The through-bolt saga

AN ENGINEERING DETECTIVE STORY

BY RICK FRITH

I RECENTLY visited Jabiru in Bundaberg to have some 500 hourly service work done on my four cylinder engine.

I have now flown over 1,300 hours behind such engines and have followed the through-bolt saga for many years. This saga involves failure of the bolts which hold the cylinders to the engine block and has led to in-flight engine shutdowns, hysterical internet forums and crippling operational restrictions imposed by CASA. Due to my technical interest, and possibly due to my engineering qualifications, Rod Stiff and Sue Woods were generous enough to show me the technical reports on research work which Jabiru has done over many years to solve the problem. In my experience, it is a classic example of engineering detective work.

STRESS AND STRETCH

When a bolt is stretched, it will initially extend in a linear manner - double the force, double the stretch. This is the elastic region. But as the force is increased, the bolt will reach its yield point and deform like plasticine. It will never return to its original length. Eventually it will reach a tensile limit and break. This is shown in Fig. 1 where the force is 'stress' and the stretch is called 'strain'.

If the bolt remains in the elastic range, the bolt should not break.

However there is a second property of materials which also affects the life of a bolt - fatigue. If a metal is repeatedly flexed beyond a certain point it will eventually break. How many bends it takes to break will depend on the size of the force applied. At high stresses, very few cycles are required– breaking a paper clip by bending it is a simple example. Breakage can occur even when the material is in the elastic region and not being deformed like the paperclip. Fortunately, for most materials, there is a lower stress, where the piece will survive an infinite number of cycles. These properties are summarised on an SN diagram (See Fig. 2) which shows the number of cycles before failure for a given stress applied to the material.

Early Jabiru engines had solid valve lifters and suffered no through-bolt failures.

However, when the standard design moved to hydraulic valve lifters, through-bolt failures started to occur. Here was the first clue. Something had changed obviously but what, in particular, was the problem? To further add to the mystery, failures were occurring primarily only in flying school aircraft. At the time of writing, Jabiru data shows every case of through-bolt failure reported to ATSB between 2009 and 2014 was in a flying school aircraft (despite ambiguous phrasing in the March 9, 2016 ATSB report which simply describes the category of use of the aircraft at the time of bolt failure and ignores the fact they were all flying school aircraft).

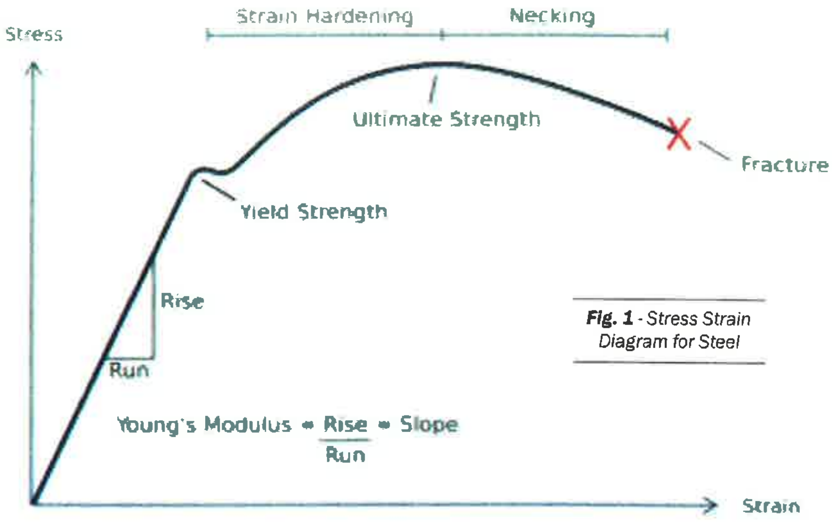

***Fig. 1** - Stress Strain Diagram for Steel*

Furthermore, the failures were mainly in flying schools operating at or near sea level. Those in alpine areas or the tablelands were trouble free.

Inspection of the failed 3/8" through-bolts showed they were failing through fatigue, at the point where theory predicted the maximum stress occurred in the threads. However, the stress-strain curve and the SN curve indicated the bolts should have had infinite life at the calculated maximum stress.

In order to reduce the failure risk, longer nuts were introduced to ensure the tension was spread over more threads than on the original bolts, significantly reducing the peak stress. While this was partially effective, even longer bolts with even more threads were introduced to further reduce the peak stress. These were installed with Loctite, making it critical the nuts were torqued up quickly to ensure uniform clamping forces before the Loctite set and influenced the force applied to the bolt. Needless to say, this did not always occur in the field, further exacerbating the problem.

The strategy behind these modifications was to reduce the peak stress in the bolt and, in accordance with the SN diagram, increase the number of cycles before the component failed. However, even when properly torqued, some through-bolt failures continued to occur, suggesting the problem was not yet completely solved.

In parallel with the program to reduce the peak stress in the through-bolts, a comprehensive research program was undertaken to identify the root cause of the failures. It is this work I studied during my recent visit to Bundaberg.

A fundamental breakthrough came when a strain gauge was installed inside a through-bolt to measure the actual stress in an operating engine. When the engine was started, the stress was found to rise unexpectedly high, before declining to the level predicted from analysis. Due to the different thermal expansion properties between the aluminium engine block and the steel bolts, the block expands more than the bolts, increasing the tension in the bolts at operating temperatures. This was expected and is shown in Fig. 3.

The surprise finding was that on engine start-up, the bolts warmed up much more slowly than the aluminium block, so the block expanded faster than the bolts, further increasing the bolt tension beyond that shown in Fig. 3. As the bolts warmed up and expanded, the tension eventually reduced to the expected level. This observation of thermal stress peak cycling explains why flying school aircraft were experiencing the through-bolt failures. They typically have short flight times (single lessons) and, during each flight, do many touch and goes, imposing higher thermal stresses on each circuit as the engine is throttled back for descent and full power is re-applied for take-off. Furthermore, at sea level, the engine will deliver more power when the throttle is wide open. At higher altitudes, the engine will develop significantly less power. For example at 3,000ft, the loss is almost 10%. At the same rpm, peak cylinder pressure and the stress in the through-bolts are essentially proportional to power, so sea level operations maximise the

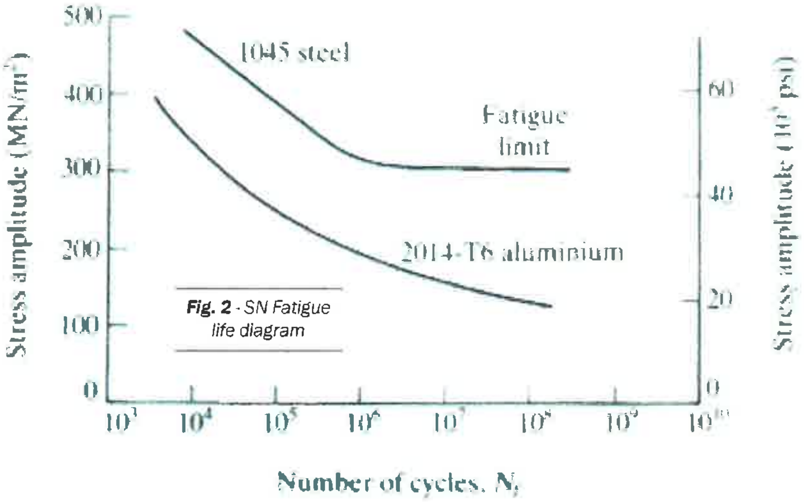

Fig. 2 *- SN Fatigue life diagram*

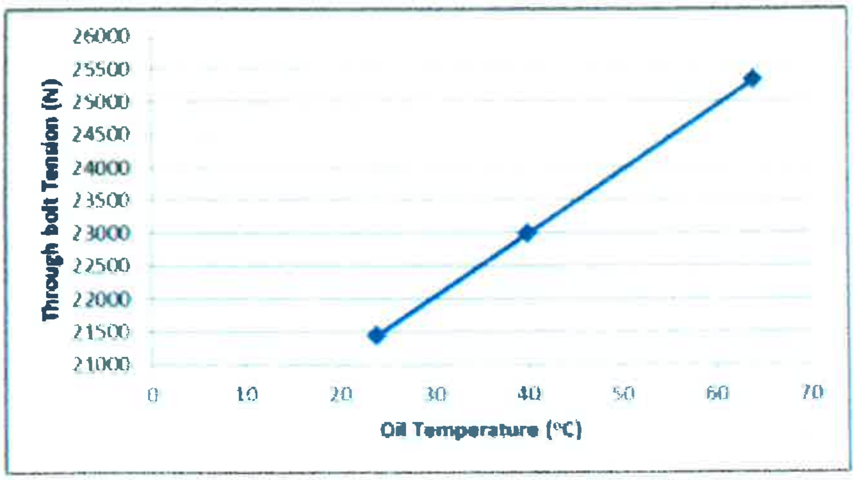

Fig. 3 *- Through bolt tension variation with oil temperature – at thermal equilibrium.*

forces on the bolts and, in accordance with the SN diagram, further reduce the number of load cycles before failure.

The solution for existing engines was simple - modify the 3/8" through-bolt design to make them more elastic and hence reduce the peak stresses generated by differential expansion rates. Flying school aircraft are required to replace through-bolts every 500 hours, ensuring a rapid take-up of the new design.

The latest model engines and those now returned to Jabiru for overhaul, all have 7/16" through-bolts, which also reduce the peak stress in the bolts. None of these have failed in more than 55,000 hours of operation.

The second breakthrough came with vibration analysis of the hydraulic lifter and solid lifter engines. The measurements were so sensitive it was possible to observe the twelve vibrations produced each revolution as individual alternator magnets passed the induction coils. The vibration spectra of both operating engines and major engine components showed a significant difference between the resonant peaks for the two models (See Fig. 4). Anyone who has pushed a child on a swing will understand that small forces, if applied briefly at the right point in a cycle, can dramatically increase the amplitude of the swings. This is resonance – the Tocoma Narrows Bridge is the classic engineering example of it in action. Just search for 'tacoma narrows video' to watch it collapse.

The solution to this resonance peak was to slightly modify the crankcase design to reduce the frequency and bring it closer to the solid lifter engine frequency. As a supplementary measure, for existing unmodified crankcases, the latest 3/8" through-bolt design also incorporates a vibration damper to eliminate any detectable lateral vibration of the bolt.

The resonance vibration was the true root cause of the problem. The differential thermal expansion effects were also present in the solid lifter engine, but did not cause failures because those forces alone did not exceed the SN curve. It appears the additional forces due to resonance further increased the loads sufficiently to cause fatigue failure. The thermal effects were a secondary, but essential contributing factor.

The root cause has been addressed in the latest crankcase design. It is still present in the earlier hydraulic lifter crankcases, such as mine, but operating experience and theoretical calculations indicate the 7/16" and the more elastic 3/8" through-bolts are effective in solving the problem. There have been no through-bolt failures in any aircraft with these modifications (including flying schools) since they were introduced. The latest style, dampened 3/8" bolts, once fully deployed in the field, are expected to totally eliminate any resonance effects in those crankcases.

This is the good news for both existing and prospective Jabiru owners. More disturbing, however, was to learn that of the more than 50 engines returned to Jabiru for overhaul each year, about half have not had all the service bulletins or service letters applied. No matter how thorough the engineering or how comprehensive the solution, it is useless if not applied in the field. As a professional engineer with almost 40 years' experience, I find it staggering any owner, or maintainer, could ignore a directive from a manufacturer. The legal liability alone should be enough to discourage the practice.

Disclaimer: Rick Frith is a Jabiru owner. He has tertiary qualifications in engineering and science. He has written this without any prompting or direction from Jabiru. It represents his own views and not necessarily those of Jabiru or RAAus.

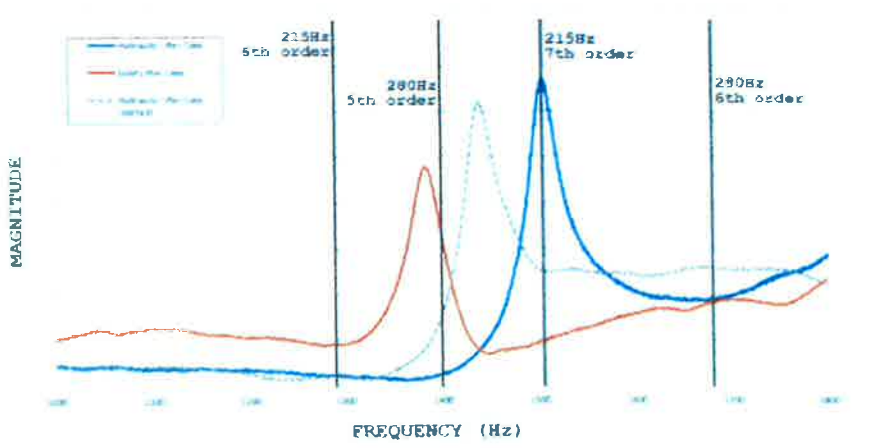

Fig. 4 *- Spectral Diagram of crankcase resonances.*
Red = Solid Lifter, Blue = Original Hydraulic Lifter, Dotted = Current "Slotted" Hydraulic Lifter