The end of flight MH370: a ditching study of the flaperon hitting the surface of the sea.

by Argiris Kamoulakos

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with Jean-Luc Marchand, Philippe Gasser , Michel Delarche and Jean-Marc Garot

https://www.3af.fr/article/sciences-et-technologies/la-fin-du-vol-mh370-un-amerrissage-force-etude-du-flaperon-heurtant

Introduction

The Newsletter from 3AF published The Enigma of Malaysia Airline Flight MH370, a view from Jean-Marc Garot, member of 3AF, on 05.11.2018, based on the work of the CAPTIO team.

CAPTIO's plausible scenario is as follows: A highly sophisticated trajectory was followed to divert MH370, but this operation failed due to a miscalculation of the aircraft's range due to over-consumption of an engine and uncertainty about fuel consumption resulting from a low-altitude flight (conducted in South Sumatra). This forced the People In Command to attempt a forced ditching of the aircraft near Christmas Island.

A very small amount of debris has been recovered from the coasts of the Indian Ocean, Africa, Mauritius and Reunion Island. Only three pieces of debris have been formally identified: the right flaperon, the inner part of the outer right flap and the trailing edge of the left outer flap.

The right flaperon, recovered from the island of Reunion, was transmitted to a laboratory of the General Delegation to Armament (DGA) and is still there because of the French judicial investigation, still ongoing. However, a structural study by this laboratory was incorporated into the final investigation report published by the Malaysian authorities in July 2018 (http://mh370.mot.gov.my Appendix-1.12A-2-Item1Flaperon (Main).pdf).

It is the only piece of debris, among the three identified, that has been analyzed.

Argiris Kamoulakos has joined the CAPTIO team. Argiris holds a PhD in Aerospace Engineering (specializing in aeronautical structures) from Imperial College London. He has extensive expertise in numerical analysis and simulation (virtual prototyping) in the aerospace and defense field. He is a Chartered Engineer, Fellow of the Royal Aeronautical Society (RAeS) and Associate Fellow of the American Institute of Aeronautics and Astronautics (AIAA).

The work he does, like the other members of the CAPTIO team, is voluntary. He is one of the Scientific Directors at ESI Group (https://www.esi-group.com/fr) and his personal work does not involve in any way ESI Group. On the other hand, we must thank Dr. Vincent Chaillou, COO, for giving him free access to the ESI Group's powerful IT tools and resources.

This article presents the result of the unique work done by Argiris Kamoulakos: the study of ditching using dynamic numerical simulations based on the methods of Finite Elements to simulate structures and Smoothed Particle Hydrodynamics (SPH) to simulate fluid flow. He concluded that it was a ditching that could have resulted in the loss of the flaperon's trailing edge, while a flight loss of the flaperon would most likely result in other types of damage than those visible on the flaperon.

The results of this analysis are consistent with the findings of the Investigation Report of the DGA Experts and give credence to the hypothesis of a ditching during the last moments of the missing aircraft.

It should be noted that, in order to conduct the work presented in this document, CAPTIO did not have access to the manufacturer's description of the geometric and material characteristics of the flaperon since they belong to Boeing. The models are based on limited data but available in the DGA report.

However, all of this data was found to be reasonably representative of the essential attributes of the flaperon in order to produce a convincing analysis of the magnitude of the problem in question.

Beyond the case of MH370, this work shows the capabilities of today's simulations, which have been developed, in particular in the context of EU-funded Research programs.

The flaperon

The photo, among many others, is the most telling of the flaperon as recovered on Reunion Island below in Figure 1, at the time it was transferred for investigation.

Figure 1: Flaperon recovered by French authorities on Reunion Island

The important part is the missing part of the trailing edge (highlighted by CAPTIO in Figure 1). The conclusion of the French report is that a ditching process is the most likely cause and not a separation in flight followed by a free fall with impact on the sea. However, no numerical simulation had been made by the French Investigators to support this claim.

Ditching modeling strategy

Ditching involves a fluid-structure interaction with large changes in fluid topology as a result of the creation of waves when the structure penetrates the water. The most appropriate way to simulate ditching is to model the fluid using the particle method in order to model large topological changes as well as "mixing", i.e. phenomena that are very difficult to model by the traditional Finite Element (FE) method. The particle method that has been used to model fluid (the sea) is the Smoothed Particle Hydrodynamics (SPH) method ("Tsunami induced Flooding Simulation and associated Fluid – Structure Interaction using the ESI Group VPS suite of codes." http://app.iahr2015.info/spreker/10985). See Figure 2 below for basic concepts.

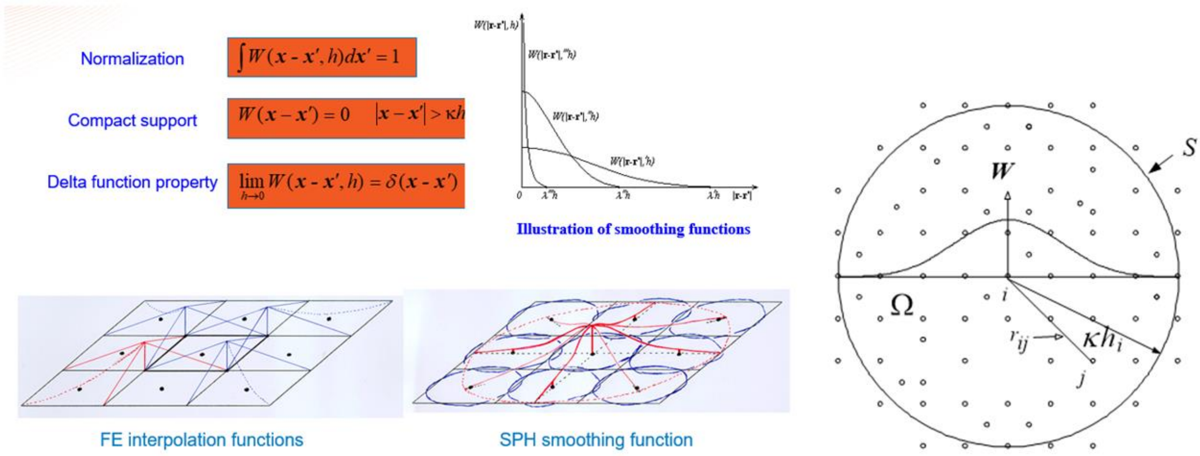

Figure 2: Principles of SPH idealizations in relation to FE

In order to choose the appropriate discretization of the fluid domain for ditching, a systematic study of the Von-Karman Wedge benchmark was conducted. The problem setup is as presented in Figure 3 below, corresponding to an infinite wedge of 120 degrees vertically striking a semi-infinite area of fluid.

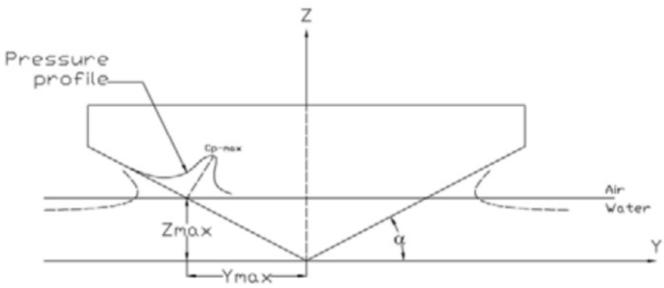

Figure 3: Definition of the Von-Karman Wedge

The choice of 120 degrees involves choosing a 30-degree angle of the outer wedge shape relative to the water, corresponding to the hypothesis of a flaperon tilted 30 degrees from its neutral position. The problem is essentially 2D (along the Y and Z axes) because the third dimension (X axis) that starts at infinity is self-similar, hence the problem corresponds to the class of "plain strain" problems, which correspond to zero X-displacement.

The simulations were conducted using the ESI group's (https://www.esi-group.com/fr/pam-crash) explicit transient dynamic code (PAMCRASH) and using the 2D option of the SPH model. Modelling of the "water" material requires an appropriate Equation Of State (EOS). Traditionally a polynomial EOS is used for impacts on water but because, in the case of a ditching (for the speeds that interest us), the compressibility of the water is very low, it is more effective to adopt the Murnahan-Tait EOS (see below),

$$p = p_0 + B \cdot \left((\rho / \rho_0)^{\gamma} - 1 \right)$$

This allows for relatively large time intervals thanks to the use of a judicious value of the speed of sound (about 10 times higher than the maximum expected speed of water, induced by splashing).

The wedge was analyzed for the penetration of a perfectly flat water surface at a given <u>constant</u> vertical speed (10 m/sec). Typical results obtained for the vector flow field in the selected segmented domain are shown figure 4 below.

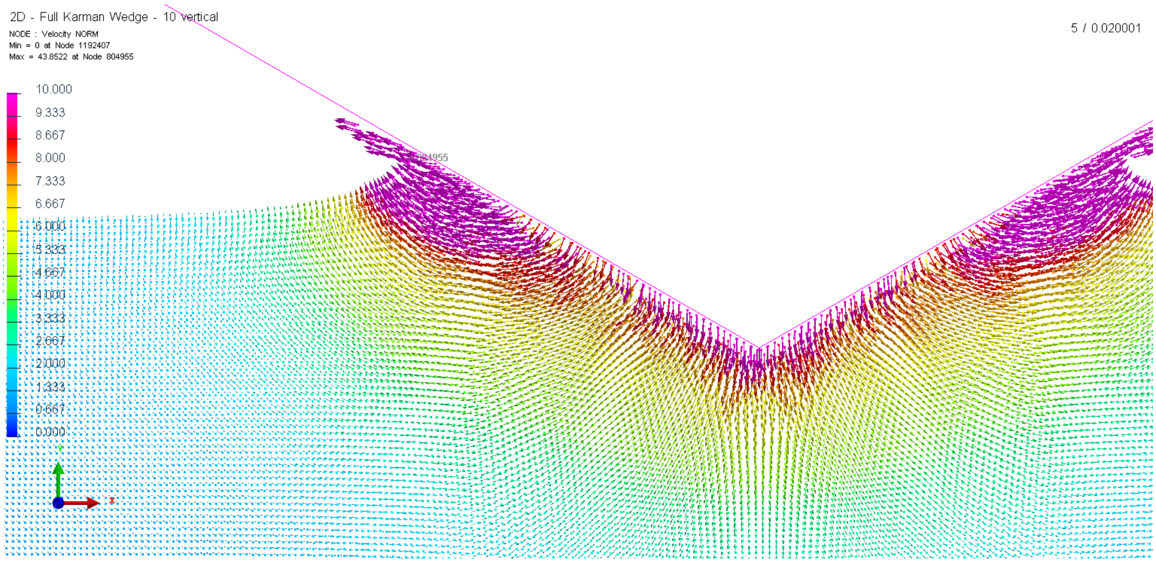

Figure 4: Vector flow field for a Von-Karman Wedge ditching in water

Similarly, the total vertical reaction force applied to the wedge as a function of water penetration is shown in Figure 5 below in comparison to the prediction of the Von-Karman theory (adapted to a <u>constant</u> vertical velocity and incorporating the "Wagner correction").

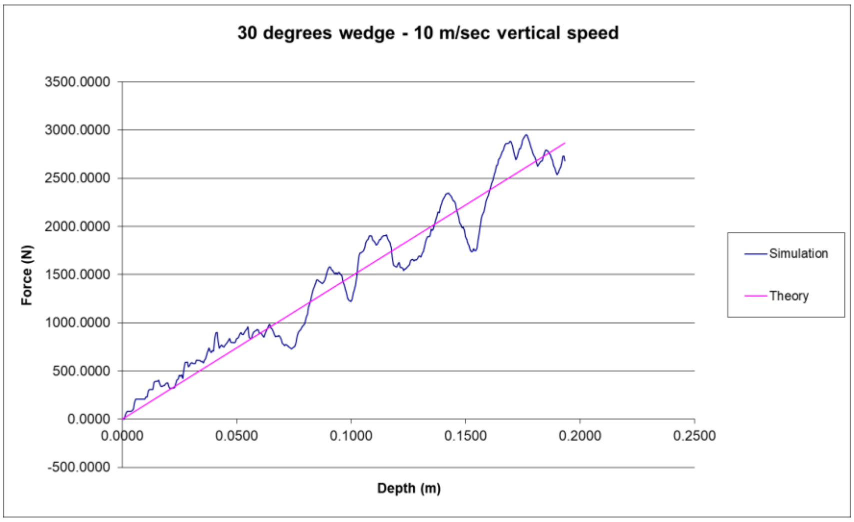

Figure 5: Comparison of Von-Karman Wedge's resulting vertical force simulation with theory (force amplitude is irrelevant, only the shape of the curve matters)

As the above comparison is very satisfactory, the granularity associated with this SPH numerical modelling as well as the associated material description used for water have been adopted and fixed for use in the subsequent analysis of the flaperon itself.

Simulation of the guided ditching of a flaperon as a rigid body in 2D and 3D

Since the geometry of the flaperon's lower surface is a half Von Karman wedge, it was possible to deduce the 2D model from a rigid plate tilted at 30 degrees.

The model was analyzed for a guided ditching scenario with a constant horizontal speed of 68.42 m/sec (153 miles per hour) and a vertical speed of 2.54 m/sec (500 feet/min) and with the SPH discretization chosen in the previous section. Figure 6 below shows a typical snapshot of the simulation.

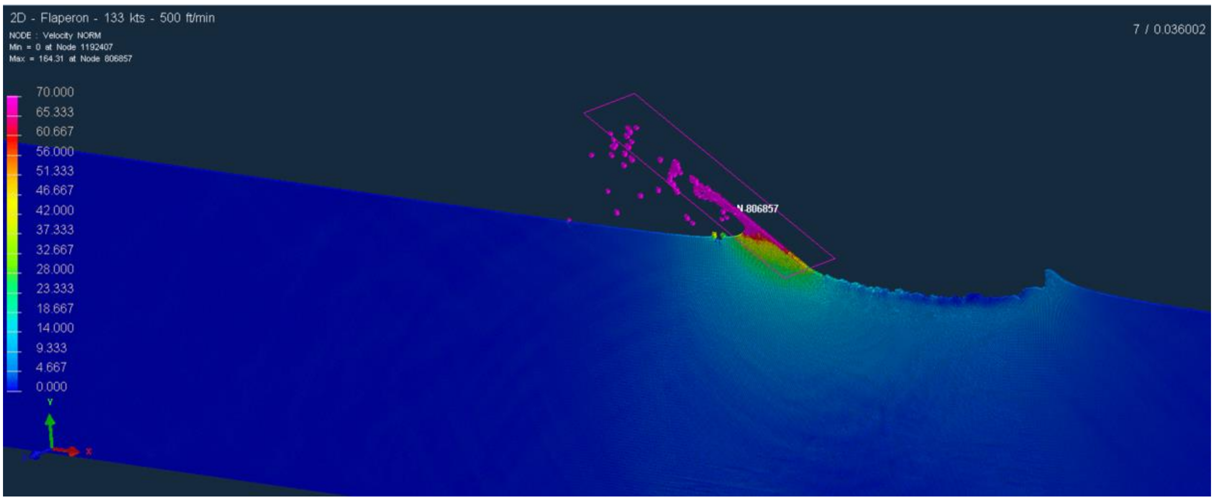

Figure 6: Speed contours of the 30-degree 2D SPH ditching simulation

The resultant pressure force on the flaperon due to ditching was calculated as the resultant force from the contact between the plate and the liquid. The temporal evolution of this force was thus obtained, as was the corresponding bending moment at the section where the trailing edge of the flaperon ruptured.

Thanks to the report of the DGA laboratory, it was possible to extract the geometric characteristics of the flaperon (load-carrying skin thickness, etc.).

The corresponding equilibrium stresses over the load-carrying thickness in the section where the trailing edge failed were assessed (see Figure 7) showing unrealistically high levels, providing a first indication that the section would break under these conditions.

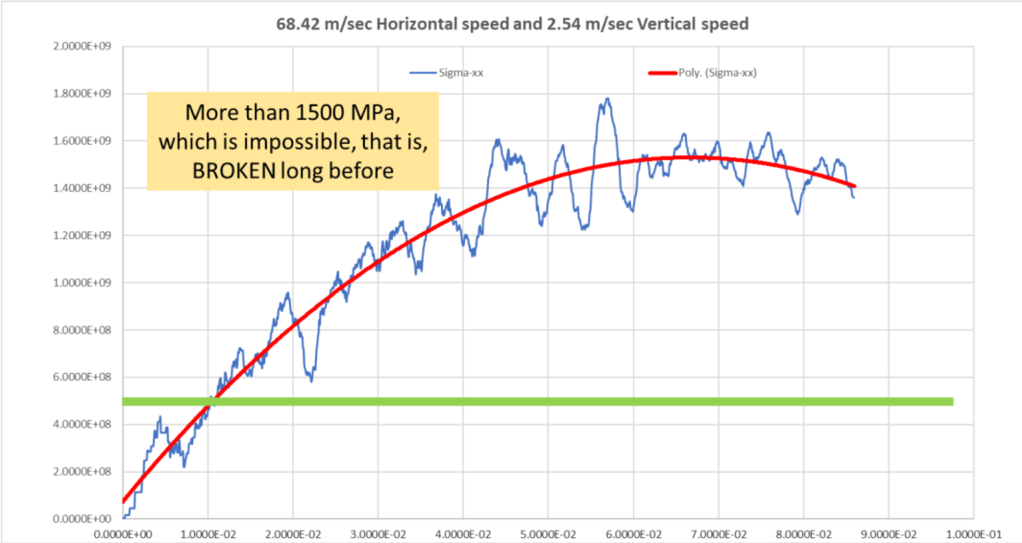

Figure 7: Temporal evolution of direct skin stress at the section where the flaperon broke

However, this 2D analysis on an infinite plate only gives an order of magnitude of the problem and overestimates the damage of a ditching event. It does not take into account the pressure reduction inherent in the lateral flow of water from the edge effects since the flaperon is actually a finite body.

The next step was to evaluate the behaviour of a complete 3D rigid flaperon model in a complete 3D ditching scenario. Figure 8 provides a snapshot of the ditching of the 3D rigid flaperon. Figure 9 shows a detailed view of the splash during the impact.

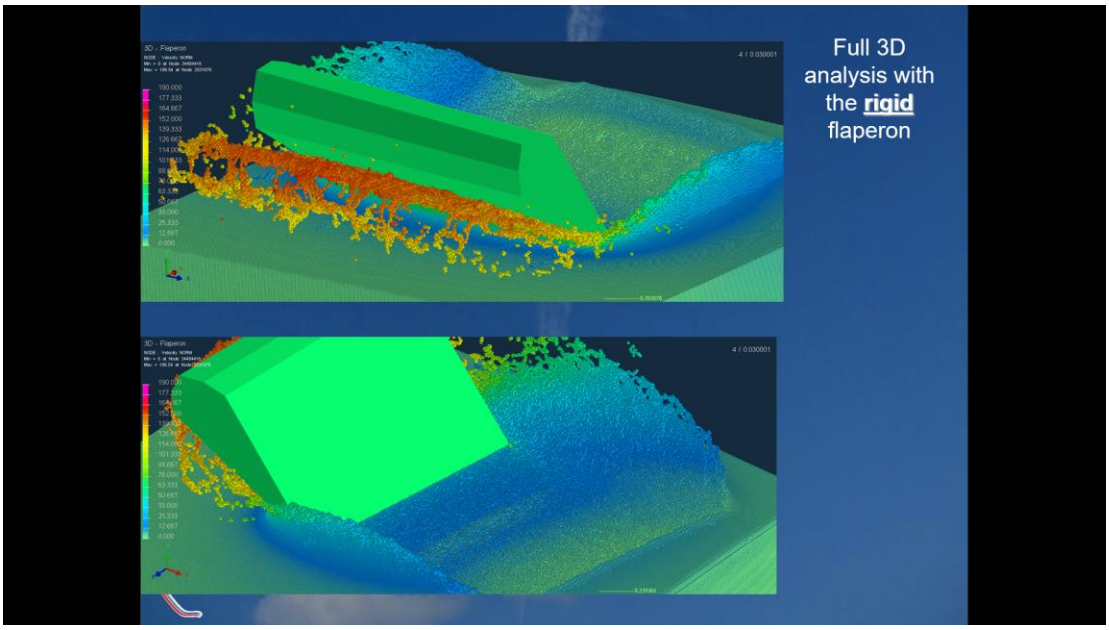

Figure 8: SPH ditching simulation of 3D rigid flaperon

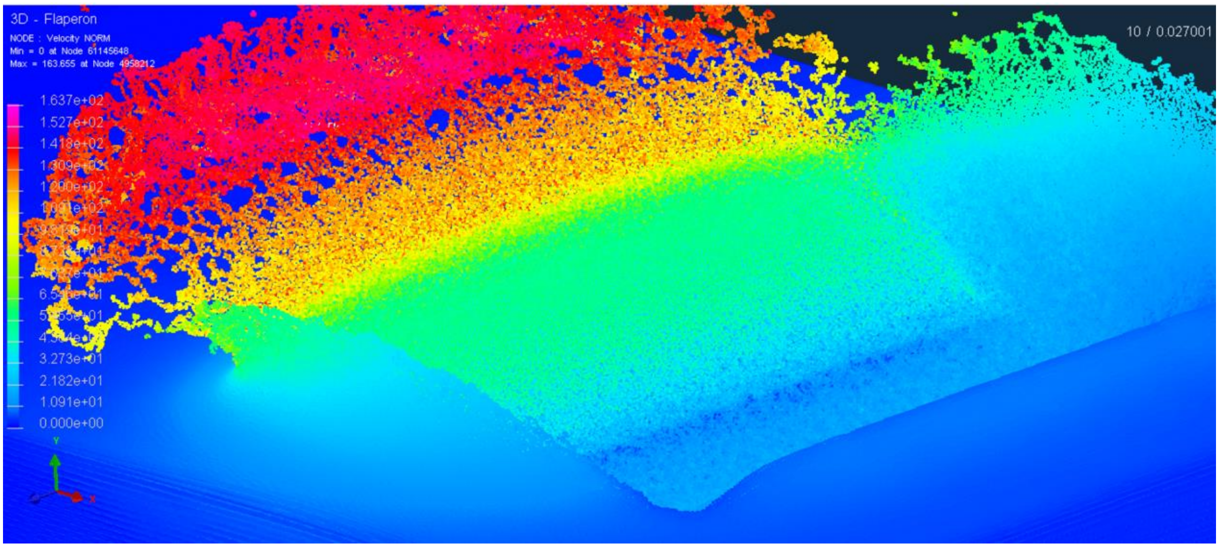

Figure 9: Detail of water speed contours in the SPH ditching simulation

The resulting pressure-induced forces had the same overall evolution as in the 2D case but with a 25% reduction compared to the latter. This does not, however, change the overall conclusion that the flaperon would experience very high stresses in this area.

Violent ditching of a rigid body usually involves (in the early stages) very high short-term pressure pulses that are caused by a stress-jump condition upon impact, before a Bernoulli flow is established (amplified at the contact interface since the body is rigid; limit of a weak Shock-Hugoniot condition). In the case of a flexible structure, the associated stresses would cause certain damage or trigger large local deformations. Since the flaperon is far from behaving as a rigid structure, the study had to continue by considering the ditching entirely in 3D as discussed above but with an elastic model of the flaperon. The study also covered the flaperon damage and associated failure.

Simulation of the guided landing of an elastic 3D flaperon

Appendix 1.12A-2 of the DGA analysis report provides the geometric and material characteristics of the flaperon. It is clearly noted that the outer skin (upper and lower) of the flaperon is composed of two composite laminates separated by a honeycomb core. Each laminate is composed of three fabric plies with a +/-45 , 0/90 and +/-45 degrees stackup sequence as shown in Figure 10 below.

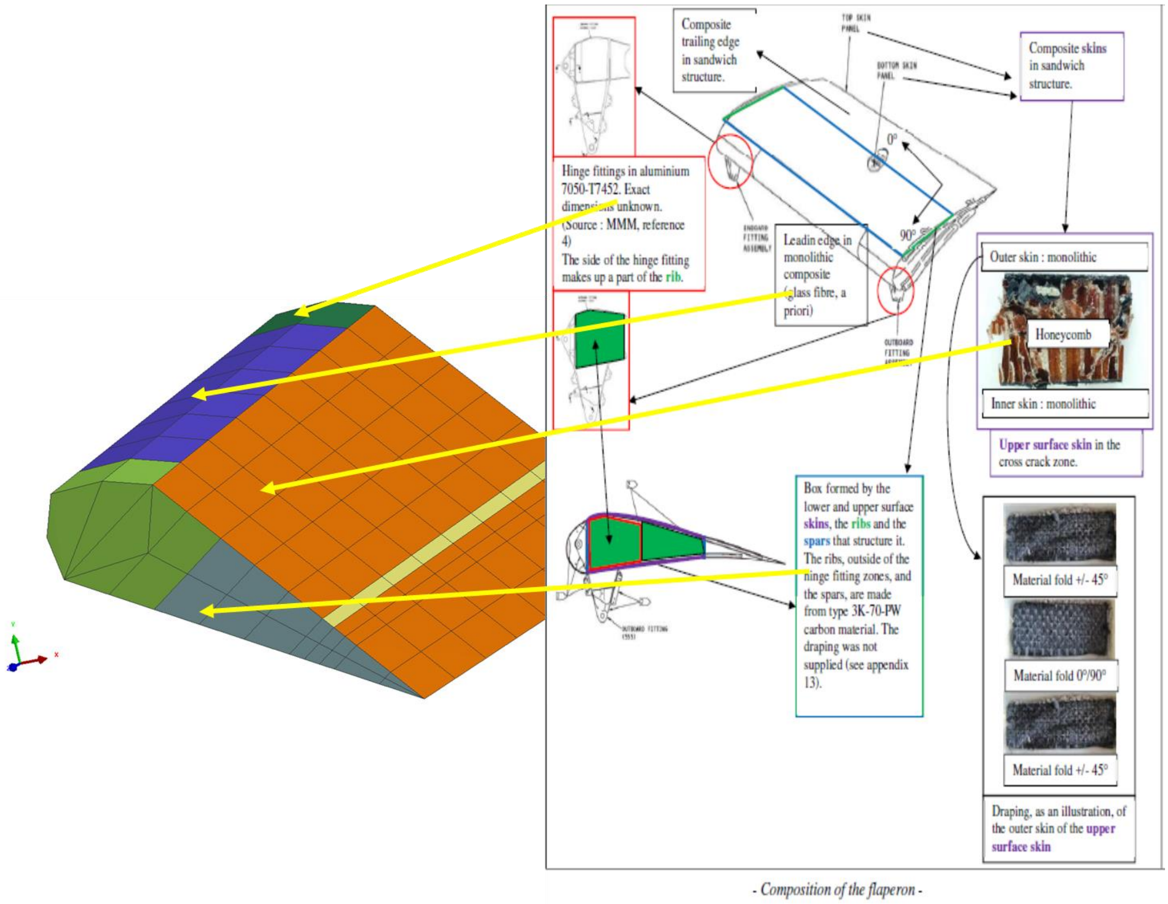

Figure 10: 3D elastic flaperon modeling information

The modelling of such a structure is based on the use of the Finite Element method applied to a 3D shell in composite materials. The advanced option in the VPS code for a multimaterial - multilayered shell has been used, allowing different plies to be mixed with different material properties and with different orientations in their stack-up.

Since the DGA report only mentions the 3K-70-PW composite as a component of the flaperon, there is no alternative but to use this material for the following analysis.

As this same report does not provide any explicit physical data on this composite, the typical properties of the 3K-70-PW composite were therefore obtained from NASA's AGATE report as shown in Figure 11.

Advanced General Aviation Transport Experiments

B – Basis Design Allowables for Epoxy – Based Prepreg

Fiberite Plain Weave Graphite Fabric T650 3K-70-PW / 7740

AGATE-WP3.3-033051-100

September 2001

J. Tomblin, J. McKenna, Y. Ng, K. S. Raju
National Institute for Aviation Research
Wichita State University
Wichita, KS 67260-0093

Fabric 3K-70-PW	
Resin Content [%]	**38 %**
Average Fiber Density	**1.778 g/cc**
Average Resin Density	**1.27 g/ccm**
Average Ply density	**1.585 g/ccm**
Ply thickness	**0.2 mm**
0 / 90 degree modulus (tension/compression)	**~69 GPa**
Failure strain (tension/compression)	**~1.3%**
Shear modulus	**~4 GPa**
"yield strain"	**~2%**
Failure strain	**~10%**
Shear Strength	**~96 MPa**

Figure 11: Details of the characteristics of the composite layered material

Figure 11 shows that each layer has properties that, in terms of axial stiffness (not failure) at the laminate level, roughly correspond to 'black aluminum'.

Damage and failure properties were estimated to match the characteristics of the above material and were introduced into the Bi-Phase fabric composite model of the ESI Group VPS code.

The trailing edge of the flaperon, the area between the section of the spar where the flaperon rupture occurred and the rear end of the flaperon, is assumed to be filled with honeycomb. This information comes from the design similarity between the trailing edges of a flaperon, a flap or an aileron in wing design. The reason for this is to provide through-thickness stiffness since the skin is so thin and flexible and the trailing edge comes to a wedge shape. This was modelled indirectly using the "self-contact" option of the VPS with a variable contact thickness, initially adjusted automatically by the VPS to be large enough to keep the upper and lower surfaces separate. In this way, there is no need to model the honeycomb itself which would have required a lot of effort and would have penalized the calculations for a questionable gain, other than to provide stiffness through the thickness.

The flaperon was therefore analyzed in the complete 3D landing scenario described above, but using the elastic model with the modeling of the material damage characterized above. The result is shown in Figure 12 and the fracture of the trailing edge just after the trailing edge spar is evident.

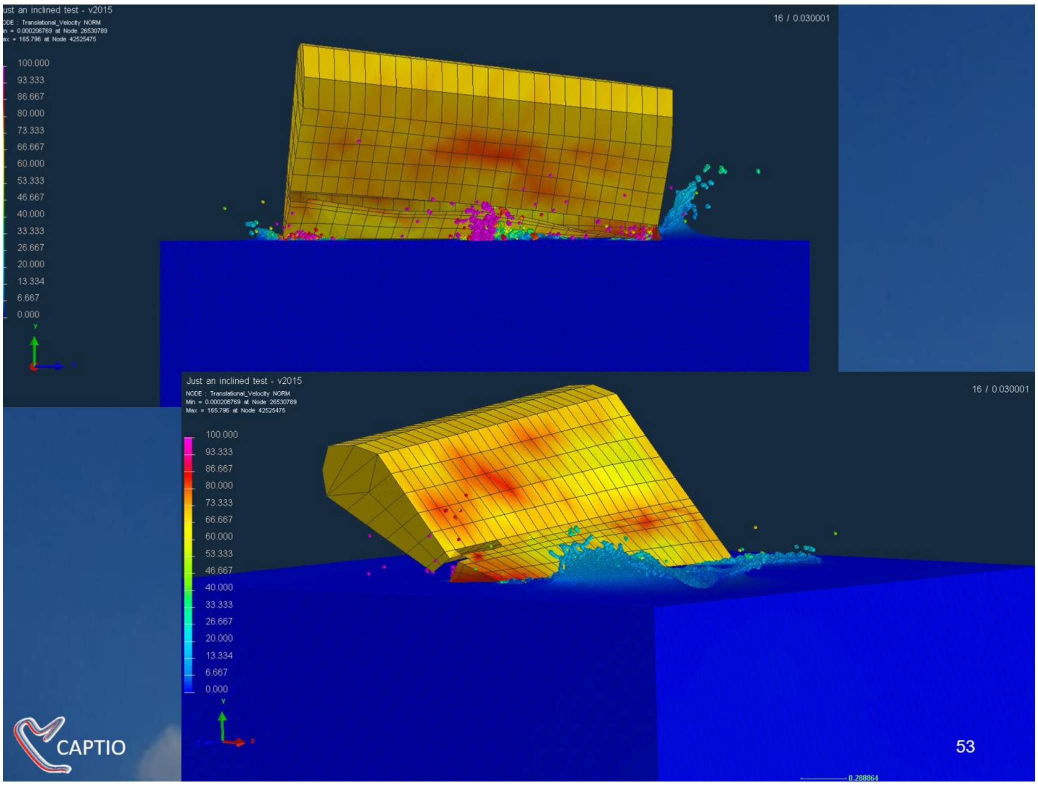

Figure 12: 3D elastic flaperon ditching simulation

This result has been systematically reproduced with slight variations in the properties of the material as well as in the extreme case, of the simulation of an equivalent aluminum sheet ("black aluminum"); a very strong local plastic deformation always occurs at the rear of the flaperon's trailing edge spar.

One of the simulations provided a better understanding of the failure pattern. It appeared that a tensile fracture appeared to occur simultaneously on the upper and lower skin of the flaperon at the rear of the trailing edge spar. It appears that the presence of the trailing edge honeycomb filler (its effect was modelled as a variable "self-contact") allowed the transmission of ditching pressure forces from the lower skin to the upper skin of the flaperon during the water impact.

The failure pattern of the flaperon skin in the vicinity of the trailing edge spar becomes more localized simulation-wise if we take into account the fact that the skin is not connected to the spar as in a continuous fashion/way but through discrete fasteners (screws). The associated holes are stress concentrators hence local damage under tension can be higher in their vicinity for a given “far-field” stress. This can be emulated by reducing the volume and/or associated damage thresholds for the locally coarse finite elements that encompass these holes and hence avoiding to model them explicitly. Screw pre-tensioning is of course an extra variable, very difficult to quantify in real life, but under impact it will not change the fact of the presence of a local stress concentration.

Simulation of ditching of a 3D elastic flaperon in free fall

Our simulation scenarios were inspired by the work done by the DGA. In his report, it was speculated that the ditching of the flaperon could have resulted in fracture of the trailing edge while a free fall would have shown a leading edge first impact associated damage.

For the free fall case, aerodynamic forces (lift and drag) and gravity were considered in order to calculate the range, speed and flight path angle evolution of the flaperon in a monotonic “quasizero" angle of attack path. As mentioned in the DGA report, the Flaperon's Center of Gravity (CG) is well ahead of its centroid. The force of gravity would therefore tend to produce a pitching down moment while the form drag would act further back. Therefore, the preferred scenario is a monotonic nose down descent with a water impact leading-edge-first.

The basic equations of motion in the absence of thrust were written in terms of longitudinal (chord-wise) and normal (thickness-wise) directions of the flaperon, assuming a flight path angle alpha. The longitudinal equilibrium contains the drag and the corresponding weight projection of the flaperon, while the normal direction contains the lift and the corresponding weight projection due to alpha. The longitudinal and normal accelerations are computed and they are integrated in time. The corresponding velocity increments are then obtained, then the flight path angle alpha update and then the corresponding horizontal and vertical velocity updates which through further time integration give the range and height updates.

Assuming a release at 5000 feet and 400 km/hour longitudinal speed with a mass of 50 kg, and using sectional properties from the FoilSim NASA program, the above scheme gives a terminal speed (impact speed) of 38 m/sec (137 km/hour), at an angle of 50 degrees nose-down, after 60 seconds of free-glide and at a range of 1626 meters from the release point.

The flaperon was simulated hitting the sea under the conditions calculated above and the results are illustrated by Figure 13.

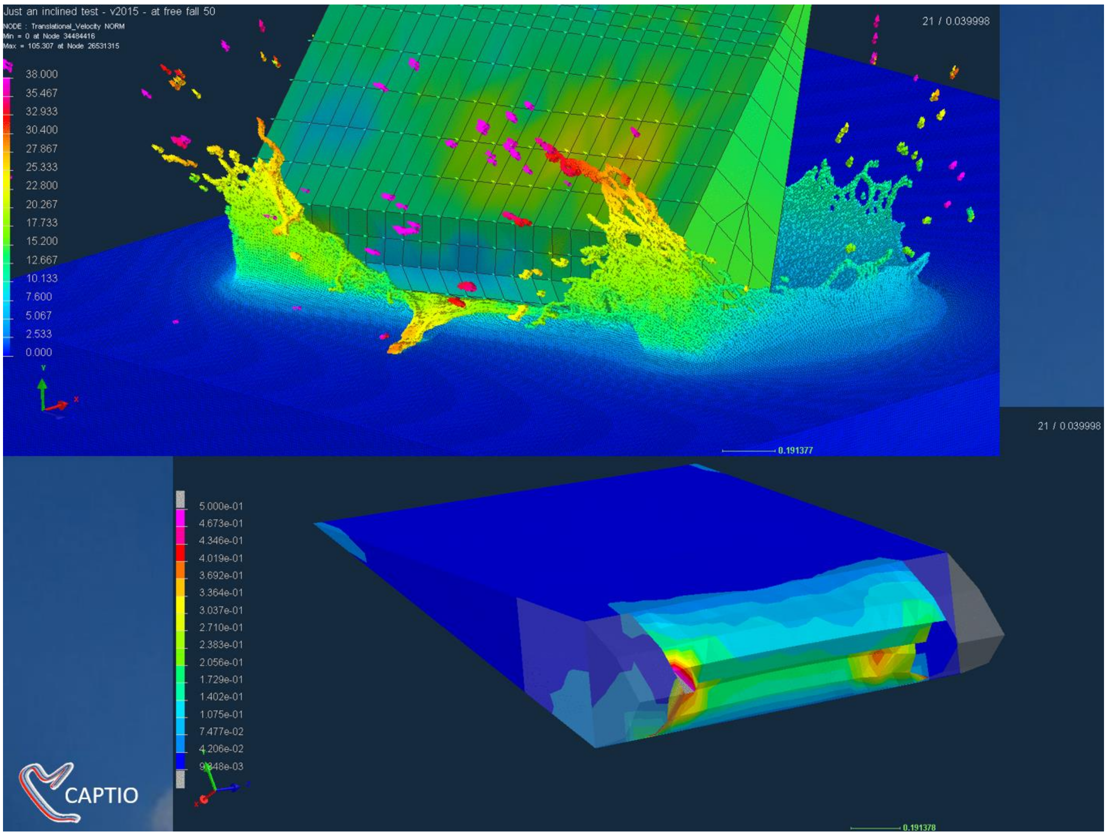

Figure 13: Sea impact simulation of elastic flaperon under free-fall assumptions

It is clear from figure 13 that, in such a water-impact scenario, the leading edge of the flaperon would most likely be the victim of local damage and rupture, something that is not seen in the photo of the recovered flaperon debris.

Discussion of the results

The comparison between guided ditching and free fall scenarios in terms of flaperon damage is shown in Figure 14.

Figure 14: Comparison of consequences on an elastic flaperon between the ditching and free fall impact scenarios upon the sea

It is clearly visible that only guided ditching (or a similar scenario) produces damage and rupture on <u>the trailing edge</u>, while a free fall scenario, according to the DGA report's assumptions, favours more localized damage close <u>to the leading edge</u>.

Conclusion

CAPTIO's analysis of the flaperon presented in this paper shows that the most likely cause of the separation of its trailing edge is in favour of a ditching scenario, i.e. that the flaperon was still attached to the wing of the aircraft until impact with the sea and that it was not detached in flight.

This is consistent with the conclusion of the DGA report.

With respect to the flaperon's trailing edge failure scenario, Figure 15 below presents the most obvious outcome of this investigation.

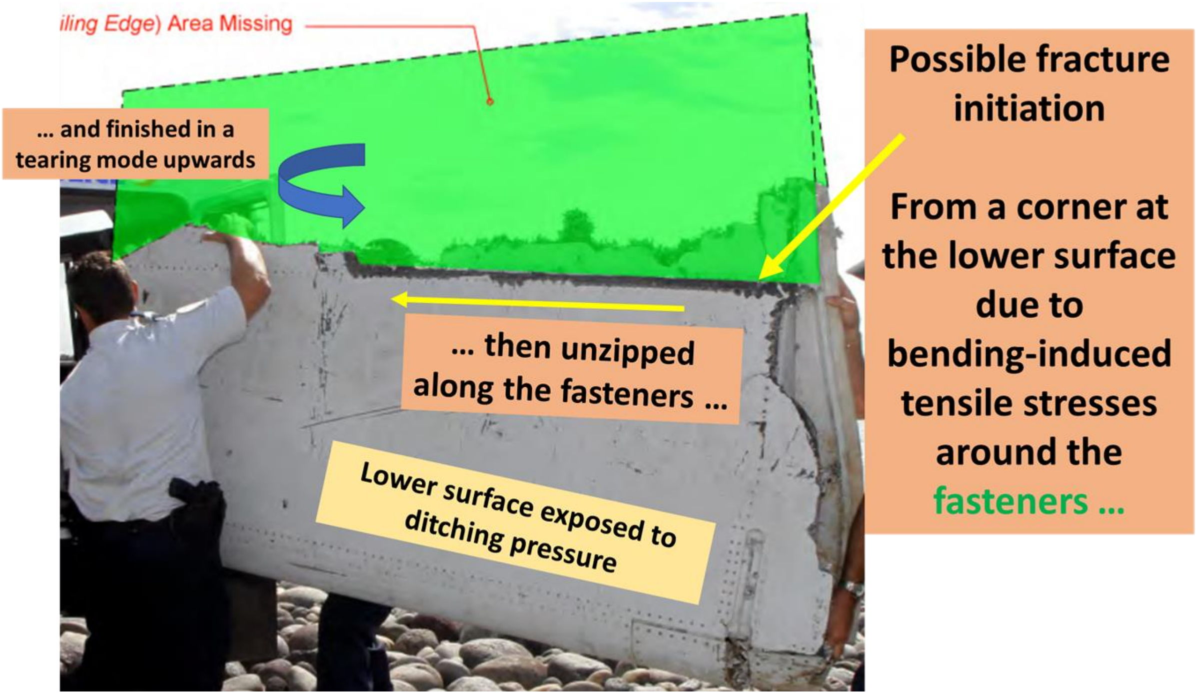

Figure 15: Possible scenario for flaperon trailing edge failure

The mechanism that allowed the sea water to slam upon the flaperon in a way to create this type of damage and the eventual total release of the flaperon from the wing is currently under investigation by CAPTIO and will be presented in a subsequent publication.