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INVESTIGATION OF VULNERABILITY OF AIRCRAFT STRUCTURE AND MATERIALS TOWARDS CABIN EXPLOSIONS

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Abstract. *Damage Tolerance of aircraft fuselage structures has a strong link to explosion resistance. Though accidental explosions can and do occur, intentional explosions are more common as the terrorist threat increases. Structural toughness is as welcome in these scenarios as it is under penetration of non contained engine debris.*

Guidelines in structural design for such conditions are obviously lacking along with knowledge of typical consequences.

The EU-sponsored project VULCAN addresses blast and fire behaviour of civil fuselage structures (cabin) with the aim of achieving significant improvements. This paper deals with blast only.

Characterisation and vulnerability of existing monolithic aluminium structures as well as modern laminated materials (Glare, CFRP).is undertaken in this four year program. It aims at understanding typical catastrophic failure behaviour on a dynamic materials and mechanical level and improving this through well-balanced design guidelines. A twofold approach is used, firmly building on a dedicated experimental program and validating and applying numerical simulation tools from there as well.

A building block approach was conceived. First level dynamic behaviour is studied at simplified structural and materials level, addressing crack initiation and propagation. A second level introduces increasing complexities due to curvature, stringers frame (castellations) and joints.

First test results from the first level are presented, concentrating on dynamic Glare prestressed panel behaviour under a special explosively generated instantaneous large crack. A comparison to a bursting pressurised cylinder as a simple model of a passengers cabin, is ongoing.

1 INTRODUCTION

The vulnerability of aircraft fuselage structures towards an explosion in the cabin is largely unknown. What is known, usually concerns older aircraft and remains hidden in the red tape of security considerations. Nevertheless, the sensitivity towards explosions is something that could be considered in a design stage if more was known about this area which has materials, structures and loads aspects to it. This paper addresses the definition and the first results of a research program specifically defined to allow significant improvements to be achieved in the future.

1.1 Explosion resistance in aircraft design

Currently there is no airworthiness regulation specifically addressing vulnerability towards internal explosions. The requirements most closely related are those concerning the resistance towards damage from non-contained engine failure (UEF) and perhaps those concerning the decompression rate (on the basis of the so-called 'FAR-hole'). The two-bay crack criterion associated with UEF as such is still a controversial issue, but its relationship towards explosion resistance is clearly present.

The research effort described in the next sections attempts to increase the knowledge base so that both design guidelines can be improved and an improved understanding is obtained of the nature of failure behaviour, the explosive load etc.

1.2 Problem breakdown

Explosion loads are not an everyday subject for a structures designer. In order to get to grips with the problem of explosion resistance, it is instrumental to make a suitable categorization of aspects. Table 1 attempts such a breakdown for purposes of structuring the research effort. The present paper deals with structural and materials response with crack propagation as a central theme. Crack initiation in this scenario is somehow assumed as this can be practically considered as something which cannot be avoided. With this assumption, crack or damage size becomes the overriding parameter and crack arrest and/or deflection become the design challenge.

Aspect	Specification	Discussion or subdivision	Remark
Loads	Three regimes	Short time (close-in) Intermediate Residual quasi-static pressure range (QSP)	Also pressure load as a function of damage/ failure process Type of explosive and location. Local perforation.
Structural response	Local versus global	local damage complex dynamic modes response including fracture processes	Simulations required for quantifying response.
Cracks	The single most important disintegrating factor for a pressurized fuselage	• Crack initiation • Crack propagation • Crack arrest	
Structural element behaviour	Specific strength and failure behaviour	Stiffened skin Frame Frame-skin joint	Castellation type Skin joints Rivet holes Doublers Riveted versus bonded stringers Pre-cracked state (aging aircraft)

Table 1 : Overview of aspects related to fuselage structure blast response

1.3 The EU Vulcan project

In order to address the issue of explosion (and fire) vulnerability of existing and future aircraft and to enable improvement in their design, the EU sponsored project 'VULCAN' was initiated[1].

The project is in its first year with present research focusing on reviewing data and obtaining first experimental data on simplified structural elements. Both topics are treated in the next paragraphs.

1.4 Materials and structures overview in relation to explosion resistance

To cover a broad range of existing and anticipated fuselage structures, three materials and their typical structure types are considered:

- aluminium monolithic structure, Al 2024 T3 baseline;
- ‘Glare’ Fiber Metal Laminate (FML) hybrid
- Carbon Fiber (CFRP) composite material

Many things can and ought to be said about all possible structure details that can be encountered in a fuselage, as listed in Table 1. Leaving aside the complexities around cut-outs, which tend to thicken the skin structure and hence make it less vulnerable, one important aspect is the frame-skin connection, the so-called castellation. This plays an important role in skin pillowing (circumferential stress field) and also in resistance to crack passage (crack stopper effect). Figure 1 illustrates one example as is encountered in the older VC10 and BAC-111 aircraft. Significant differences can be found in radial stiffness and rigidity, especially relating to the connection between stringer and frame. At this point it suffices to say that aircraft like ATR42 and Fo100 have relatively flexible (‘floating’) frame designs while other types (especially the bigger aircraft) have stiffer castellations.

About Glare it can be said that crack initiation may be significantly more difficult. Nevertheless, also a Glare skin is typically joined to the castellations using rivets. Since Glare stringers are more likely to be bonded however, this is a significant difference with respect to large crack initiation and dynamic propagation.

CFRP structures are not very common yet in civil transport aircraft. For defining ‘typical structure, we may look at the new Boeing 787 structure for typical design details. It becomes obvious that the skin-frame connection has a more or less conventional configuration using bolts for load transfer. This is significant, since an interlaminar load transfer would behave very much differently. Nevertheless, interlaminar failure will play a role in the structural behaviour of for example layered CFRP castellations which will delaminate in their radii in response to high out of plane loads.

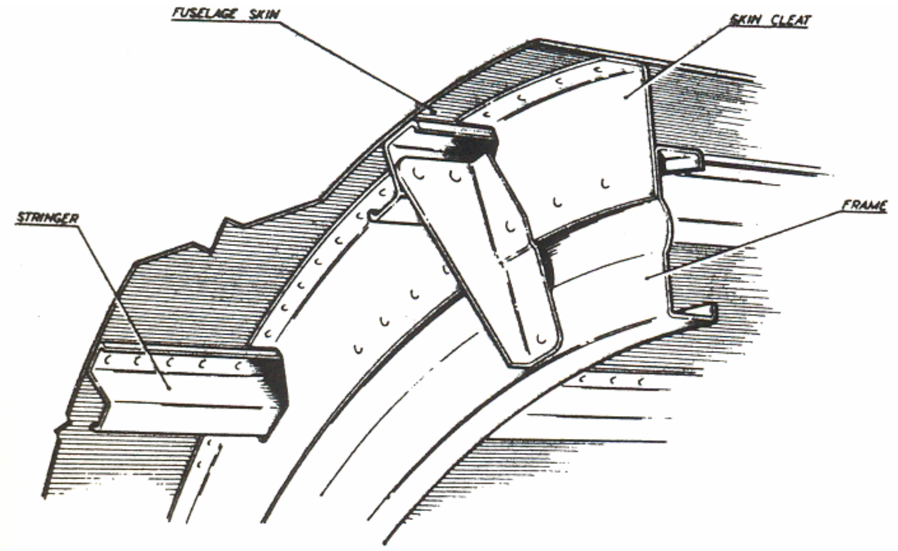

Figure 1: Example of a critical design feature: the frame-skin joint or castellation (VC10/BAC-111)

2 SCENARIOS AND REVIEW OF DATA AND ACCIDENTS

2.1 Accident review

A review of explosion and cabin decompression related accidents was done to see whether valuable lessons could be learned from past experience. Some 140 explosion related accidents in civil aircraft were on record. Moreover, accidents involving UEF were analysed, as were specific accidents like the Aloha accident.

2.2 Review of cabin explosion experiments

Since the terrorist attacks from the sixties, some experimental work has been done to study the effects of explosions on pressurised fuselages. By far the most of these were not accessible to the open research community however. Mostly, the results have been used to establish threshold data for detection limits of explosive substances, which is classified information for obvious reasons. Table 2 lists some data which were more or less publicly available for study.

Organisation	Aircraft	Explosive scenario	Type of failure
FAA	Lockheed Tristar	Cargo hold front fuselage	Catastrophic disintegration
CAA, DERA	Boeing 747	Rear cargo hold	Catastrophic disintegration involving longitudinal skin joints
Myth Busters (Discovery Channel)	B 727?	On window frame	Blast out window, controlled decompression
Ibid	Ibid	Shaped charge onto skin/frame/stringer below window belt behind wing fuselage connection	Catastrophic longitudinal rupture

Table 2 : Overview of some publicly available fuselage explosion data sources

Figure 2: Catastrophic failure behaviour demonstrated in the 2001 DERA test

Figure 3: Incipient catastrophic failure behaviour in a public demonstration experiment with an internal focussed blast. Note the longitudinal crack extending below the window belt.

2.3 Review of Glare crack resistance

Extensive data have been generated on the crack resistance of several Glare grades as reported by de Vries[2]. In principle, a guideline is thus available about critical crack lengths as a function of stress level with the model of a crack resistance curve as a material property.

The main questions, when translating such behaviour to an explosion scenario of a real fuselage, are twofold:

- is flat panel behaviour directly comparable to fuselage behaviour?
- to which extent do dynamic effects play a role?

These issues are addressed in the definition of the building block test program as described below.

3 DEFINITION OF (EXPERIMENTAL) BUILDING BLOCKS

The experimental work was defined to generate data in configurations with increasing complexity, allowing quantification of material and structure behaviour and supporting the modeling work. A working assumption was that somehow local breaching of the skin or fuselage structure can not be avoided and therefore crack propagation was of major interest.

3.1 BB0 High velocity (strain rate) coupon testing

An ideal dynamic tensile test has controlled strain rate in the right regime, sufficiently large specimen size and allow laminate or sheet to be tested with holes to cover complex failure behaviour of real structures. TNO had developed such a test in the past for study of dynamic strength of composite laminates, notched strength and pinned and bonded joints. This dynamic tensile test machine is based on a shock testing platform. A frame is accelerated by a spring load which is released by a breaking bolt. The specimen is clamped to this frame on one end while the other is clamped to a dead mass. By recording the acceleration of this mass, a specimen load is obtained. Strain rates in the range of 10 to 20 /s can thus be obtained.

This is representative of the medium strain rates representative of global dynamic response during an explosive event.

3.2 BB1 Crack initiation in flat sheets

The subject of dynamic crack initiation in flat or dynamically bulged sheet material under nearby blast load is being investigated on an 800 x 800 mm size sheet mounted in a frame. Belgium partner RMA investigates this behaviour which yields a critical explosive charge – stand-off combination for rupture and enabling verification of failure models.

3.3 BB2 Crack propagation in prestressed flat sheet

Crack propagation must be studied under well controlled conditions. Both uni-axial and bi-axial tests are possible, both in flat or curved configuration. The flat uni-axial set-up was designed and realised. Proper instrumentation with high speed video crack monitoring along with crack-opening displacement measurement as well as strain gauge measurements throughout the specimen enable study of the dynamic material behaviour. Also crack-arrest can be studied using in-plane crack-stopper for example. It is important that the specimen is long enough so that there is sufficient strain energy in the sheet to support crack extension and so that the effective load does not drop to sub-critical stress levels when a sudden crack is introduced. Moreover, for Glare a maximum width was sought so that realistic crack lengths and stress levels could be applied. For that purpose specimen dimensions were chosen of 800 mm width and 1500 mm length.

A specific and unique dynamic element was added to this test by effectively generating an instantaneous crack by an explosive cutting device. In this way, the strain energy that is released is partly available to drive the crack extension process. We can designate this type of specimen as an ECCTS (explosively central cracked tensile specimen). The hydraulic jack should be able to be operated in both displacement and load control mode. Such a set-up is shown in Figure4 along with a failed Glare specimen.

3.4 BB3 Crack propagation in cylindrical configuration

The crack propagation and arrest can be studied also on a next level of complexity in a cylindrical configuration. A bare cylinder allows a basic introduction of the complexity of curvature and (transient decreasing) pressure load as well as a more realistic ‘crack driving force’ from the stressed cylinder including all inertia effects.

A bare skin is possible, as well as the introduction of frame simulators to study dynamic crack arrest or passage as a function of frame stiffness and castellation rigidity. Obviously, also configurations with rivet holes for stringers or castellations can be included for additional realism. The 1.2 m diameter allows study of the crack problem on a 1:3 scale approximately.

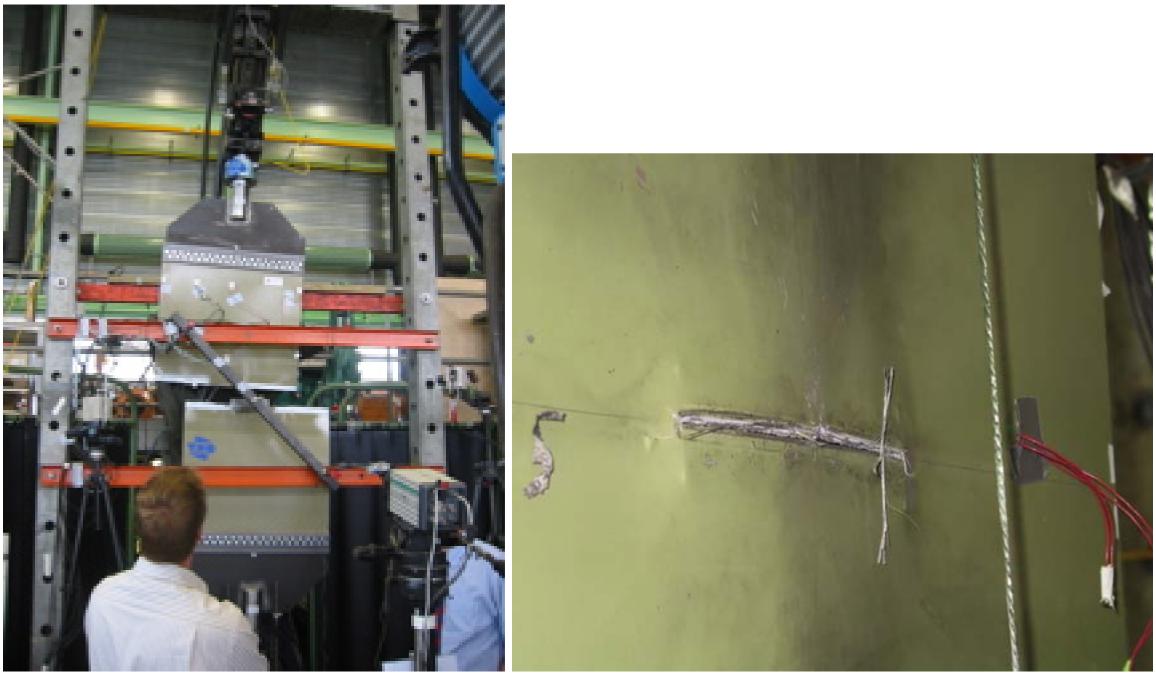

Figure 4: Test set-up uniaxial ECCT test with sudden crack initiation after failure in test 2 (left) and a close-up of the 200 mm ‘sudden crack’ as generated in test 1 (right); note the appearance of broken fibers.

4 RESULTS FOR TEST TYPE BB2 APPLIED TO GLARE 3

4.1 Test set-up pre-stressed sheet experiment

A frame was constructed including a 350 kN hydraulic jack (which can be operated in both displacement and load control mode). At an ECCTS width of 800 mm this roughly enables 300 MPa stress level to be applied. The two-row bolted joint is made through a specimen padded up with bonded aluminium doublers. The Glare was of type 3/3/2 0.3 and was manufactured by FMLC in conjunction with Stork/Fokker.

The ‘sudden crack’ which is essential to this test is generated using less than 10 g of sheet explosive mounted on ‘shock wave reflection tape’ and bonded onto the specimen. At the other face, the Glare sheet is supported by a steel block with a recess, allowing a suppression of transferred lateral loads as well as effective instantaneous cutting of the glass fibers.

Multiple cameras running at a speed from 5000 fps to 70000 fps are aligned with the anticipated crack region as well as monitoring displacement of the two areas adjacent to the crack. Strain gauges monitor internal strain, hence stress, along the undisturbed width, along the cracking line and perpendicular to the crack. Also jack displacement and load are recorded, all with a sampling frequency such that a 2μs sampling rate is obtained.

4.2 Crack stability and propagation

Stress levels and crack lengths have been selected in order to ensure that crack propagation could be recorded at different stress levels, so that data could be obtained in support of validating the numerical modeling schemes. Also, recording of situations with stable crack (extension) was intended and achieved, enabling an even better case for tuning the material models.

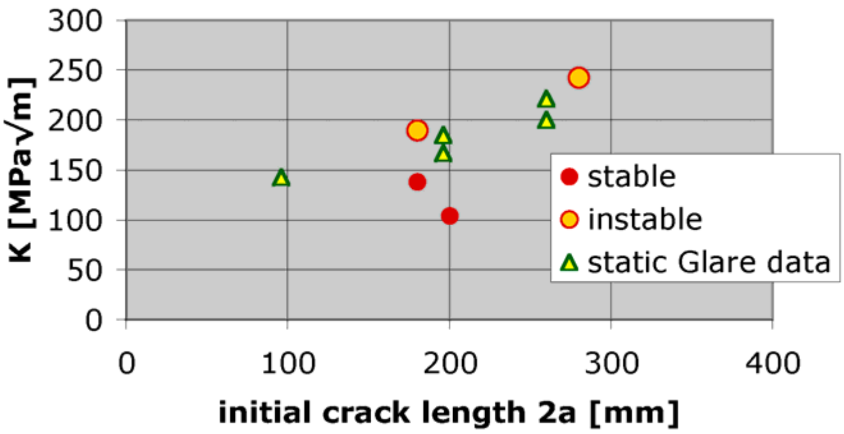

Figure 5: Crack stability plot of current experiments compared to literature data (based on initial crack length)

At this point, only a preliminary view of the quantified result can be given, as no extensive postprocessing has been done and simulations are not yet available. Some qualitative remarks and a brief discussion of strain gauge and transient force data are presented.

The conditions for the first experiment at 200 mm crack and 110 MPa stress were well below the critical condition so that the specimen could be scanned and analysed for internal damage due to crack formation and internal energy conversion. The stiffness drop was less than 20% due to the long specimen length. This was intended to keep the drop in effective stress limited, so that crack propagation was more likely to occur.

A second test was performed at a high stress level of 220 MPa so to guarantee crack formation which could be filmed. The third test then applied an intermediate stress level of 160 MPa allowing to generate strain data at an almost critical condition. The fourth test then proceeded at the maximum ‘instantaneous crack’ length of 180 mm at a slightly higher stress (174 MPa) to guarantee crack propagation here as well.

Some data for this fourth test are presented here. To begin with, it can be seen from the force and especially the hydraulic test cylinder displacement in Figure 8 that the reaction time lag of the test set-up is 2 to 4 milliseconds before load control starts to have an effect. From 2 ms onwards also the load sensor indicates a drop in load.

Looking at the crack tip propagation left and right (Figure 6), both have traveled roughly 120 mm towards the edge (at 260mm) within these 4 milliseconds. During the remainder of the test the actual displacement of the clamping plates tears the sheet completely apart and the crack propagation proceeds towards the edge in a total timeframe of 12 ms. This propagation is graphed in Figure 6 where it is also seen that the velocity in the first propagation branch can be quite high (400 m/s was the recorded maximum) relative to the second part which takes approximately 2 ms and where 50 m/s is a typical value. This then drops down to an order of 10 m/s for the ‘residual tearing’

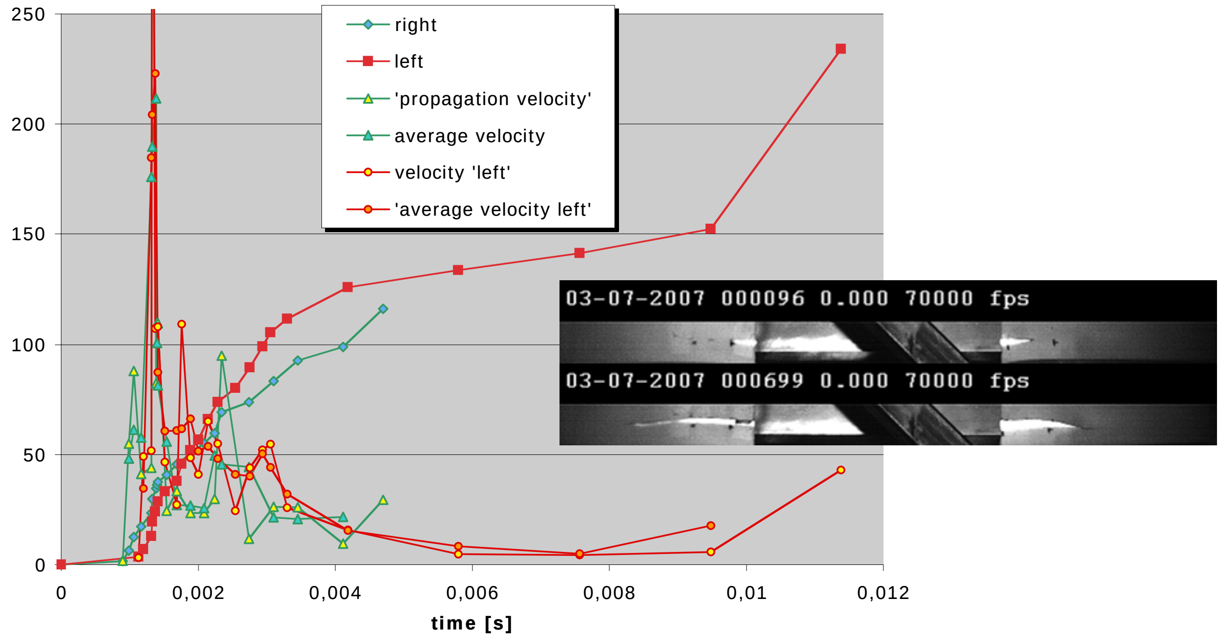

Figure 6: Crack propagation velocity for experiment 4 with initial crack 280 mm and 260 mm crack extension path on both ends.

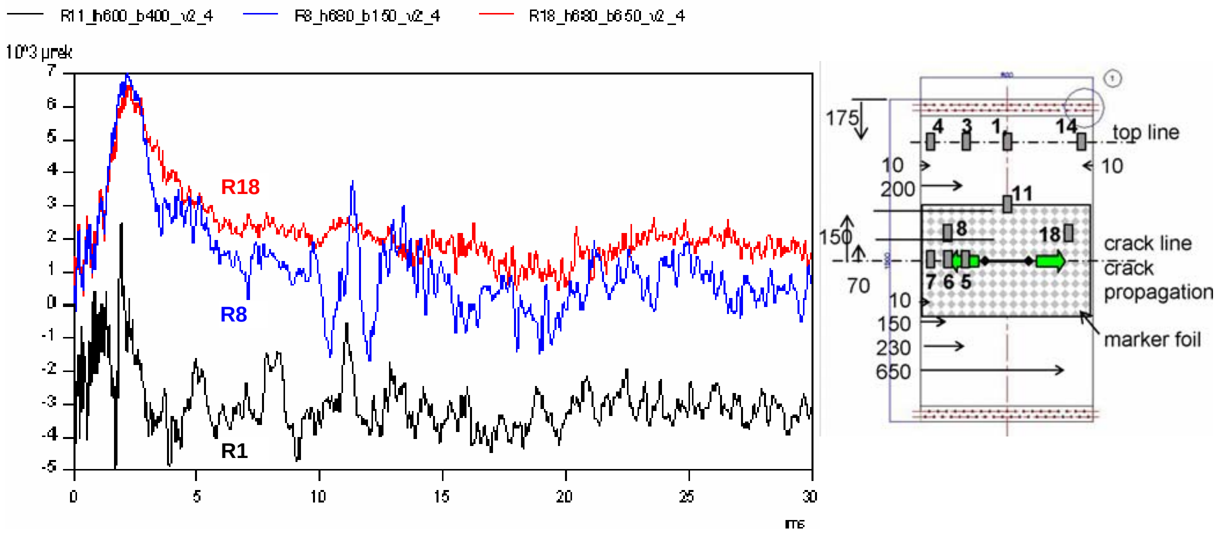

Figure 7: Strain change versus time (in ms) for central and side gauges (#11, 8, 18)

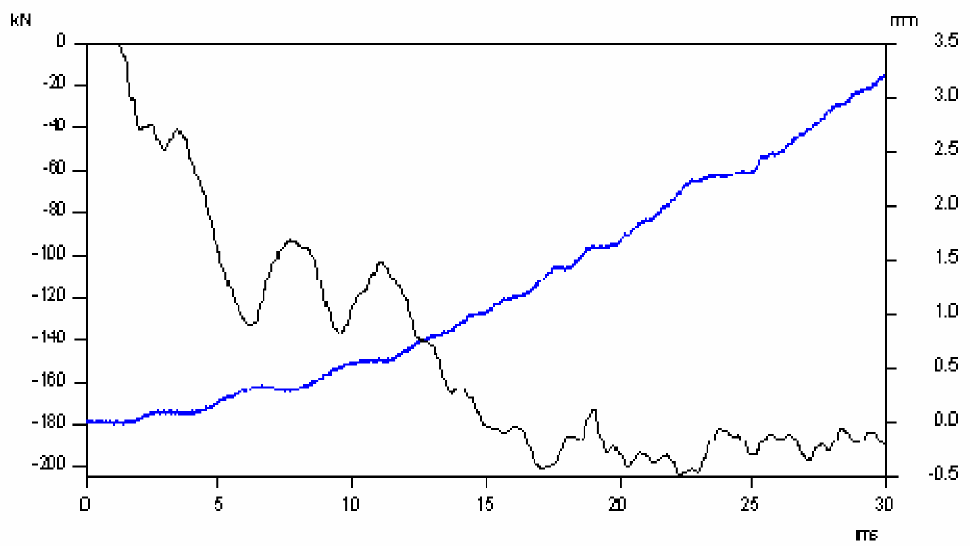

Figure 8: Displacement (blue) and force (black) of hydraulic jack after the explosive cut initiation.

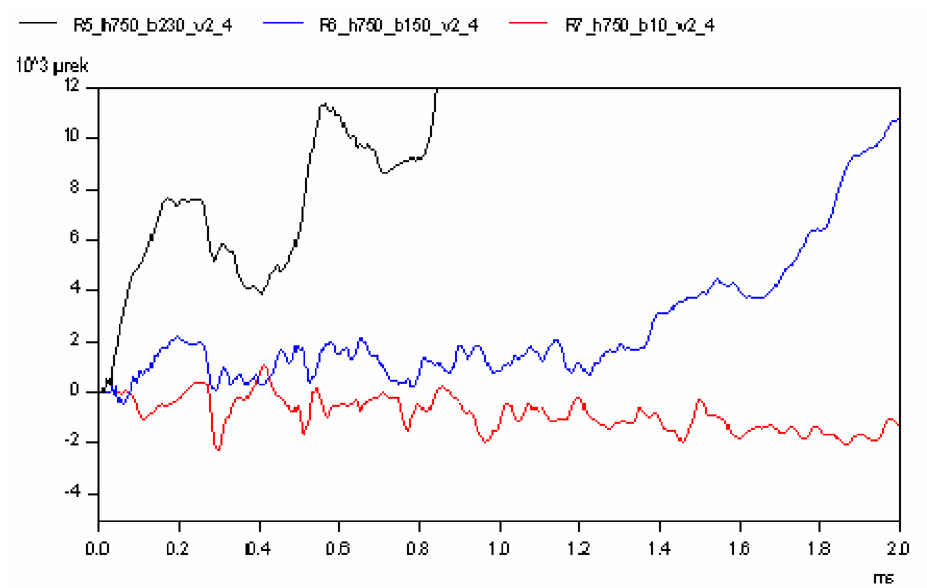

Figure 9: Strain change next to the crack during the first two milliseconds after cut initiation (strain gauge positions as in Figure 7.

5 CONCLUSIONS AND OUTLOOK

This paper could only address the first steps of the research work as the programme isstill in it's first year. Soon, a wealth of information will be released to those who will perform simulations for the purpose of tuning their numerical models. This will ultimately enable the making of a 'vulnerability map' of aircraft cabins. Complexities concerning variable pressure loads, laminated materials and frame-skin interaction will have to be overcome using a well-balanced approach of theoretical models and tailor-made experiments on an engineering level.

From the work so-far, the following conclusions can be drawn:

- In the Vulcan project, a major backbone of the work on fuselage response to blast load is an experimental building block approach allowing both fundamental and practically applied analysis.
- The single most important aspect on a materials and structural level is crack extension.
- Materials under study are aluminium 2023-T3 alloy as well as Glare and CFRP materials.
- In terms of crack stability limits, early examination suggests that 'dynamic limits' roughly correspond to static values for Glare 3 3/2 0.3.
- Crack extension for two unstable situations was analysed and yielded variable crack propagation speeds in the order of 50 m/s. Together with strain recordings, simulations of dynamic response will enable the formulation and tuning of crack models, involving energy absorption parameters on a crack tip element scale.

ACKNOWLEDGEMENTS

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The Vulcan team acknowledges the support of the European Commission, while at the technological end the contributions are acknowledged of the FMLC company and TU Delft as well as the excellent experimental work of TNO's 'blast team' Peter van Ierschot and high speed cameraman Etienne van Daelen who will no doubt perform even more remarkable feats as future experiment challenges increase.

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[1] European Union 6th framework project VULCAN (VULnerability analysis for near future Composite/hybrid aerostructures: hardening via new materials and design approaches against fire and blast due to accidents or terrorist attacks. Contract number

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