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Structural Integrity – the unfinished business

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A E R O S P A C E

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Structural Integrity – the unfinished business

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Jerzy P. Komorowski, Aerospace Portfolio, National Research Council Canada

Abstract

During my over 30 year career as researcher-engineer and then research manager at the National Research Council Canada Aerospace I have had the opportunity to deal with a broad range of structural integrity challenges. This paper is a review of several of these, while highlighting the opportunities for further inquiry.

The late 1970s and 80s saw a significant effort to develop aircraft structures built from fiber, primarily graphite, reinforced resins. Common considerations of strength, stability and fatigue life were made more complicated given susceptibility to moisture, temperature and impact. Black metal was not a fitting metaphor and new joining and repair approaches were required.

New and novel experimental techniques to better understand the performance of these structures were developed at NRC. Automated photoelasticity, image correlation, and double pass retro-reflection along with more common strain measurement and non-destructive inspection tools, had provided new insights into these new and into the aging aircraft structures. These techniques were used to support full scale aircraft tests at NRC with success.

Double pass retro-reflection often referred to as D-Sight has led to new understanding and models of corrosion. Aging aircraft concerns: fatigue, various mechanisms of corrosion, and multisite damage have prompted NRC to join forces with other organizations to advance the Holistic Structural Integrity Processes. Development still continues, already showing that physics based approaches offer improved understanding and successful applications.

The next steps in structural integrity, particularly the integrated health monitoring offer much promise, however structures engineers will have to contend with some old and with new challenges such as cyber security threats.

The paper demonstrates that structural integrity in spite of great progress continues to be an unfinished business.

I am greatly indebted to my NRC colleagues and supervisors for their contributions, support and mentoring. The relationships and professional exchanges facilitated by ICAF played very significant role in my career and I will remain forever grateful to many individuals that have shaped my thinking.

Standing on the shoulders – *whose shoulders?*

Figure 1 The giants

In the daily rush to solve pressing problems we face, many of us forget how much we owe those that came before us. Worse, many new papers are published without a link and acknowledgment to previous works. As I approach the twilight of my professional career and look back, particularly at the years of my involvement in ICAF I consider myself lucky to have met some of the aircraft structural integrity giants. They too owe much to those that came before.

I had the pleasure of being present at many Plantema lectures going back to 1987 in Ottawa when I attended my first ICAF Conference and Symposium. My respect for the giants and modest contributions I made do not allow me to consider myself a member of this group (Figure 1). Even more so I am very grateful to the National Delegates for giving me the honor of being Plantema Memorial Lecturer in Helsinki.

This lecture – a personal journey of a Structural Integrity researcher at NRC Aerospace

The journey began when I joined Structures Group of Structures and Materials Laboratory at the National Aeronautical Establishment (NAE) of the NRC in 1982. I came from Warsaw Technical University with some experience in experimental stress analysis and an interest in composite materials. That year marked the entrance of F18 fighter aircraft into Canadian Forces as CF-188 Hornet. The aircraft has a significant percentage of wetted surfaces made of carbon reinforced epoxy structures. This had created a pressing need to understand performance of these structures and their potential susceptibility to moisture and temperature. Thus begun my adventure in Structural Integrity.

About NRC

Before continuing the story of my 'journey' I would like to describe the immediate environment of my travel, namely the National Research Council Canada (NRC), the Canadian Aerospace Industry which is the main partner and customer of the Aerospace Laboratories of the NRC.

The NRC is an agency of the federal government with the primary mandate of supporting the Canadian economy (www.nrc.ca). The NRC has a broad spectrum of research facilities with about 3600 staff deployed in every province of Canada. Aerospace facilities are concentrated in Ottawa and Montreal.

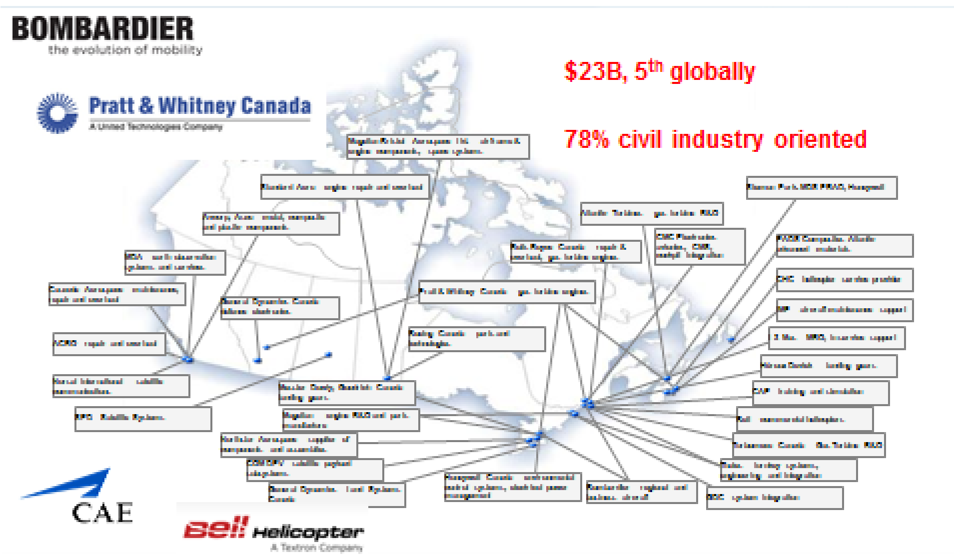


Figure 2 Distribution of major aerospace companies throughout Canada.

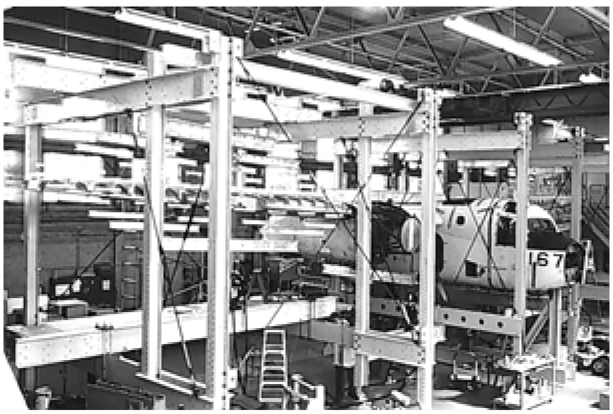
As NRC adjusted to changes in global and Canadian research and technology development (R&TD) needs it has been introducing organizational changes. So in early 1990's NAE became the Institute for Aerospace Research (IAR) and finally in 2012 the NRC Aerospace Portfolio.

The NRC Aerospace Portfolio operates various facilities: wind tunnels, engine test cells, test aircraft, structural and materials testing laboratories as well as aerospace manufacturing equipment. The current replacement cost of these facilities exceeds 500 million Canadian dollars.

NRC Aerospace works with Canadian Aerospace industry which currently is ranked 5th globally in terms of revenues (23B$/year) and is focused on the civil aeronautics sector. It is worth noting that this industry is truly national with companies active in all provinces while largest clusters are in Montreal and southern Ontario. Canada exports many fixed and rotary wing aircraft (Bombardier and Bell), maintains a dominant role in: small gas turbine engines (Pratt & Whitney Canada), flight simulators (CAE) and landing gear (Goodrich, Messier-Doughty, Heroux-Devtek). These OEMs and 1st tier companies are supported by a large number of lower tiers of companies. Only some of the companies are represented against the map of Canada in Figure 2. Aerospace Industries Association Canada (AIAC) publishes comprehensive reports on the status of the Canadian Industry on their website (www.aiac.ca).

My SI experiences:

Roy Hewitt has published an excellent review of the NRC history of structural testing from lead shot bags used to statically load wood and fabric aircraft to computer controlled servo-hydraulic actuators applied to current hybrid composite/metal structures tested under randomised spectra [1]. At the time of my arrival at NRC in 1982 the Structures and Materials Laboratory had already accumulated over 35 years of experience in aircraft structural integrity. The first aircraft test that I had opportunity to witness was Grumman Tracker Test (launched in 1978 and completed in 1982) – Figure 3



- life extension test
- 6 symmetrical load conditions
- 6 actuators and 4 control channels
- random load application using 35 levels
- fractographic marker block consisting of 51 constant amplitude cycles
- aluminum whiffletrees
- strain, load and deflection data recorded every 5000 hours

Figure 3 CS2F (Grumman) Tracker wing test.

Strain analysis

The next full scale test (FST) to be undertaken at NRC was the CT-114 Tutor (a jet trainer) aft fuselage and empennage fatigue test. The test was largely prompted by catastrophic failure of the horizontal stabilizer rear attachment fitting during aerobatic team flight. Subsequent to the accident the fitting was redesigned and new steel fittings replaced aluminium alloy construction. In parallel with the FST, a coupon joint test specimen was developed by the OEM (Canadair) under contract to the Canadian Air Force. NRC was tasked with strain analysis of the coupon. By this time (1988-89) my expertise, acquired as assistant professor at the Warsaw Technical University, in the photoelastic coating strain analysis was beginning to be recognized at NRC. Hence I preformed the full field analysis which indicated that the specimen needed to be redesigned to include a new area of potential interest just below the fitting (Figure 4). Photoelastic analysis of the revised coupon specimen indicated that the steel fitting resulted in new critical location (just below the fitting). This analysis was fully confirmed when the area failed under fatigue in the FST [2,3].

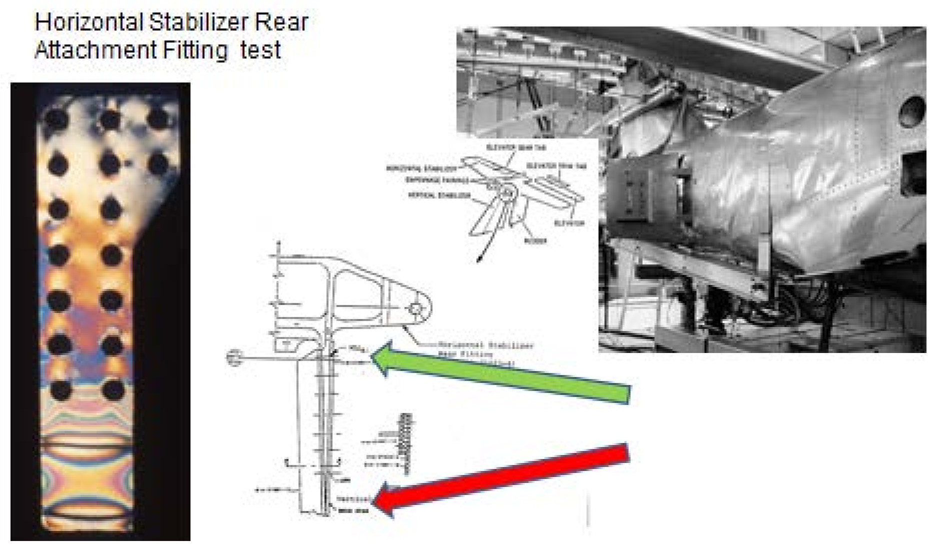


Figure 4 Horizontal stabilizer rear attachment fitting test.

The experience highlighted the need for careful design of coupon tests and the power of full field strain analysis methods. Today at NRC the photoelastic coatings have been largely replaced by another full field analysis method - Digital Image Correlation technique [4]. The reference also includes information on most recent FST activity at NRC Aerospace.

Composites

The F-18 fighter aircraft was introduced to Canadian Air Forces in the early 1980's. The aircraft has over 40% of wetted surface built from composites (carbon fibre reinforced epoxy). At the time composite material structures were new and NRC was tasked with building up the competence so as to be in a position to support the in-service aircraft should problems arise. My first task at NRC Aerospace was to look into the impact of moisture and temperature on composite structures. Having performed a very extensive literature review I set out to document my findings in a 6 part report [5,6,7,8]. Only 4 parts were published as I was urged to establish testing facilities and produce data. Thus began the 'unfinished business'. As I reflected on my career I saw more examples of 'unfinished business' which points to the fact that SI is an engineering rather than science driven activity (more on that later).

Working with Sylvie Beland (a graduate student at the time – today Director of Structures, Materials and Manufacturing at NRC Aerospace) we have demonstrated that moisture diffusion in composites often does not follow simple Fick's model [9,10]. The thermoset matrix (typically epoxy resin) has areas of lower and denser (higher) cross linked chains. The denser areas absorb moisture at a much slower rate resulting in weight gain rates for composites as shown in Figure 5. Understanding of these phenomena is needed in material qualification, modelling, as well component and full scale testing. Stopping moisture absorption at the first appearance of stabilisation may lead to underestimation of moisture levels needed for material strength testing (red line in the Figure 5). Very few practitioners reach for 30+ year old publications fortunately there is some evidence that this two-step diffusion process is known at least to some of them.

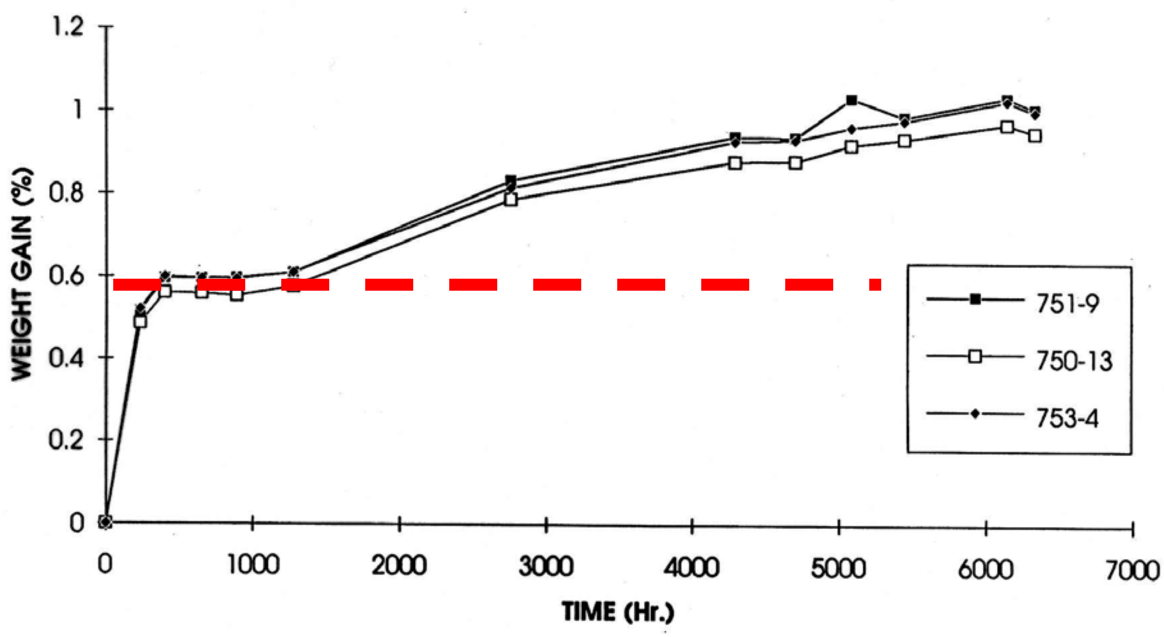


Figure 5 Importance of using longer moisture exposure times.

During the 1987 ICAF Symposium Robin Whitehead shared his experience with testing of primary composite aircraft structures [11]. He has shown that the majority of failures, which were difficult to predict, were out-of-plane failures caused by secondary loads (Figure 6). Some of these problems have been addressed by the use of stitching and better design and modeling tools.

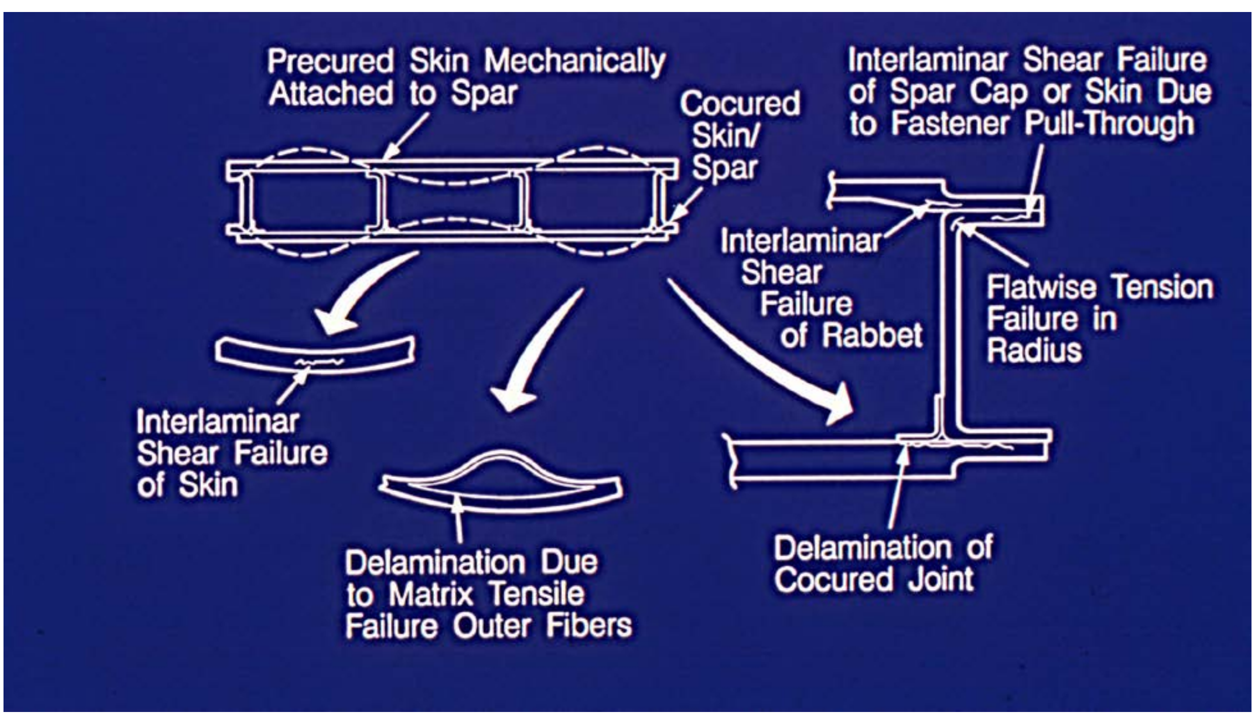


Figure 6 Out-of-plane failure modes [11]

Over the last 40 years of development composites have gained a significant share of total aircraft structural weight (B787, A350 and CS100/300). It is generally accepted that static hot/wet test is critical in certification of composite structures. When large scale test does not allow for testing moisture soaked composite structure at elevated temperature, then higher loads are applied (knock-down factors). Most failures are matrix or interface failures due to secondary loads (just as Whitehead observed in the 1980's). It should be remembered that matrix under hot humid conditions displays pronounced viscoelastic behaviour.

My recent conversations with current practitioners indicate that there is no written policy on how to deal with tests and analysis required to demonstrate that secondary loads (bending, shear etc.) are also 'scaled' appropriately so as to consider viscoelastic nature of the matrix. These are not linear effects while knock-down factor is a 'linear' approach.

Another problem 'bound' but not understood in composites is related to damage resulting from low energy impacts (hail, stones, tools etc.). Since the impacts are random events and regular deployment of non-destructive inspection equipment to in-service aircraft does not appear practical, the accepted approach is to ensure that a barely visible impact damage (BVID) can be tolerated by the structure. As my and others' research studies have shown [12,13,14,15]:

- BVID is an ill-defined metric as it depends on: coating color and lustre, angle of illumination and observation, aided or unaided vison
- Post impact surface perturbation will change with time and load exposure (up to 30% reduction in dent depth).
- Impact on a composite aircraft surface is an event that has certain distribution of energy vs. probability
- The impact event will result in surface 'perturbation' which also depends on other factors such as composite material toughness, laminate thickness, boundary conditions (support).

The BVID approach would seem to favour the use of higher impact energy to be applied in testing of tougher composite materials systems than less desirable brittle materials (Figure 7). In current practice it is accepted that BVID damage can be 'bounded' by open hole test which is regarded as having more severe impact on strength.

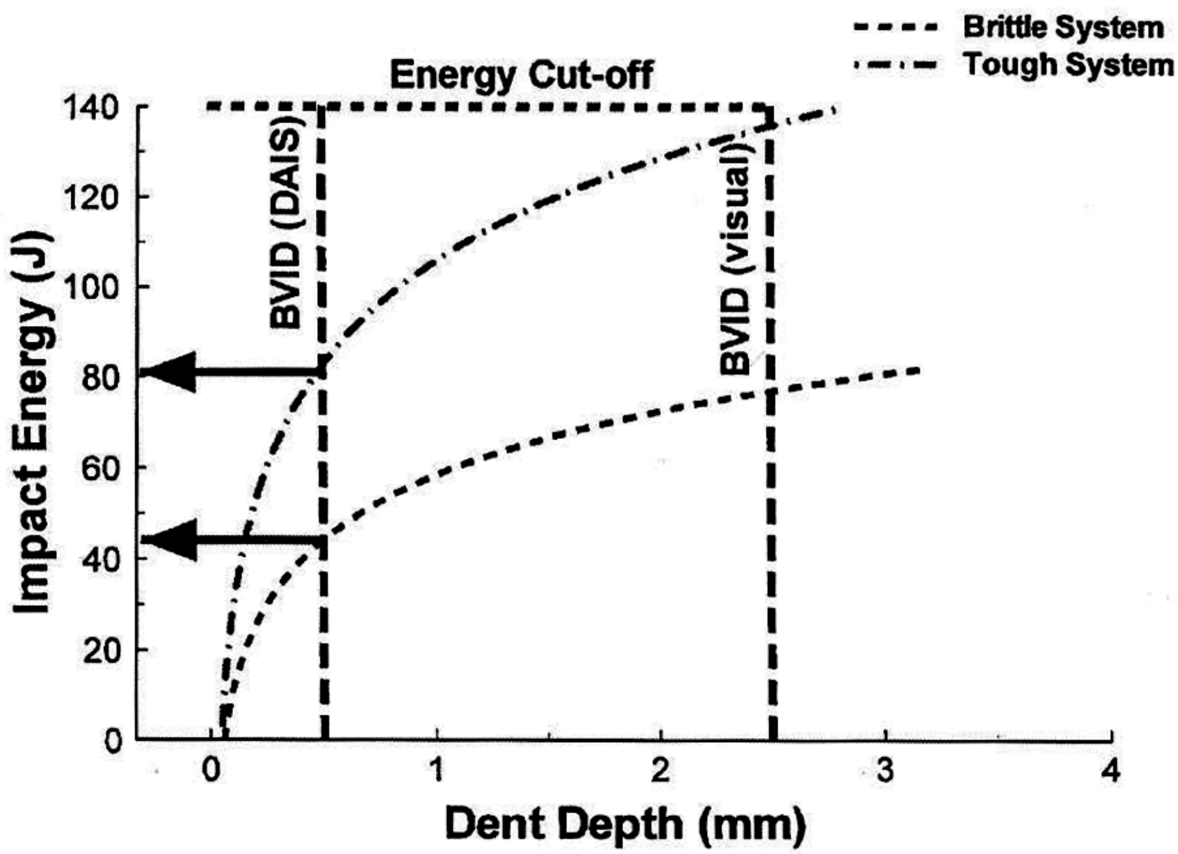
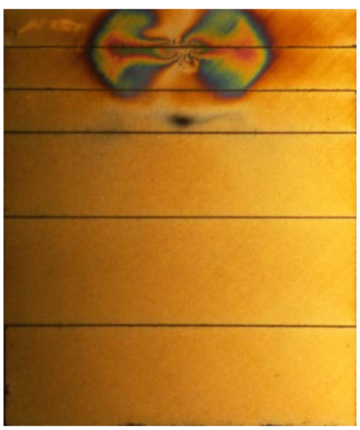


Figure 7 Higher energy is required in tougher systems to produce BVID [14].



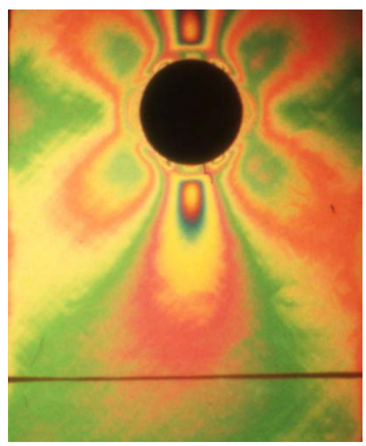


Figure 8 Photoelastic coating images of impact damaged (left) and open hole (right) composite panels under compression.

Figure 8 shows the striking difference in strain patterns observed with photoelastic coatings between impact damaged and open-hole panels under static compression loading. Initial look at the images seems to support this 'bounding' approach. A deeper understanding of the evolution of the impact damage versus open-hole under realistic cyclic loading conditions is still needed.

In late 1970's NASA produced a series of reports (i.e. [16]), which included comparisons of structural efficiency of transport aircraft wings built from aluminium alloys to wings built using composites. It was shown that large transport highly loaded wings made of composite will only show weight savings when designed to higher strain allowables (0.006 and more). While allowables used in current designs are considered by OEMs as confidential it can be expected that these are higher than used by manufacturers in the 1970's and 1980's (0.004 and below). Significant in-service experience accumulated with these lower strained composite structures has led to the popular opinion that composites are resistant to fatigue.

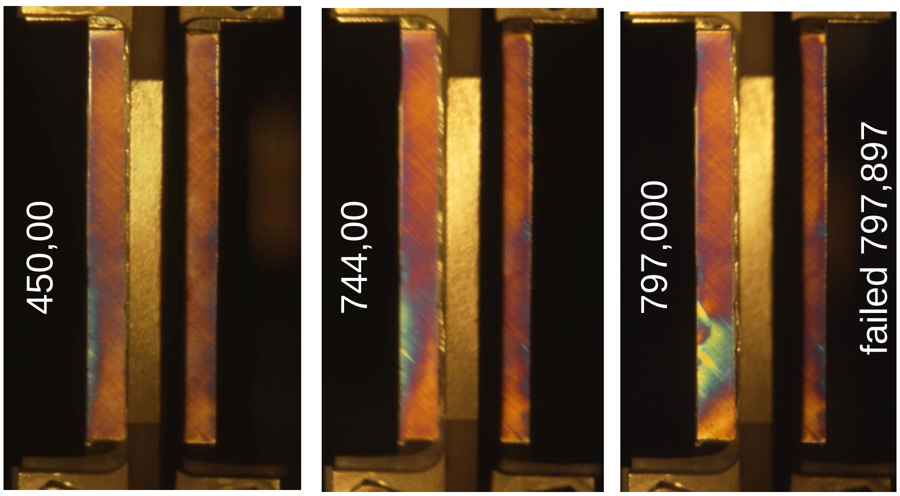


Figure 9 Photoelastic coating on a cyclic compression-tension loaded specimen vs number of cycles.

Experience with small coupons tested at higher strain levels points to complex micro-damage accumulation processes which manifest themselves very late in the total life of the specimen (shortly before the specimen failure to carry the loads - Figure 9).

While much of my own research in composites has been conducted in the 1980's and 1990's [17,18,19] many of the questions which were opened remain to be resolved. There is a need for physics based models to better understand degradation and failure of composites structures under service conditions. It is encouraging that NASA has launched a consortium which aims to look into many of these issues. The recent headline "NASA-Led Consortium will bring science to the art of composites" [20] has caused much consternation among the 'practitioners' who took offense to the word 'art'.

The engineering approaches typically lead to solutions which 'bound' the problems while the inside of the 'bounded' area remains ill understood unfinished business. Do we understand all the risks? In this context I would highly recommend an excellent book by Nassim Taleb "The Black Swan – the impact of the highly improbable" [21].

NDI

The work I did in composites has led to an increased interest in the field of non-destructive inspection (NDI) of aircraft structures. I have proposed that an optical system (double pass retro-reflection) known under its trade name D-Sight be used to rapidly inspect large aircraft exterior surfaces. First for impact damage and then for corrosion in lap joints [22,23,24]. In order to better understand the requirements for aircraft NDI equipment, with my NRC colleague (Ron Gould), we have created an “Aging aircraft specimen library” using sections of structures retrieved from retired aircraft. The experience of travel to aircraft bone yards, inspection and selection of specimens and subsequent comparisons of different NDI techniques were an invaluable lesson in aircraft structures integrity (Figure 10).

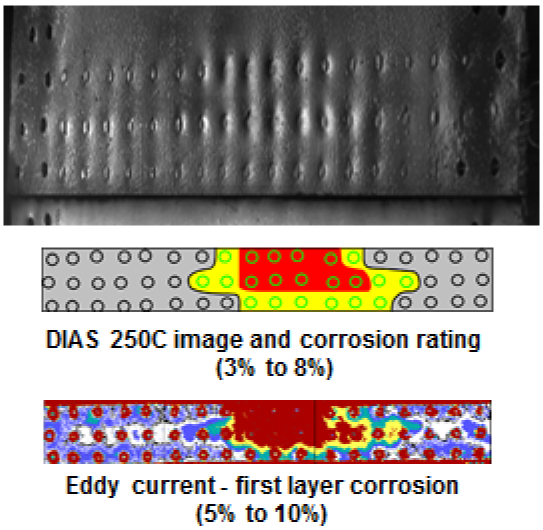


Figure 10 Comparison of D-Sight and Eddy Current test.

The interactions with aircraft operators, manufacturers and certification authorities point to a lot of questions which continue to be unresolved:

- Do we want less or more NDI?
- What, Where, When, How often, How? – to inspect
- What are the probability of inspection (POI) and probability of detection (POD)?
- Models of discontinuity growth, criticality? Do we have these?

Unfinished business continues.

Corrosion

In order to start to address the questions that NDI of corroded lap joints experience provided, Nick Bellinger and I have developed finite element based models [25,26,27,28,29]. Pillowing or bulging of riveted aluminum alloy (typically 2024T3) aircraft skins results from accumulation of the corrosion product on the faying surfaces (Figure 10). The volume of the corrosion product is much higher than the volume of the pristine alloy and results not only in deformation (pillowing) of the skins but also in high tensile stress at the faying surface near the rivet (Figure 11). By the time the corrosion models were indicating high levels of pillowing stress we had already been identifying pillowing cracks in the x-rays of specimen retrieved from our aging aircraft specimen library (Figure 12).

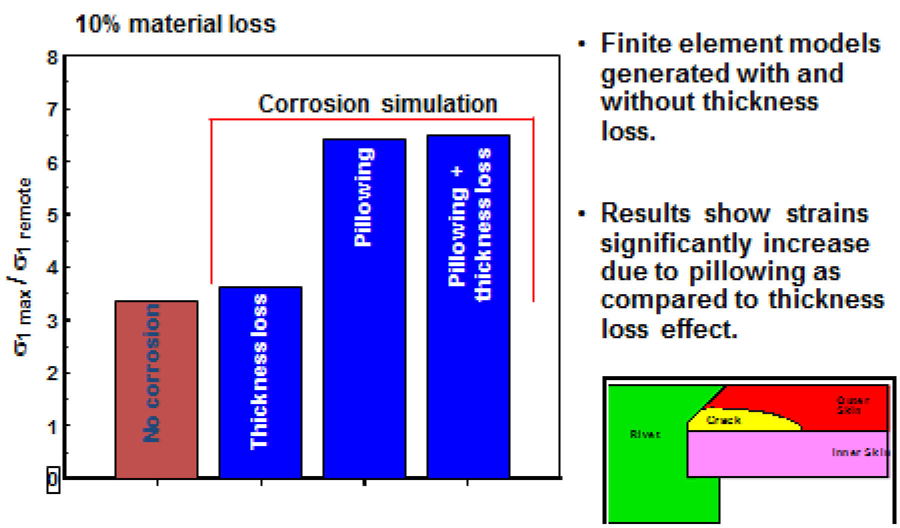


Figure 11 effect of corrosion on stress in a lap joint.

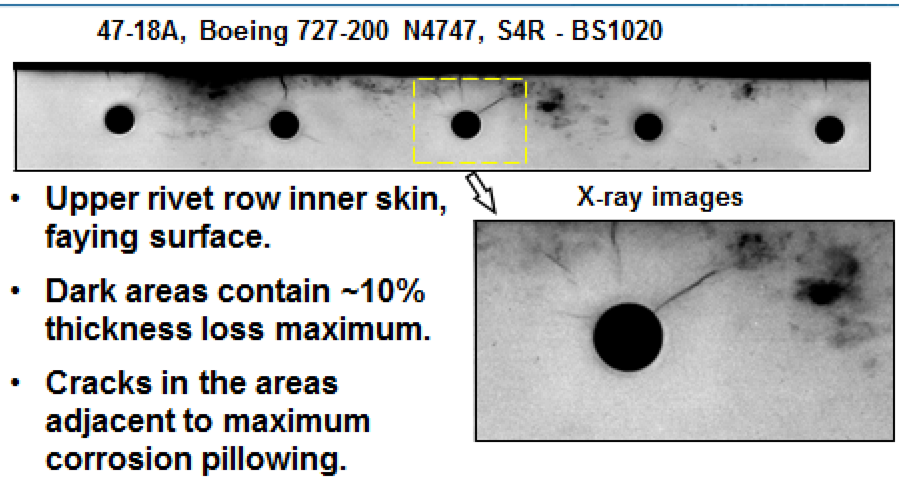


Figure 12 x-ray images showing pillowing cracks in lap joint skins

Pillowing also leads to high tensile stress in rivets. In a particular case involving a Boeing 727 aircraft we have observed failed rivets held in place by paint or interference fit. In this case, of the 56 rivets, 7 had failed completely. Of the remaining 49 rivets, 31 were cracked (Figure 13). In short our work has indicated that considerations regarding 'acceptable' levels of corrosion (10% of thickness loss) may not be conservative when pillowing is involved.

Several specimens of lap joints we had retrieved from aging aircraft indicated that some areas had been subject to in-service corrosion removal repairs. Typically once corrosion is identified and the joint is opened then corrosion is removed using sanding/grinding (Figure 14). It is evident that pillowing stress deforms skins in lap joints permanently (plastically) and grinding removes excessive amount of metal near rivet holes (up to 30%) as shown in the X-ray thickness map in Figure 14 [30]. This was well beyond the 10% thickness loss considered acceptable. Further work involving impact of exfoliation corrosion repairs in aircraft aluminum alloy wing skins on their fatigue life (with Min Liao and Nick Bellinger [18]) has shown that grinding out of exfoliation damage may be more damaging than arresting corrosion and leaving corroded material in place.

While our work has been available for over 10 years in the open literature I have no evidence that the above results have been given consideration by practitioners adding to my growing unfinished business list.

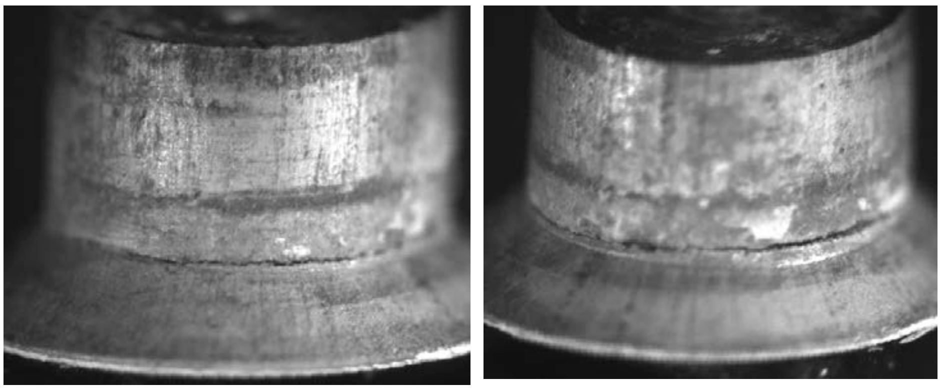


Figure 13 Cracked rivets retrieved from a corroded lap joint.

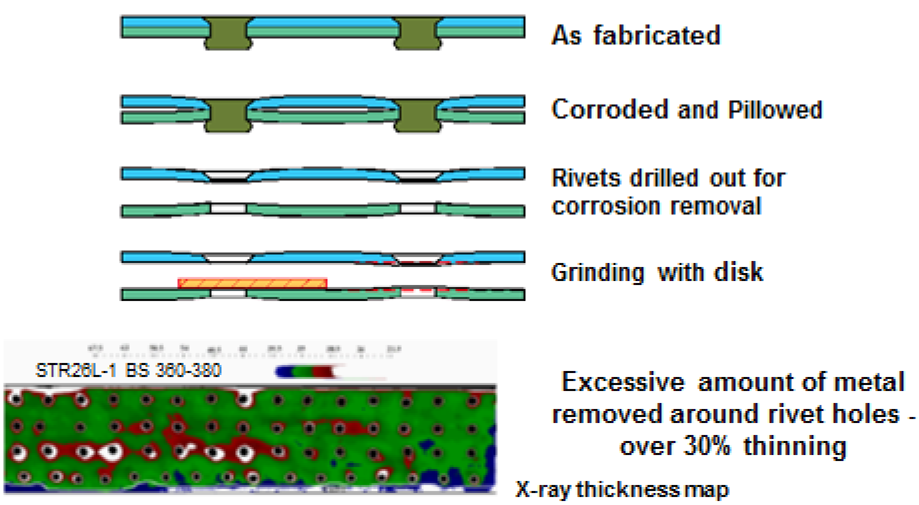


Figure14 Damage from corrosion repairs.

Our specimen library continued to yield new evidence that aging processes impacting structural integrity have to be considered together not separately. A section of a lap joint skin in which both pillowing cracks and fatigue cracks are visible shown in Figure 15 is a perfect illustration.

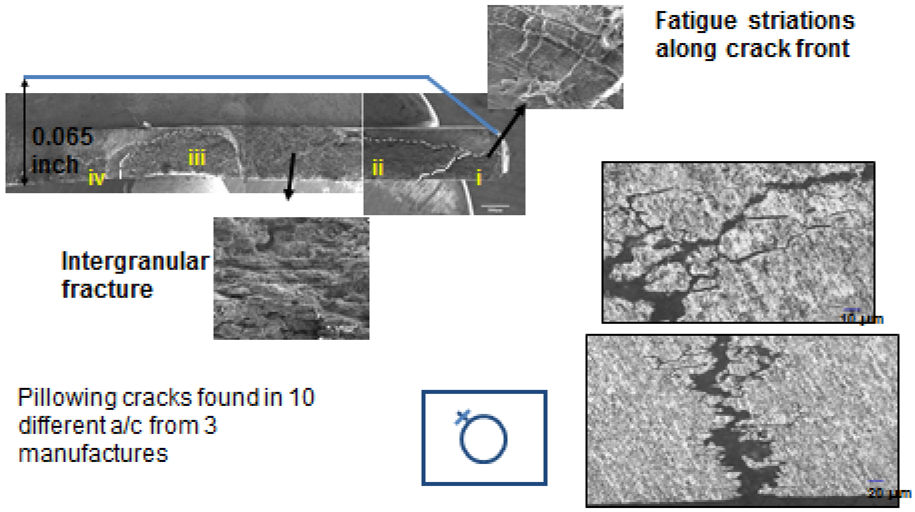


Figure15 Lap joint skin with a crack surface showing both intergranular and fatigue zones.

HOLSIP

The structural integrity work that my NRC colleagues and I were doing with partial support from the Canadian Department of National Defence led to an invitation to join a larger team funded by United States Air Force. Our primary collaborators became APES group lead by Craig Brooks and University of Utah experts headed by David Hoeppner. Hoeppner in particular proposed a systems approach to dealing with whole life of aircraft taking into account all external and internal influencing factors [32]. Collectively (David Hoeppner, Craig Brooks, Nick Bellinger and I) launched a Holistic Structural Integrity Program (HOLSIP) in 2002 with the first annual HOLSIP Workshop which took place in Park City, Utah. Last February (2015) saw the 14th Workshop [www.holsip.com].

Some of the most fundamental aspects of HOLSIP are:

- Design is "closed loop" and concepts of failure processes and "pathology" of structures pervade all phases of design and operation.
- The material is characterised as manufactured, considering intrinsic variability and process variability.
- HOLSIP considers fatigue as a multi-faceted process with extensive internal and external interactions in all stages of the process. (see Table 1).
- HOLSIP uses continuum mechanics but defines limits of applicability - is material and process specific.
- HOLSIP defines "defects" in relation to representation, variability, probability of detection (POD), and fitness for purpose. Introduces Discontinuity, Heterogeneity concepts.
- Surfaces are recognised as Discontinuity sources - thus they are characterised, modelled, evaluated, and controlled related to requirements and variability.
- Nondestructive inspection and destructive characterisation are pervasive throughout the design process. Probability of detection is intrinsic to activities. Inspectability is part of the design requirement.

- Variability in cyclic load response, variability in material behaviour, and variability in processes are intrinsic parts of design. Determinism is not used except for simplistic explanations.
- Probabilistic Life Estimation Techniques always are used. Fatigue, fracture, and related activities are recognised as intrinsic parts of the design process. Testing technology development is an ongoing activity.
- The load spectrum is recognised to be structure specific, and thus extensive effort is expended to develop standardised load sequences. Dwell effects are considered.
- Extensive effort is expended to understand the failure processes and methodology is developed for specific physically based degradation processes. Initiation concept used only to refer to start of a specific failure process. Physical characterisation of the degradation process is pervasive throughout, with control of material and process related to the specific failure mechanism. Inspection is pervasive throughout related to the specific degradation/failure process.

Table 1. Stages in fatigue life (after Hoeppner[33]). Total life L=L1+L2+L3+L4.

L1	L2	L3	L4
NUCLEATION	"SMALL CRACK" GROWTH	STRESS DOMINATED CRACK GROWTH	FAILURE (FRACTURE)
Material failure mechanism with appropriate stress/strain life data Nucleated discontinuity (not inherent) type, size, location Presence of malignant D*, H* Possibility of extraneous effects: • Corrosion • Fretting • Creep • Mechanical Damage	Crack Prop. Threshold related to structure (micro) Structure dominated crack growth Mechanisms, rate Onset of stress dominated crack growth Effects of: • R ratio • Stress state • Environment (t, chemical, T) • Spectrum ⇒ waveform	Fracture mechanics: • similitude • boundary condition (LEFM – EPFM?) Data base** Appropriate stress intensity factor Initial D*, H* size, location, type Effects of: • R ratio • Stress state • Environment (t, chemical, T) • Spectrum ⇒ waveform	K_{Ic} etc. C.O.D. Tensile/compressive buckling

*Discontinuity, Heterogeneity, **i.e. Mil. Handbook 5

- Probabilities of occurrence of specific corrosion, wear, fretting, and thermal degradation mechanisms acting singly or conjointly with fatigue are acknowledged as part of the failure process. Constant evaluation, model development, test method development, and design methodology development are intrinsic to design process.

- Attempts to characterise details of the failure process. ACTIONS based on understanding and recognition (of knowledge gaps) of failure PROCESSES.
- Recognises probability of localised discontinuity formation in relation to failure processes. Recognises high probability of multiple discontinuity sites (e.g. fatigue cracks, corrosion pits, etc.) Recognises need for assessment of Principal Structural Elements, Structurally Significant Items, and Structurally Significant Locations on the basis of failure process interaction effects. Defines "damage" growth in trackable inspection parameters or recognises need to limit lives of components.
- Microstructural control through process control always used to control and optimise response of materials for specific failure mechanisms.
- Design is viewed in terms of response brought about by extrinsic factors. Develops response parameters. Approach is holistic.
- All life assurance personnel are trained in failure processes and structural pathology. A proactive methodology to provide immediate feedback into the design system of "lessons learned" is a part of the design system.

In short HOLSIP framework aims to augment *safe-life* and *damage tolerant* paradigms with the *ultimate* goal to evolve HOLSIP into a new paradigm for <u>both design and sustainment engineering</u>. The key elements are physics and probabilistic models, loads monitoring, environmental effects, advanced non-destructive evaluation and structural health monitoring (SHM), and risk assessment.

Over the years NRC, APES, U. Utah were joined by other developers, Tri/Austin, AFRL/USAF, JAXA, SRI and others. HOLSIP is far from complete and others are welcome to join as much unfinished business remains.

At this 2015 ICAF conference the US and Canadian National Reviews presentations discussed much of the HOLSIP progress achieved over last couple years [4, 34]. Those interested are also encouraged to read ICAF 2015 Symposium papers by Min Liao [35], Paul Clark [36], Kim Jones [37], and their coauthors.

Future – more unfinished business

Aircraft structural Integrity field has made great progress and has contributed to making aircraft travel incredibly safe. As the manufacturers continue to seek to include new technologies new 'unfinished business' will open. A good example is Structural Health Monitoring (SHM) which is new mechanical/electrical/IT **SYSTEM** operating in real environments with sensors, signal interpretation, software, cyber threats adding to the growth of 'unfinished business' [38].

Concluding thoughts - ICAF

As a long time ICAF supporter I am concerned that the new generation of practitioners, particularly from OEM organizations do not seem to participate as they did in the past. The danger is that keeping company structural integrity approaches a "secret" will bread complacency and result in "we are the best!" – syndrome. How do we know we are the best if we do not communicate with others?

The ICAF mission is largely sharing and learning from each other and it will remain valid for a long time as much remains to be learned.

Will the structural integrity 'business' ever be finished?

Acknowledgment

The Plantema medal which has been bestowed to me by ICAF is in my opinion the recognition of contributions of all my NRC colleagues. I therefore dedicate this lecture to my NRC Structures colleagues past and present-many of whose names appear in the list of references. In particular I would like to acknowledge David Simpson my mentor, supervisor and predecessor as Canadian National Delegate to ICAF.

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