions for dynamic buckling are estimated by a sudden large change in dynamic responses, according to the Budiansky-Roth criterion [8, 16]. Consequently, to get the dynamic critical load subjected to suddenly applied compression with finite duration, it is necessary to solve the equations of motion for several load parameter values, so as to obtain the dynamic responses. The dynamic critical load is determined as the lowest load at which there is a large sudden change in transient response.

Consequently, the time history of impulsive loading with finite duration and constant in magnitude is varied, and the equations of motion are solved for the various values of the loading. To get the value at which there is a significant jump in the response, the system response is monitored through displacements of selected points. For small values of the loading parameter, small oscillations are observed, the amplitude of which gradually increases as the loading is increased. When the loading reaches its critical value, the maximum amplitude experiences a large jump.

To be able to get good results from the analyses, the points for which displacements are to be monitored have to be carefully chosen. Both the radial displacements of several points where the largest displacement values are expected, and the edge shortening are considered in this study.

During the finite element analyses, performed using ABAQUS/Explicit, the compression is transferred to uniform nodal forces along the edge nodes, and the load is suddenly applied with finite duration and constant in magnitude, as shown in Figure 8.

Three different time durations are analysed: T = 1 *ms*, T = 5 *ms*, and T = 10 *ms*.

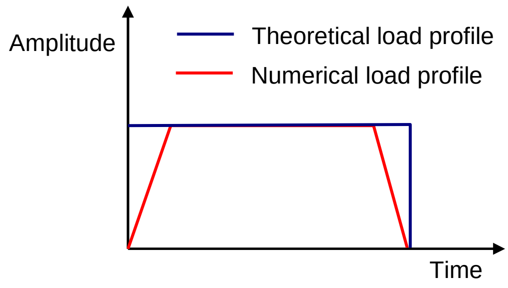


Fig. 8. Load profile for the short time duration loading

The analysed dynamic load cases are reported in the matrix of Table 1, where the load amplitude is the sum of the compression loads applied at all the edge nodes along the loaded short edge, B means that the buckling is reached, while NB means that no buckling is evidenced in the structural behaviour.

		Duration		
		1 ms	*5 ms*	*10 ms*
Amplitude	*48.8 kN*		NB	NB
	97.6 kN	NB	NB	NB
	146.4 kN	NB	NB	B
	195.2 kN	B	B	B
	244.0 kN	B	B	

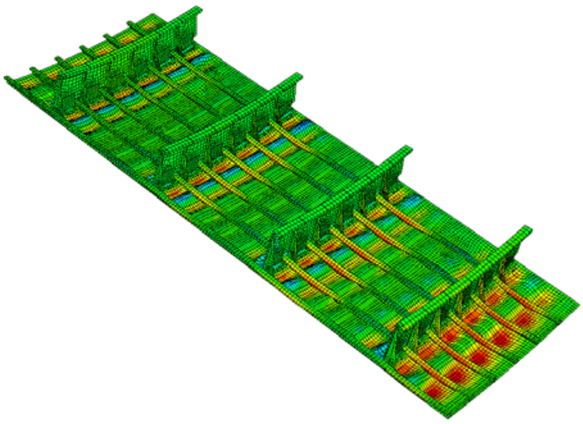
Table 1. Dynamic load cases matrix

Reporting the single node load to the buckling load of the whole structure, the results are represented as dynamic buckling loads versus load duration in Table 2, compared to the reference static buckling load (130.5 *kN*).

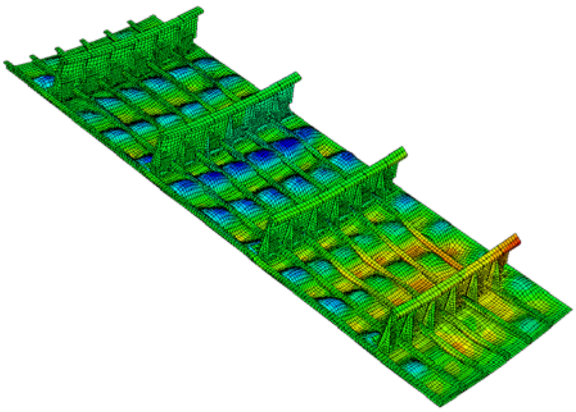
Load duration T [*ms*]	Dynamic buckling load [*kN*]	Ratio of dynamic to static load
1	244	1.8
5	170	1.3
10	122	0.9

Table 2. Dynamic buckling load versus load duration

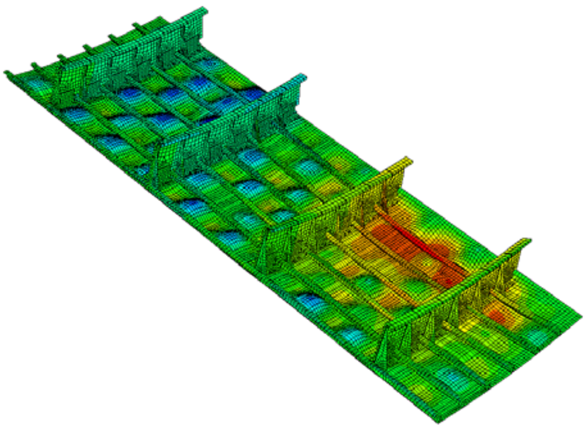
Figure 9 reports the dynamic deformation of the panel for the different load durations.



T = 1 *ms*



T = 5 *ms*



T = 10 *ms*

Fig. 9. Dynamic deformation for different load durations

The dynamic critical loads of the panel decrease quickly with increasing load duration. Indeed, for short time duration, the dynamic buckling loads are higher than the static buckling loads. With increasing load duration, the dynamic buckling loads decrease quickly and can get also smaller than the static ones.

6 Conclusions

This paper presents exemplarily the results of a numerical study of the structural behaviour of orthotropically stiffened aircraft panels subjected to short time duration loading. Focus is placed on a stringer-frame stiffened circular aircraft fuselage panel loaded by different duration load pulses.

The simulation of the behaviour under a static load through buckling and the post-buckling regime is presented. The panel's own dynamic characteristics are presented followed by the application of different time pulses.

The panel could carry dynamic buckling loads larger than the static buckling loads, provided their duration is very short. If the load duration is longer, the panel may only carry a dynamic buckling load smaller than the static one, which means that taking the static buckling load as the design point for dynamic problems might be misleading.

The ratio between the dynamic buckling load and the static buckling load may become of practical interest for the designer, since it provides a direct indication of the load carrying capacity of the structural elements exposed to rapidly applied loads relative to almost statically applied loads.

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