ACCIDENT

Aircraft Type and Registration:	Reims Cessna FRA150M, G-BDNR
No & Type of Engines:	1 Rolls Royce O-240-E piston engine
Year of Manufacture:	1976 (Serial no: 284)
Date & Time (UTC):	1 August 2021 at 1426 hrs
Location:	Approx 4 miles NNE of Retford Gamston Airport, Nottinghamshire
Type of Flight:	Training
Persons on Board:	Crew - 1 Passengers - 1
Injuries:	Crew - None Passengers - 1 (Minor)
Nature of Damage:	Nose leg collapsed, prop bent and engine cowling damaged. Subsequent engineering inspection found number 3 cylinder and piston had detached in flight
Commander's Licence:	Commercial Pilot's Licence
Commander's Age:	21 years
Commander's Flying Experience:	534 hours (of which 300 were on type) Last 90 days - 223 hours Last 28 days - 59 hours
Information Source:	AAIB Field Investigation

Synopsis

The number 3 cylinder and piston broke free from the engine causing engine failure during flight. A forced landing was carried out in a field resulting in significant damage to the aircraft but only minor injury to the passenger.

Examination of the engine crankcase found that the number 3 cylinder's base studs had all failed in fatigue due to crack progression. When cylinder studs were replaced with new items on other engines of this type during overhaul or maintenance, some of the studs' threads stripped before the required torque values could be achieved. Analysis revealed that the nuts used to fasten the cylinders were distorting and stripping the threads of the studs before reaching their required torque value or were failing at values just above the published maximum, leaving only a small safety margin. The investigation revealed that there was a mismatch of tensile strength between the nuts and studs.

Safety actions have been taken by the Type Certificate Holder to introduce a Service Bulletin to replace cylinder base studs during RR O-240 engine overhaul and carry out repetitive torque checks following their replacement. The cylinder base studs will be replaced with compatible alternative base studs which achieve consistent torque values above the maximum stated within the engine manuals.

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History of the flight

On the return leg from a training flight to the Humber Bridge, the aircraft's engine started to "run 'rough" around 5 nm from Retford Gamston Airport (Gamston). A carburettor heat check was carried out at which point the pilot noticed that part of the right engine cowling was protruding outwards. Shortly afterwards, "control of engine power was lost" and the engine stopped. A MAYDAY call was transmitted on Gamston's radio frequency and a forced landing was made in a field 4.5 nm NNE of the airport. The aircraft touched down a quarter of the way into the field, but the aircraft could not be stopped before it hit a hedge at the edge of the field. The aircraft came to rest upside down (Figure1). Both occupants climbed out of the aircraft without assistance, although the passenger had sustained a minor leg injury.

Figure 1

After hitting a hedge, the aircraft came to rest upside down

Aircraft information

The Aircraft Renewal Certificate Part ML[1] was valid until 6 November 2021 and the aircraft's last maintenance check was a 50-hours servicing completed 5 July 2021. There were no faults recorded prior to the accident flight relating to the Rolls Royce (RR) produced O-240 engine fitted to the aircraft.

The aircraft had flown 233 hours since the engine, serial number 40R-079, had been overhauled on 7 October 2020.

Footnote

1 EASA Part ML is a continuing airworthiness standard that dictates which maintenance must be performed on the aircraft and who can certify it.

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Engine manufacturer and Type Certificate Holder

The RR O-240 four-cylinder piston engines were produced approximately 50 years ago before the FAA transferred ownership of the engine Type Certificates to Continental Aerospace Technologies (now the Type Certificate Holder - TCH) on 12 December 1983[2]. The O-240 engine Instructions for Continued Airworthiness (ICAs) and parts catalogue have been maintained at the last revision published by Rolls Royce in 1979. There has been no equivalent engine produced by the TCH in the intervening years.

Engine crankcase examination

During the initial examination of the aircraft, it was evident that the number 3 cylinder and piston had broken free from the crankcase and been ejected through the engine cowling during the flight. They were not recovered.

After removing the engine from the aircraft, examination of the engine crankcase revealed that the six engine cylinder base studs and two crankcase through-studs which attach the number 3 cylinder to the crankcase had failed (Figure 2).

Closer inspection of the fractured ends of the studs revealed crack growth marks and fatigue failures. The engine crankcase was sent for metallurgical and fatigue analysis including comparison to the manufacturer's material specifications. A second engine crankcase, serial number 40R-116, which was unrelated to G-BDNR but with a similar failure mode to cylinder 3 was also sent for comparative analysis.

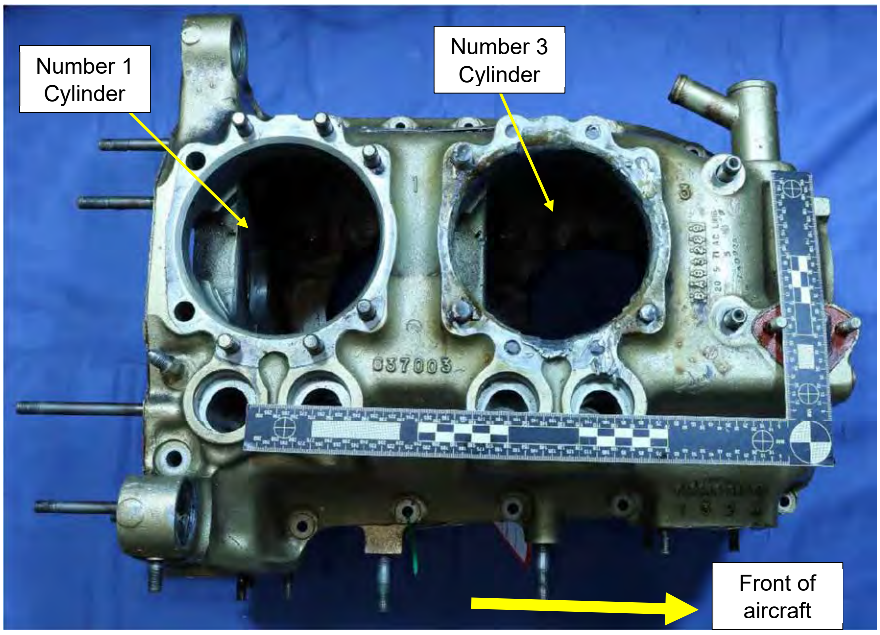

Figure 2

Crankcase right side showing numbers 1 (intact) and 3 (failed) cylinder studs

Footnote

2 Continental Service Bulletin SB00-12A.

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History of engine cylinder stud failures

Research into similar engine failures revealed further accidents where the number 3 cylinder's base studs had failed while the engines were in use:

> Aircraft G-PHUN: cylinder number 3, six base stud failures on engine serial number 40R-356 after 1,074 hours in service. The engine was overhauled on 16 May 2015. The engine was replaced with an overhauled unit.
>
> Aircraft G-BDNR: cylinder number 3, six base studs plus two through studs had failed on engine serial number 40R-079 after 233 hours in service. The engine was overhauled on 7 October 2020. The crankcase was beyond economical repair.
>
> Aircraft G-BDRD: cylinder number 3, six base studs and two through studs failed on engine serial number 40R-116 after approximately 900 hours since overhaul. The engine crankcase was beyond economical repair.
>
> Aircraft G-BBEO: cylinder number 3, one cylinder base stud failed on engine serial number 40R-373 after 1,734 hours in service. The engine was overhauled on 19 December 2014. The failed stud was replaced.
>
> Aircraft G-PPFS: cylinder number 3, one cylinder base stud failed on engine serial number 40R-347 after 1,214 hours in service. The engine had been overhauled on 16 July 2018. The base studs were replaced with studs from a new batch shortly after the accident to G-BDNR revealed legacy stud failures. When a 50-hours check was carried out, the lower front base stud on cylinder number 3 had sheared off and two of the front upper base studs had stretched and lost torque. Further examination found that the threads had deformed on the two upper studs.

Replacement stud issues

Following this accident and during the overhaul of an unrelated engine, the overhaul company decided to replace all the engine cylinder base studs with new studs and nuts 'on-spec'. When the engine cylinders were re-installed and the nuts on the studs torqued to between 34 and 36 ft/lbs in accordance with the engine overhaul manual, some of the studs failed before achieving the required torque. The threads on the studs appeared to have stripped during the torque process. The failures occurred despite using the manufacturer's supplied studs and nuts which were sourced from different batches and from various suppliers. Samples of the replacement studs were sent with the two damaged crankcases[3] for materials analysis and comparison with some of the legacy studs still installed in the crankcases. The legacy studs that had failed had done so after many hours of use rather than during initial installation.

Footnote

[3] Crankcases 40R-079 and 40R-116.

Further inquiries with two other engine overhaul companies revealed that issues with replacement studs failing during RR O-240 engine rebuilds was not uncommon. The cylinder base studs and nuts had simply been replaced and no action was taken to determine the cause.

Fatigue failure analysis of installed studs

For ease of reference, the cylinder 3 crankcase base studs from G-BDNR's engine, 40R-079, were arbitrarily numbered #1 to #8 (Figure 3).

Studs #2, #5 and #6 had failed just above the cylinder mounting face. The remaining studs had failed just beneath the cylinder mounting face. Studs #5 and #6 were through studs to help bolt the two halves of the crankcase together.

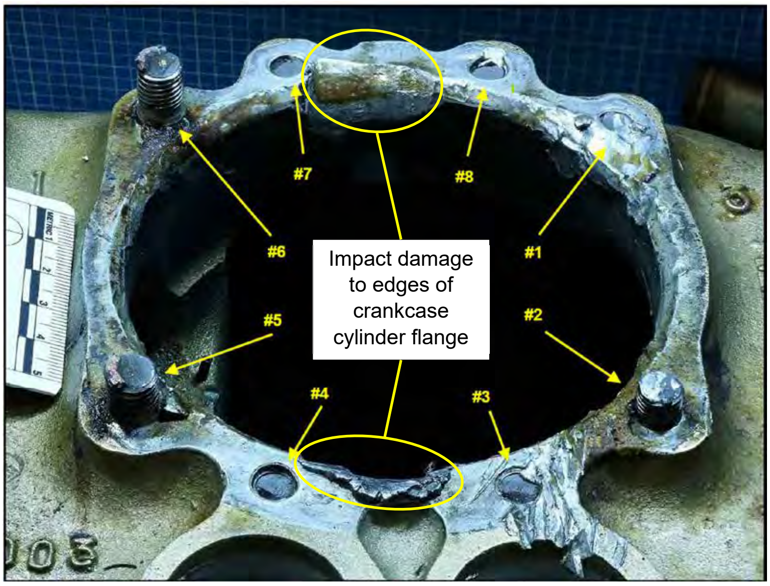

Figure 3

Close inspection of number 3 cylinder mounting surface

Hardness testing

Table 1[4] shows the hardness test results were within the Rockwell Hardness Rating C (HRC) specification (spec).

Some of the six fractured studs fitted to each of the two crankcases achieved hardness test results that were slightly above spec which, due to potential precision bias, would still be deemed acceptable. None of the samples from the three batches of replacement studs were out of spec.

Footnote

4 Through Studs #5 and #6 were not included in the hardness analysis.

	Stud #1	Stud #2	Stud #3	Stud #4	Stud #7	Stud #8
Engine 40R-079	32.1	32.6	30.1	29.1	30.3	31.8
Engine 40R-116	31.5	32.0	33.9	28.7	33.3	32.5
Batch GR063178	31.4	30.5				
Batch GR063924	30.3	29.6				
Batch GR13318	31.6	31.0				

Table 1

Rockwell Hardness Rating stud test results

Material composition testing

Results from material composition testing showed that both the fractured studs in the crankcases and the replacement stud batches were mostly aligned with the manufacturer's spec, with only slight deviations that would not have caused the problems experienced by the overhaul company.

Crankcase stud failure results

Closer views of the in-situ stud fracture surfaces show signs of post fracture damage (Figure 4). Crack progression markings on each of the fracture surfaces appear to show fatigue failures. The directions and extent of stable fatigue crack growth are shown in Figure 5.

On studs #1 and #2, fatigue cracks had propagated across almost the entire stud diameter, with only a small region of static fracture. This was consistent with a relatively low magnitude of stress repeated for a high number of cycles. In comparison, the remaining studs show larger regions of static fracture consistent with a greater magnitude of stress, repeated for fewer cycles. These findings indicate that the fatigue cracks on studs #1 and #2 had initiated first and would have accelerated the remaining stud failures. In each case, the fatigue crack fronts had initiated from multiple sites within the inside edge of the thread roots nearest the cylinder and propagated outwards.

Evidence from the scanning electron microscope revealed that fatigue striations could just be resolved in places around the edges of the studs. Their fine spacing was consistent with a high frequency vibration load spectrum. There was no evidence of corrosion pitting or pre-existing material or mechanical defects associated with crack initiation.

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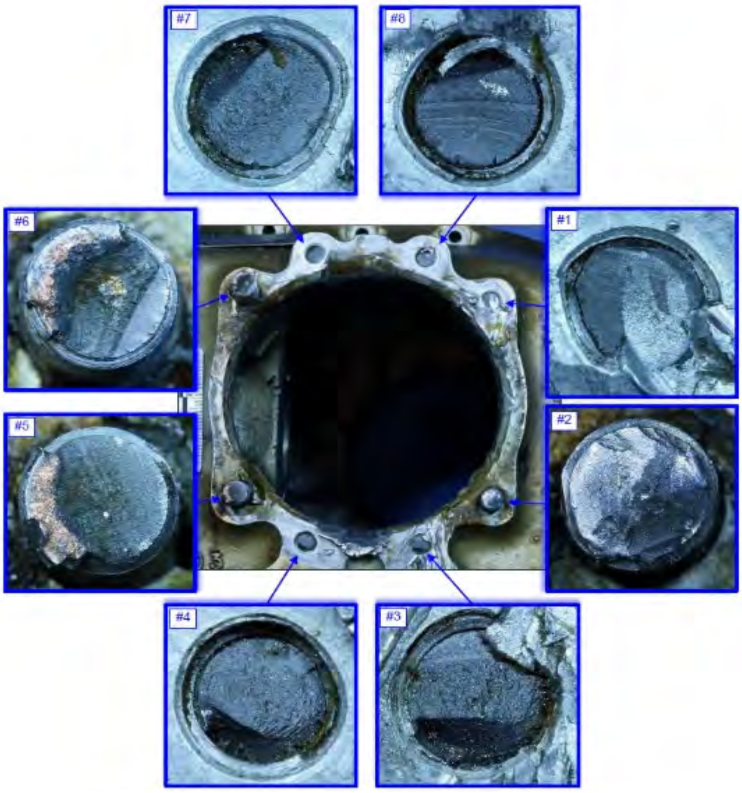

Figure 4

A closer view of the in-situ stud fracture surfaces

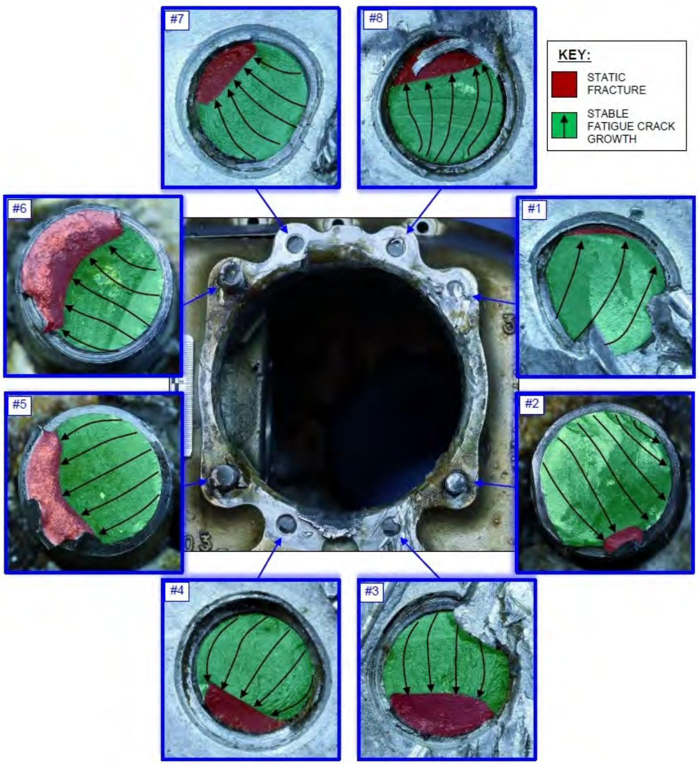

Figure 5

Directions and extent of fatigue crack growth

Failure of replacement studs and nuts

Comparing the results from the materials analysis and hardness testing did not reveal any significant differences between the legacy studs and the new stud samples from the three different batches, potentially ruling out the studs as the cause of the failures. As a result, attention turned to the replacement nuts. A series of torque tests were undertaken using combinations of nuts and studs from the engine TCH and nuts from an alternative engine manufacturer (AM)[5]. As the failure torque was often inconsistent, three studs and nuts were used in each of the 11 tests shown in Table 2 in order to draw statistically meaningful conclusions from the results.

	New Continental Stud (PN 401977)	New AM* Stud (PN 38-13)	Legacy Continental Stud (PN 633181)	High tensile Bolts (With luricant)	High tensile Bolts (Dry, no lubricant)
New Continental Nuts (PN 652421)	36-33-33 Ft/Lbs (T3) Nuts stripped thread	40-40-38 Ft/Lbs (T6) Studs failed in tension	38-37-35 Ft/Lbs (T8) 2 x failed in tension, 1 x stripped	46-48-44 Ft/Lbs (T7) Stud and nut threads stripped	54-50-52 Ft/Lbs (T9) Stud and nut threads stripped
New AM* Nuts (PN 383B)	68-65-60 Ft/Lbs (T5) Studs failed in tension	57-56-56 Ft/Lbs (T1) Studs failed in tension	57-56-56 Ft/Lbs (T2) Studs failed in tension	83+ Ft/Lbs Tensile failure	120-100-110 Ft/Lbs (T10) 2 x Tensile, 1 x thread failures
Legacy Continental Nuts (PN 652421)	38-38-42 Ft/Lbs (T4) Nuts stripped thread				

*Alternative Manufacturer

Torque values in O-240 engine overhaul manual for the cylinders are 34 - 36 Ft/Lbs.

The three numbers represent torque values from the results of 3 samples per test.

NB: T1 - T10 indicates test sequence, ie Test 1, Test 2 etc.

Note, all studs lubricated iaw Continental Manual except High tensile bolts (Dry, no lubricant).

All lubrication iaw Continental's Standard Practices Maintenance Manual M-0 which differs from the Engine Overhaul Manual (no lubrication).

Table 2

Torque test results using different combinations of nuts and studs

To eliminate the studs as a factor in the investigation, high tensile steel bolts were used in place of the studs on four of the tests to determine what effect the nuts had on the bolts when torqued to failure. The results showed a marked difference between the TCH nuts and the AM nuts. In addition, there was a difference in failure torque depending on the application of lubrication.

In general, the TCH supplied nuts and studs either failed at or below the required maximum 36 ft/lbs torque value in the engine overhaul manual, or at a maximum value of 40 ft/lbs (11% above the maximum torque value). By contrast, the AM nuts failed at a minimum of 56 ft/lbs, 55% above the 36 ft/lbs maximum torque value. The tests were carried out with all studs lubricated except in tests 9 and 10 (T9 and T10).

Footnote

[5] Note that the AM nuts were not approved by the TCH for use on the RR O-240 engine – as they had similar dimensions to the TCH nuts they were used for comparison purposes.

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Thread damage

Studs

Closer examination of the threaded and damaged sections of the studs revealed that the threads had been stripped. The crests of the threads appeared to have been progressively fractured by the nut as it was torqued, and the fractured crests pushed into the thread roots. This created a flat region around the circumference of the stud causing the nut to lose torque. There was also some evidence of stripped spiral thread material which could be remains from the nut thread (Figure 6).

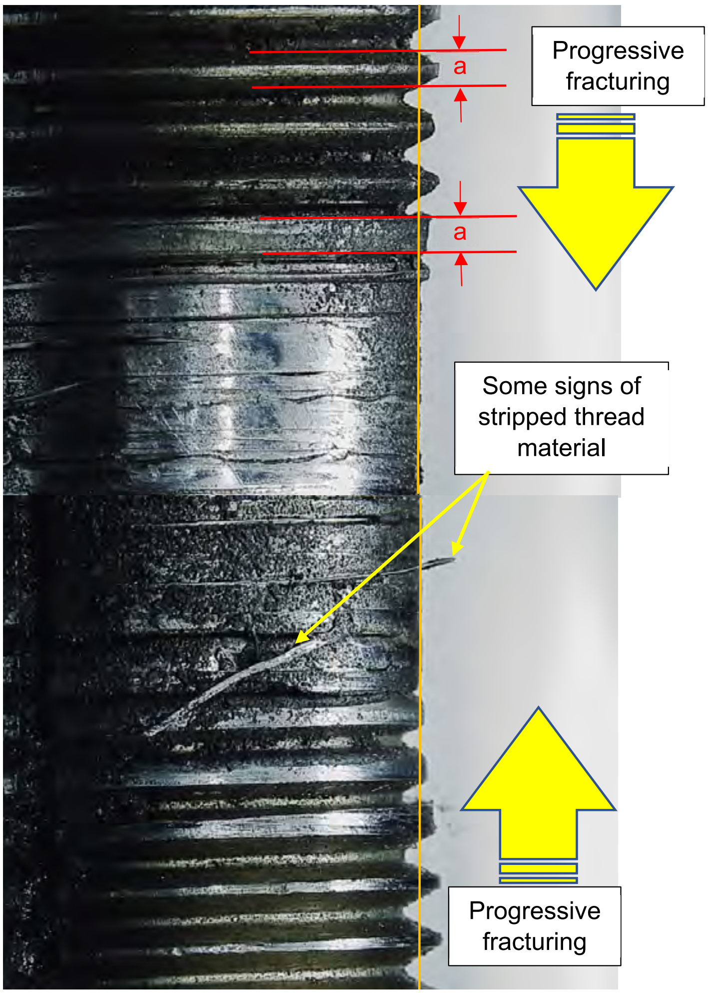

Figure 6

Test 3 - Stud with progressively fractured thread crests (a) and flattened section to half the depth of the intact threads

Nut design

Two types of TCH nuts were used during the tests; one of the samples from Test 3 used a nut employing Spiralock[6] technology (Figure 7) where a 30° ramp had been manufactured between the thread roots which was designed to resist loosening (See Spiralock section below).

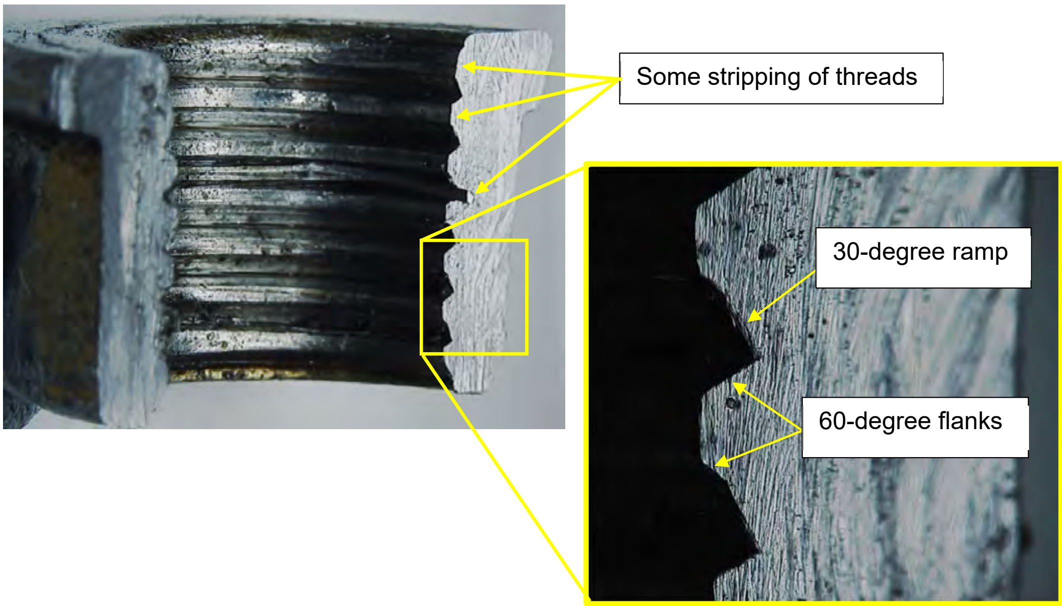

Figure 7

Test 3 - Section of Continental Spiralock nut showing stripped threads (left) and 30° Spiralock ramp (right)

Test 4 used legacy nuts from an old RR O-240 engine which had a standard 60° thread profile (Figure 8). All TCH nut types tested resulted in similar stud failures when torqued.

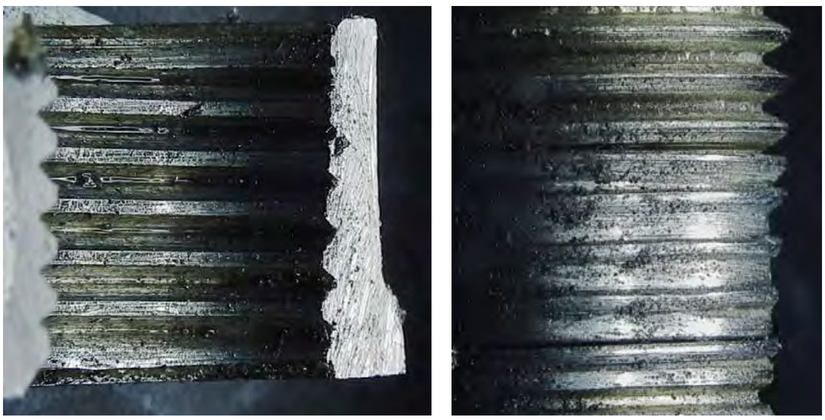

Figure 8

Test 4 - Section of Continental legacy nut showing some thread stripping (left) and distorted threads on the associated stud (right)

Footnote

6 Spiralock is a registered Trademark.

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Spiralock technology

During the tests of the different combinations of nuts and studs in Table 2, it was noted that the majority of the new TCH nuts were stamped with the letters 'SPL,' indicating that they employed Spiralock[7] technology. Spiralock is an anti-vibration technology which uses a 30° wedge ramp at the root of internal threads (Figure 9).

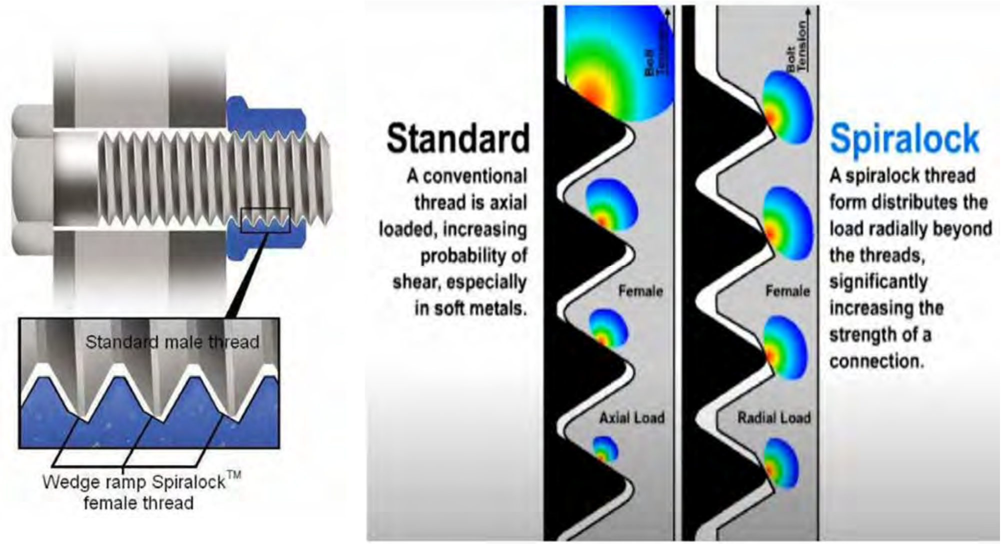

Figure 9

Spiralock anti-vibration thread
Images used with permission

When the clamp load is applied to the nut thread, the crest of the bolt thread is drawn tightly against the wedge giving a continuous spiral line of contact along the length of the engaged threads.

As the clamp load increases, the wedge eliminates the radial clearance that allows fasteners to loosen under vibration. This spreads the clamp load more evenly and allows a lower torque requirement than conventional threads.

The ramp profile at the root of the threads changes the load path on the in-contact thread from an axial direction, which increases the probability of shearing, to a radial load on the crest of the threads. This is designed to eliminate the requirement for secondary locking devices and to allow repeated use of the nuts. The AM nuts used conventional 0.375-24 UNF[8] threads.

Footnote

7 https://www.stanleyengineeredfastening.com/en/brands/optia/spiralock [accessed 12 February 2023].
8 0.375 inches or 3/8 of an inch width - 24 threads per inch Unified Fine Thread (UNF).

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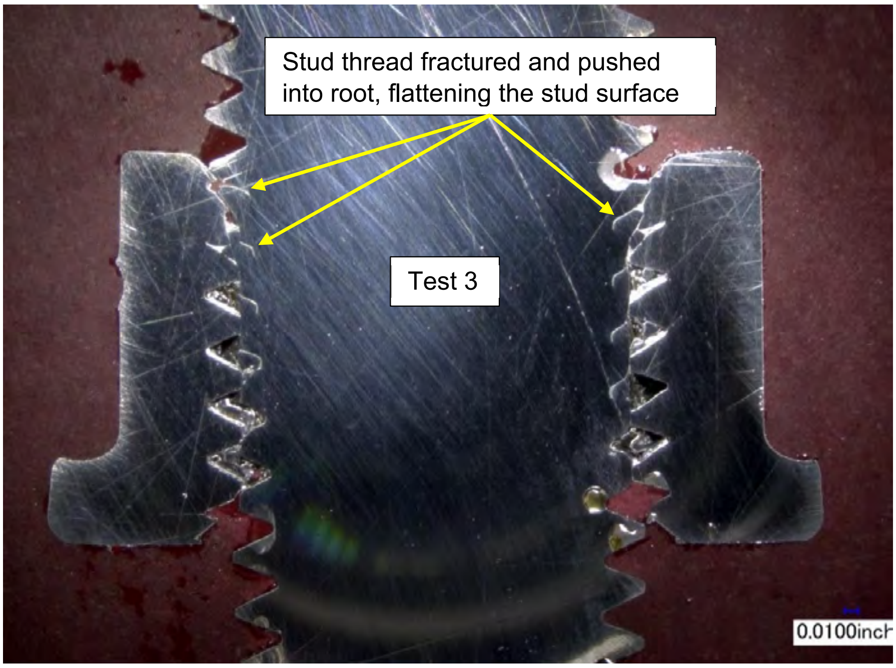
Test results from the manufacturer



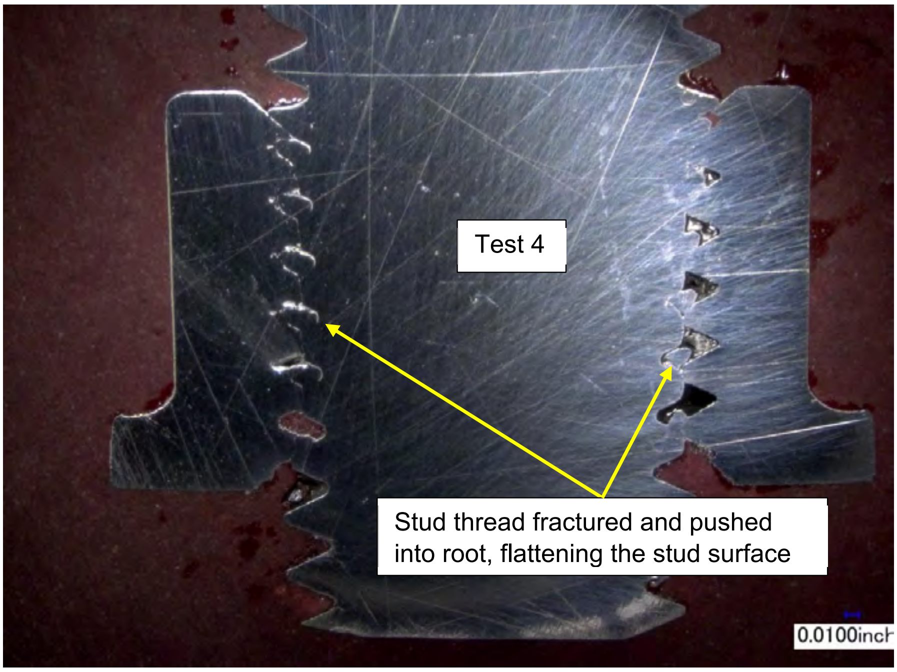


Figure 10

Sectioned samples from Tests 3 and 4 showing failure mechanism
Images used with permission

The manufacturer sectioned and examined some of the failed nuts and studs from Table 2 (Test samples 3 and 4), and the results can be seen in Figure 10. They show the stud threads had been damaged by the nuts in both samples. The broken thread crowns were pushed into their roots creating a flat section around the stud's circumference which caused the nuts to lose torque. Note both samples sectioned had not used Spiralock nuts.

Figure 11 shows that the crowns of the nut threads do not appear to extend fully into the roots of the stud. As a result, only approximately half the flank of the nut threads is in contact with the flanks of the stud threads. With only half the flanks in contact, the shear load is effectively increased which may have contributed significantly to the thread stripping. In addition, it is possible that with nut threads that fully engage with the stud thread flanks, the stud is more likely to fail in tension at high torque values than to strip the threads, as observed when the AM nuts were used.

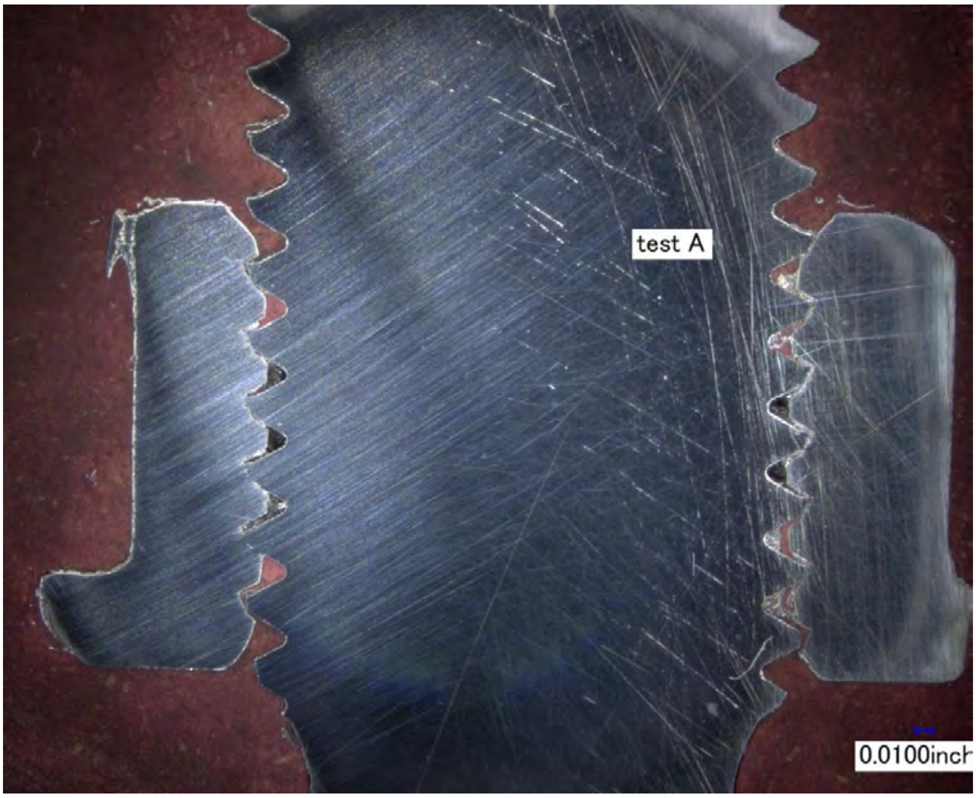


Figure 11

AM stud with matching tensile strength to Spiralock nut
Image used with permission

The manufacturer found that the base nuts had a higher tensile strength of 180 Ksi[9] than the studs, 140 Ksi. This mismatch of tensile strength allowed the nuts to fracture the crown of the stud threads creating a flat surface around the circumference, which probably contributed significantly to the torque failures. When an AM stud was used with a matching tensile strength to the nut, the nut torqued up to 55 ft/lbs before failure, 53% above the maximum torque value (Figure 11).

In this example, the nut threads do not extend fully into the roots of the stud threads which increases the axial shear forces for a given surface area of thread contact.

Footnote

9 Ksi – Thousands of pounds per square inch.

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Alternative cylinder base studs for RR O-240 engines

The TCH proposed the introduction of new base studs that more closely matched the tensile strength of the current cylinder base nuts. They stated that the new studs should be more resistant to thread stripping and have higher failure torque values. The replacement studs part numbers were 643651-1 for RR O-240 engines serial numbers 40R-200 onwards, and 643651-2 for engine serial numbers 40R-001 to 199. The test results in Tables 3 and 4 show that all the proposed replacement studs tested achieved the maximum torque value detailed in the respective engine overhaul manual and, when torqued to failure, they failed in tension with no thread stripping. Table 3 shows the results from the first batch of testing, Table 4 the second batch with each series of tests taking place at different workshops. A slight change was made to the torque technique for the second batch in Table 4 with the nuts slackened between incremental torque increases until failure.

	Continental Nut (PN 652421)							
	T1*		T2*		T3**		T4**	
Proposed New Continental Stud - Long (PN 643651-1)	Achieved 36 ft/lbs Y	Failure torque? 38 Ft/lbs	Achieved 36 ft/lbs Y	Failure torque? 37 Ft/lbs	Achieved 36 ft/lbs Y	Failure torque? 37 Ft/lbs	Achieved 36 ft/lbs Y	Failure torque? 37 Ft/lbs
Failure mode?	Tension		Tension		Tension		Tension	
Proposed new Coninental Stud - Short (PN 643651-2)	Achieved 36 ft/lbs Y	Failure torque? 44 Ft/lbs	Achieved 36 ft/lbs Y	Failure torque? 42 Ft/lbs	Achieved 36 ft/lbs Y	Failure torque? 54 Ft/lbs	Achieved 36 ft/lbs Y	Failure torque? 52 Ft/lbs
Failure mode?	Tension		Tension		Tension		Tension	

*Batch of Nuts supplied by Air Parts ** Batch of Nuts supplied by Multiflight

Torque values in O-240 engine overhaul manual for the cylinders are 34 - 36 Ft/Lbs.
NB: T1 - 5 indicates test sequence, ie Test 1, Test 2 etc.
Note, all studs lubricated iaw Continental Standard Practices Manual M-0.

Table 3

Torque test batch 1 results using proposed replacement studs

	Continental Nut (PN 652421)									
	T1		T2*		T3*		T4*			
Proposed New Continental Stud - Long (PN 643651-1)	Achieved 36 ft/lbs Y	Failure torque? 44	Achieved 36 ft/lbs Y	Failure torque? 56	Achieved 36 ft/lbs Y	Failure torque? 48	Achieved 36 ft/lbs Y	Failure torque? 47		
Failure mode?	Tension		Tension		Tension		Tension		T5	
Proposed new Coninental Stud - Short (PN 643651-2)	Achieved 36 ft/lbs Y	Failure torque? 52	Achieved 36 ft/lbs Y	Failure torque? 48	Achieved 36 ft/lbs Y	Failure torque? 51	Achieved 36 ft/lbs Y	Failure torque? 48	Achieved 36 ft/lbs Y	Failure torque? 51
Failure mode?	Tension		Tension		Tension		Tension		Tension	

*After T1, nuts slackened between each incremental increase in torque.

Torque values in O-240 engine overhaul manual for the cylinders are 34 - 36 Ft/Lbs.
NB: T1 - 5 indicates test sequence, ie Test 1, Test 2 etc.
Note, all studs lubricated iaw Continental Standard Practices Manual M-0.

Table 4

Torque test batch 2 results

Analysis

Fatigue failures

Metallurgical analysis revealed that the installed studs in the two RR O-240 engine crankcases had failed due to crack progression in high cycle fatigue. There was no evidence of corrosion pitting or pre-existing mechanical defects. As the nuts and studs fitted to the RR O-240 engine cylinders are not tracked items, it was not possible to determine when they had been replaced or their operational life.

The result of these high cycle fatigue failures was that two RR O-240 engines failed in flight leading to forced landings and exposing the pilots and passengers to significant safety hazards. Both aircraft were substantially damaged and both engines were beyond economical repair. As there was no way to determine how long engine cylinder base studs and nuts had been fitted to these engines when they failed, the engine studs and nuts should be replaced. Therefore, the following Safety Actions have been taken by the manufacturer:

Safety action taken

> The Type Certificate Holder will issue a Service Bulletin to replace engine cylinder base studs for the RR O-240 engine series during their next overhaul.
>
> The Type Certificate Holder will issue a Service Bulletin to introduce a repetitive torque check of engine cylinder base nuts following engine overhaul or replacement of any of the RR O-240 engine series cylinder base studs or nuts

Failure of replacement studs

When all the cylinder base studs were replaced with current TCH studs on the engine fitted to G-PFFS, one stud failed, two studs stretched and their respective nuts were found to have lost torque after only 50 engine running hours.

Noting the failure modes of the studs in Table 2, those fitted with AM nuts failed in tension once their maximum torque value was reached and provided a good margin of safety. The current TCH nuts with Spiralock technology did cause stud failure at slightly higher torque values, (close to the recommended values in the engine overhaul manual). Although the failure torque of the studs was inconsistent, when the TCH nuts did achieve their recommended maximum torque value, the margin before failure was no more than 11%.

The TCH's analysis found there was a tensile strength mismatch between the current replacement cylinder base studs and nuts. The higher tensile strength nuts stripped the threads of some studs during installation which resulted in a loss of torque. Two potential alternative cylinder base studs were tested which had closely matching tensile strength with the current nuts. The results resolved the issue of thread stripping, and failure torque values were above the maximum stated in the respective engine overhaul manuals.

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As the cylinder base studs needed to be replaced due to the potential fatigue failure risk, the mismatch between the studs and nuts could be resolved by introducing compatible higher tensile studs already in use on other engine types. Accordingly, the TCH decided that standardising production components by replacing the studs was the best solution for the RR O-240 engine series. Therefore, the following Safety Action has been taken by the TCH:

Safety action taken

> The Type Certificate Holder will issue a Service Bulletin to replace the current cylinder base studs in RR O-204 engines, with studs which achieve consistent torque values above the maximum stated in their engine manuals when using the current nuts.

Conclusions

Multiple failures of cylinder base studs on the RR O-240 engine type have been recorded since 2014, but unless they resulted in engine failure in flight, they were not reported to the manufacturer. Two of the three RR O-240 engine failures listed in this report resulted in in-flight failures but in all three cases, the stud failures were caused by crack progression in high cycle fatigue.

Some engine maintenance workshops had been aware that new, replacement studs could fail during initial installation. These occurrences were not reportable and the studs were simply replaced. When new studs were tested, some of them would not achieve their required torque values, and those that did failed at values just above the maximum stated in their respective engine overhaul and maintenance manuals. Further testing and analysis revealed that the nuts were causing the threads of the studs to strip.

Safety actions have been taken by the manufacturer to introduce a Service Bulletin to replace cylinder base studs during RR O-240 engine overhaul and carry out repetitive torque checks following their replacement. Suitable alternative base studs have been identified which achieve consistent torque values above the maximum stated in the engine manuals.

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