Structural Integrity: A Technological Term Synonymous with Safety

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1. Preamble

Way back in 1972, on a nice sunny Wednesday (considered auspicious day in Karnataka), I submitted my Ph.D. thesis at the Indian Institute of Science and stared into the sky thinking what future has in store for me. The mind of a young engineer who completes his Ph.D. program at a reputed University finds the research world to be of wider scope, vast, but hazy. Gone are the nice days when one was a student working with and guided by a distinguished Professor. The guide would define the problem, periodically keep track of the progress, change direction of work when the need arose and help when the student is stuck. Having received the degree, the student would have to look for a career in industry or academic career in an academic institution /research laboratory. In industry or research laboratory the work is many a time governed by the organisation depending upon where funding is available and only a few could successfully take up research lines of their own choice. In an academic institution where there is no hierarchy the young researcher need to relate his/her program of work to possible funding sources for acquiring minimum scientific infrastructure. The present faculty are lucky that they get a substantial start-up grant, but this was completely absent in our days in 1960's.

Now the struggle starts for the young faculty. I remember always the words from my brother who is a distinguished Professor of Bio-Physics in USA and a Fellow of US Academy of Physics. He said that "when your supervisor is correcting your thesis do not concentrate on somehow to finish your thesis, but learn how to guide and bring your student's thesis to an acceptable level in future". The wisdom and advice from my mercurial Professor & Supervisor, Prof. A.K. Rao, that "in particular in a developing country like ours, at least some of us should concentrate on research lines which directly should benefit the Indian industry". These two have been my total guidelines when I started my research career. I later passed on these sentiments to my students.

I looked up to two areas among many needing considerable research inputs for the scientific and technological developments in the country. One is structural integrity covering "Fracture Mechanics as the Science and Damage Tolerance as the Technology". The second is Wave Mechanics with several applications to NDT, rock mechanics, earth quake engineering…etc. At that time I moved towards fracture mechanics which seemed to be of direct relevance to the then aerospace programs. In later years I found many of my colleagues have made tremendous in roads in to the wave mechanics using Mini-, Micro- and Nano sensors to identify defects and monitor their growth in primary structural components in both off-line and on-line (during the flight) situations. Structural Health Monitoring (SHM) and Integrated Vehicle Health Monitoring (IVHM) have become buzz words and research to successfully implement them is considered to be necessary to ensure Aviation safety.

2. **Integrity of Structural Joints**

Joints are one of the critical parts of an aircraft in ensuring safety in design and operational phases. The configurations which threaten the structural integrity of large scale structural systems are structural joints causing concern to engineers conducting design. These structures are often made in parts and assembled using joints such as fastener, riveted, adhesively bonded or welded. The last one is preferred in steel structures whereas the aerospace adopts other types. Fastener and riveted joints are preferred in metallic structures. Bonded joints are used in a limited sense in metallic structures. With the advent of composite structures as primary material for aerospace vehicles bonded joints have become extremely popular. All these joints are discontinuities and are potential sources for crack (or de-bond) initiation and their growth leading to structural failure. Many of these problems are non-linear of different variety, but can be handled by the well-developed Finite Element (FE) software.

Fastener joints exhibit loss of contact along bolt-hole interface and material non-linearity in some cases of interference joints. Bonded joints get in to large deformations due to eccentricity of load path and material non-linearity due to low yield stress for the adhesives. These nonlinearities can be handled with finite element software even when more than one type of non-linearity occurs together. Ultimately combining non-linear analysis with fracture mechanics poses challenge in both conceptually and in keeping the computational time to be reasonable. These problems are handled using iterative and/or inverse formulations and there is considerable ingenuity required to save computer time. We were aware a well knit group was required for success. Self and my colleagues Prof. T.S. Ramamurthy and Prof. C.R.L. Murthy became the nucleus around which we built the activity in fracture, fatigue, finite element methods and NDT.

"The strength of a chain is the strength of its weakest link" is a well-known statement. Similarly in structures with large number of joints, the strength of individual components is the strength of the weakest joint. The safety regulations during design and during operational phase are stringent and need be followed strictly by the operators. If the health monitoring becomes mandatory in all flight vehicles, the joints will be the sites needing continuous monitoring. A wide parametric study conducted by our research students showed the effect of joints on the stress distribution and maximum stresses which cause crack initiation and growth. Misfit parameter values (negative corresponds to clearance fit, positive to interference and zero to push fit), elastic modular ratio of pin to the plate, Poisson's ratios, Interfacial friction (zero corresponding to smooth, infinity corresponding to rough/bonded or interfaces with finite friction) are the parameters of considerable interest to designers. Among these the interference joint is known to increase fatigue life.

When I was in Air India as a summer visiting faculty in 1970, Boeing replaced many major joints with interference joints. The concept used is a taper lok. This certainly impressed us and later it has been a pleasure to see the influence of geometric and material parameters from our work is being picked in the real design exercises in some of the industries. The greatest happiness for an engineer is when he sees his research contributions find a place in design procedures and/or data sheets published for use in design. Technological innovation sometime went ahead of the computational/analytical developments. The innovative minds of engineers have intuitively predicted higher fatigue life due to introduction of initial stresses using interference bolt in fastener joints much before such a benefit was analytically estimated. Besides interference and interfacial friction play an important role in predicting fretting fatigue failures in fastener joints.

Adhesively Bonded Joints

Adhesively bonded joints were used in a limited sense in metallic structures in several non-aerospace industries. Classical work by L.J. Hartsmith of Mcdonnel Douglas corporation, USA brought out several advantages of bonded over conventional fastener and riveted joints. The clear ones are less sources of stress concentration since cracks starting from riveted holes have been a major worry for designers and operators. However only in 1980's with the advent of composite structures adhesive bonding method of joining became more popular. USA conducted in 1980's a US National program PABST (Primary Adhesively Bonded Structures) program to resolve certain crucial issues such as Damage Tolerance of large area bonding in aero-wing type of structures. I had the benefit of working at NASA, Langley those years and contributed to computational methods to estimate de-bond growth. A team of Scientists including me developed software known as GAMNAS (Geometric and Material

Non-linear Analysis of Structures). This software is available on COSMIC where all the US Government funded software is stored. The type of defects and their growth in bonded joints are distinctly different from fastener joints and require special attention for detection (diagnosis) and growth (Prognosis).

Growth of Fracture Research at IISc along with National programs

This is the background which created the enthusiasm in some of us to pursue research & development activity in the field of fracture & fatigue. Dr. K.N. Raju of NAL developed facility for full scale testing of aircraft. We learnt a lot related to fatigue and fracture from him. National Aerospace Laboratories (NAL) and Defence Metallurgical Research Laboratory (DMRL) have become centres of this activity under the exceptional guidance of the then Directors Dr. S.R. Valluri and Prof. P. Rama Rao. ICF 4 (International Congress on Fracture) was brought to India and was conducted in 1984. NAL Organised the International workshop on Fatigue, Fracture and Failure Analysis. It was soon evident that given reasonable funding and facilities, India will be soon be self-reliant in handling the Fracture Control in Design of Pressure vessels/ Rocket casings, Launch vehicles and the other Indian aero-vehicle programs covering fighter aircraft, helicopter and missiles without depending on the West. Aeronautics Research and Development Board (ARDB) sanctioned large number of projects to academic institutions and research laboratories from 1973 in all areas of significance to aeronautics. Their contribution to generation of large competent scientific man power was outstanding. This helped immensely the National programs which were launched in later years. Dr. A.P.J. Abdul Kalam who moved from ISRO to DRDO started Joint Advanced Technology Program (JATP) in 1983 at IISc and funded projects of relevance to DRDL programs in all branches of Aerospace. Around the same time ISRO started Space Technology Cells (STC) at several Institutions including IISc. This was the beginning of a "Golden era" for Indian Aerospace and the young engineers were bubbling with great enthusiasm to conduct research in certain novel areas and as well contribute to the national programs. Fracture Mechanics is one of these areas which designers were keen to get inputs into their vehicle programs. We could see the initiation of DRDO Aircraft programs like LCA and Missile programs through IGMDP, Space programs including SLV, ASLV, PSLV and GSLV, HAL Helicopter program ALH and it is clear that aerospace received the most important boost.

VSSC organised a task force in 1985 to bring together fracture Scientists with a mandate to bring out the procedure for the fracture analysis of Pressurized components. The procedures set by this committee were subsequently used in defence and aerospace programs. Generally, everyone is satisfied with the progress till then for their projects. However, both Aeronautics R&D Board (AR&DB) and Joint Advanced Technology Program (JATP) supported research in this area including emerging technology of Acoustic Emission for online monitoring of aircraft in flight. The use of Acoustic Emission for incipient detection of failures during ground fatigue testing of structural components seems to be well understood by then.

Early Research Lines

As young faculty members at IISc, we were not satisfied by participating only in projects though they are of National importance. IISc mandate certainly includes conducting research of national and International importance and place the institution at a high pedestal.

To help these national projects we developed certain novel research lines in finite element techniques to accurately determine the fracture parameters SIF and SERR in all the three modes of fracture. Modified Crack Closure (MCCI)) technique is known in literature, but limited to simple constant strain triangular, and linear quadrilateral elements. We developed the technique to exploit MVCCI to be applicable for several singular and non-singular elements in both 2-D and 3-D cracked fields. Later for higher order elements a numerically integrated crack closure technique has been successfully implemented. This removed any issues in applicability of the technique to certain elements and made it more versatile to handle all situations. The MVCCI equations developed by us for the singular elements have been adopted in the famous FRANC2D software of Prof. Anthony Ingraffea of Cornell University.

Experimental programs were carried out with collaboration from National Aerospace Laboratory. Dr. K. N. Raju and Dr. R. Sunder of NAL wholeheartedly helped IISc students to work on the excellent facilities in their laboratory. Crack closure measurement with striations developed with special closure fatigue cycles, fatigue failure in structural joints and explanation of crack growth retardation and the effect of temperature exposure on the retardation were some of the topics where collaborative work was carried out. IISc Aerospace department soon became an integral part of the teams on fracture and damage tolerance on most of the National programs. IISc acquired a Fatigue testing machine and primary work done on this machine was combined with NDT techniques. Prof. C.R.L. Murthy pioneered research on Acoustic Emission (AE) when major attempts were being done all round the world to adopt this technique for online monitoring and for incipient damage detection. As a technique AE at that time got accepted as an online monitoring technique during the ground test of components or full scale testing of aircraft. Many more years later with the advent of micro and nano-sensors, I do find this technique is being developed further.

These projects have resulted in several accomplishments. (i) Failure of one of the pressurised air bottle is detected much before the actual failure using AE. The project Director was very happy and he exclaimed "your project budget is 1.8 lakhs and the cost of the project is paid for since we saved one vessel which costs more than the cost of the project", (ii) Several proof tests on pressure vessels in non-aerospace industries were cleared with AE monitoring, (iii) Software is developed for estimating the Stress Intensity factors (SIF) and Strain Energy Release Rates (SERR) in different modes of fracture, (iv) Certain critical thicknesses in high technology components had to be marginally changed to accommodate both fracture and DT criteria and (v) permissible crack sizes were determined in several critical situations.

Damage Tolerance to SHM

Last couple of decades have seen a distinct change with the scientific revolution leading to the availability of micro- and nano-sensors. Fibre reinforced composites as primary structural material also changed the approach of designers in safety critical structures such as in aerospace industry. Micro sensors can be embedded in layered composites and the diagnostic methods are based on wave propagation in the structure. I could not visualise in my younger days the potential of wave mechanics, but extremely delighted that many of my competent younger colleagues have been exploiting this technique quite extensively for damage detection.

National programs NPSM and NPMASS headed by Prof. V.K. Aatre gave a tremendous fillip to the emerging micro sensors and systems, and put the safety aspect into a different perspective. It is possible to continuously monitor the structures and possible to detect cracks as they occur and grow. The information can be used in two ways: (i) If the damage or cracks detected are critical this information can be used for online Structural Damage Mitigation i.e., temporarily mitigate damage till you land and (ii) allows the cracks to be attended off line and provides prior information to MRO operations where the cracks have occurred. The later saves considerable time in diagnosing the damage locations.

Currently we are working at the International Institute for Aerospace Engineering and Management (IIAEM), Jain University on prognostic aspects of crack growth in critical components. Crack growth in standard configurations can be handled using well-known software such as NASGRO. On the other hand when one needs to investigate prognostics of crack growth in problems such structural joints where non-linearity is prevalent, special methods need be adopted and these are the aspects dealt with in the studies at IIAEM.

Structural health Monitoring (SHM) and Integrated vehicle Health Monitoring (IVHM) have become Buzz words for all operators of high technology and safety critical structures. "Can we decrease the stringent requirements of Damage Tolerance if we continuously monitor the structure" is the natural question by the LCA chief designer Dr. Kota Harinarayana. I would love to see his anticipation for the future flight vehicles come true.

Working Closely with Industry

Industry obviously needs reliable answers to their problems involved in safety critical components. They would depend on premier institutions with strong research base for this. Generally the problems faced by them do not need inputs from cutting edge research, but simple calculations done by Institutions with strong research base will be accepted with confidence. Many times we realise that there is a need to approach industrial problems with simple theories and use common sense than jump into complex methods and solutions. Engineer must carefully groom his mind to pick the right approach for the problem at hand. Design of every bracket need not be done with fracture mechanics and damage tolerance approach. I would like to highlight a few examples to bring out how problems are solved.

1. Some industry had to reproduce a bolt to be used under tension. Their reproduction was perfect including the material and dimensions. Among the dimensions they reproduced the length and shank accurately. However they did not bother about the bolt head dimension to be of any significance made it marginally bigger for operational advantage. The bolt was failing at much lower fatigue cycles than the original bolt. It was a mystery till it was discovered that the dimension considered to be unimportant viz., bolt head size is the main cause. When a given load is distributed over longer length, the root bending moment is larger. 15% larger bending stresses cause loss of 70- 80% of fatigue life. It did not require further fatigue testing and the modified bolt worked. Typical example when an engineer's mind should be alert and often complex looking problems have simple solution often based on strength of materials only.

2. A crack was discovered in a solid propellant couple of days before it was to be fired. We were rushed to the spot in view of the time constraint. The main issue is to profile the crack and later standard equations could be used to check the integrity during firing.
   We worked hard for a period of 4-6 hours to complete the job and declare the crack to be safe. The firing justified our conclusions.

3. The first time I had an opportunity to use fracture mechanics knowledge along with my distinguished colleagues was in an event happened in a major power generating station. In a rainy season a large size mud block flowed in a semi-liquid form on to a pen stock and pushed it out of its anchors. It was contemplated to replace a few hundred meters of the penstock, but there was a delay in carrying it out. In the mean a team from IISc consisting of myself and another 7 distinguished Professors visited the site. The crucial point which was identified by the team is that during the type of loading such as the one which occurred in pushing the pen stock off the anchors, only very few circumferential joints would have been damaged. Just as sugar cane breaks at one or two junctions when one tries to break it using bending load. When one or two joints break, there will be stress relief everywhere and this makes the other joints to remain intact. This logic made it possible to think of restoring the pen stock and carryout required repairs instead of replacing large section of the penstock. Then the program was to identify the damaged joint/joints using NDT, re-gouge and re-weld it and push the pen stock back to the original position and anchor it. While refilling the pen stock we used Acoustic Emission monitoring to check on the structural integrity. This operation took 3-4 months and it was a success and 30 years later we did not find any report of further damage on the restored pen stock.

4. A company used bonded joint in their road driven vehicle. They observed frequent failures at the end of lap length and this was spreading inside. When we looked at the configuration, the first comment we made was that the adherends should be tapered. The industry man said" Yeah, I should have thought about it myself" and he was about to go. We asked him to wait to allow us to estimate what taper angle to be given, using fracture calculations on Strain Energy Release Rates. In particular the peel mode causes early failure and we recommended a 60^0 which brings the peel effect to near zero value. It was implemented and no further failure has occurred. I have given this example how one should combine the use engineering sense to computational structural mechanics to arrive at the optimum answer.

Closure

I narrated four examples, but there were many. If we consider the entire IISc, the faculty would have dealt several cases of this type. My narrating these here is to make the point is to emphasise that Engineer is a bridge between science and technology. In bringing these together he needs to also use "engineering sense" (some may call it common sense and there is not much difference between these) to successfully implement. Ultimate proof is successful implementation. Development of correct theory is necessary, but not sufficient till it works and also stands the test of time. The mind of an engineer has to assimilate the theoretical part and spend considerable time to realize it.

Safety of operations is needed in every engineering field to protect their structures. Appreciation of all methods of safety could save disastrous loss of human life and money for the state. In each one of the problems there are no common solutions. This is the reason damage tolerance is called a strategy which has to evolve for each case. As such now continuous monitoring of Structures is the scientific method which could be the front end of this approach. SHM and IVHM will generate enormous data and the next few years need to concentrate on how to handle Big Data Analytics to isolate and pick the signals of warning from continuously generated huge data.