ENGINEERED SYSTEM FAILURE ANALYSIS REPORT

A947-1 FLEXPLATE FRACTURE
FORWARD FLEXIBLE COUPLING MAIN ROTOR DRIVE-TRAIN
ROBINSON R22, VH-MIB
Occurrence 200401917

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A Robinson R22 helicopter, VH-MIB, was involved in a fatal accident on 30 May 2004 when control was lost during low level flight.

Examination of the wreckage at the site of the accident revealed that the tail rotor blades had fractured during operation. The airfoil section of one tail rotor blade was found close to the wreckage of the helicopter. In contrast, the airfoil section of the other blade was not located during the examination of the wreckage site and search of the surrounding bush by ATSB investigators. The remnant of the blade was found subsequently, approximately 70 m from the wreckage site. Analysis of the tail rotor blade fractures and other physical evidence present on the blades established that blade fracture occurred as the result of contact with the ground, while the blades were rotating, and parts of the tail rotor structure.

Examination of the wreckage also revealed that one arm of the main rotor drivetrain forward flexplate had fractured during operation. The fracture of the flexplate allowed the drive shaft to be displaced laterally and the flexible coupling to flail against the surrounding structure.

Analysis of the flexible coupling failure established that fatigue cracking in the flexplate arm at the bolted joint between the flexplate and main rotor gearbox yoke resulted from a lack of clamping force between the members of the bolted joint – flexplate, bolt, nut, washers, and yoke. The lack of clamping force resulted in disbonding of the two adhesively bonded reinforcing washers at the bolthole and fretting wear on the surface of the flexplate bolthole. The combination of the loss of structural reinforcement, through the disbonding of reinforcing washers, and bolthole wear damage led to fatigue crack initiation, fatigue crack growth, and flexplate final fracture.

Effective joint clamping is normally achieved by applying a specified torque to the nut installed on each bolt in the flexible coupling. Bolted joint looseness or lack of clamping is not, however, a simple case of not applying the specified torque. An additional level of complexity in the assembly of the bolted joint is created by the designed provision of longitudinal adjustment of the drive-sheave/clutch assembly. Longitudinal adjustment is achieved by adding or removing spacer washers between the drive shaft yokes and flexplate. Adding or removing spacer washers has the effect of changing the thickness of the bolted joint. Variation in joint thickness requires the selection of a bolt of the correct length and washers of the correct thickness to ensure adequate clearance between the nut thread and bolt thread run-out, and sufficient exposed bolt threads to allow the installation of the secondary locking nut (palnut).

It is apparent that the looseness in the bolted joint at the flexplate failure location is due to a mismatch between joint thickness (single thin washers under the bolt head and nut, and no spacer washer between the yoke and flexplate), bolt grip length, and nut position. Tightening to achieve effective clamping would have required the nut to be advanced along the bolt thread to a position which exceeded the specified thread run-out clearance.
Examination of contact marks on the bolt thread created during nut tightening indicated that the nut, installed on the bolt at the flexplate failure location, had not been advanced any further along the nut thread than its recovered position.

There were differences between the selection of washer thickness and placement in the bolted joint at the failure location (NAS -6 bolt) and the remaining two intact bolted joints in the flexible coupling (NAS -6 bolt), the standard practice of washer selection during factory assembly using a NAS -6 bolt, and the manufacturer’s assembly records for the helicopter (ship s/n 3357M):

- The remaining two intact bolted joints differed from the bolt at the failure location by the inclusion of two thin washers under the nut instead of one
- An independent review of flexible coupling assembly practices revealed that, in cases of the absence of a spacer washer a thick washer is included under the nut when a NAS -6 bolt is used
- A review of the manufacturer’s build-sheets for the forward flexible coupling (ship s/n 3357M) revealed that NAS -6 bolts were used and a spacer washer had been included in each bolted joint and one thin washer had been installed under the nut.

These differences indicate that it is likely that the joint had been disassembled and reassembled at some time after initial assembly in the factory.

The forward flexible coupling is a critical assembly in the main rotor drivetrain. Failure of the coupling creates a direct threat to safe operation. Safe operation is achieved by implementing a comprehensive fracture control plan which is based on limiting stress levels in components, defining assembly procedures, requiring inspections at specified intervals, and replacing components after a prescribed period of operation. The initiation of fatigue cracking at a flexplate bolthole, and its growth to final fracture, represents a failure of the flexplate fracture control plan.
INTRODUCTION

A Robinson R22 helicopter, VH-MIB, ship s/n3357M, was involved in a fatal accident on 30 May 2004 as a result of loss of control during low level flight. The helicopter was engaged in a survey of pastoral property fence lines at the time of the accident.

Examination of the wreckage at the site of the accident revealed that the tail rotor blades had fractured during operation. The airfoil section of one tail rotor blade was found close to the wreckage of the helicopter. In contrast, the airfoil section of the other blade was not located during the examination of the wreckage site and search of the surrounding bush by Investigators. The remnant of the blade was found subsequently, approximately 70 m from the wreckage site.

In addition, the flexplate in the forward flexible coupling of the main rotor drive train was found fractured at one of the two attachment points to main rotor gearbox yoke.

The tail rotor blades and the remnants of the main rotor drive train were recovered for detailed analysis in order to resolve the mechanisms of fracture and the sequence of failure.
2 EVIDENCE

2.1 Reported evidence
The survivor of the accident (the passenger) recalled that a loud bang was heard while the helicopter was turned to gain a closer look at a section of fencing. After the bang, the helicopter began to rotate quickly and then collided with the ground.

2.2 Physical Evidence
The main rotor drive train, engine and the helicopter cabin were affected by a post-impact fire. The intensity of the fire was such that aluminium components of the drivetrain, such as the clutch sheave, had melted. The nuts installed on several fasteners had split longitudinally due to the effects of the fire. The end of the tail rotor boom, complete with the tail rotor gearbox and remnants of the tail rotor blades was unaffected by fire.

2.2.1 Forward Flex Plate
Power to drive the main and tail rotors is transmitted from the engine to the rotor drive train through a Vee belt drive system. An outline of the drive system is shown, schematically, in figure 1.

Flexible couplings are located at the input to the main rotor gearbox (also known as the “forward” flexible coupling) and at both ends of the tail rotor drive shaft. The flexible coupling at the forward end of the tail rotor drive shaft is commonly known as the “intermediate” flexible coupling. The flexible couplings in the R 22 drive train accommodate differences in drive shaft axial alignment during helicopter operation. They are constructed by bolting a single, four-armed, thin stainless plate between the main rotor gearbox yoke and the drive shaft yoke. A composite photograph showing the components of the forward flexible coupling is shown in figure 2.
Figure 1: An outline of the main and tail rotor drive system

Figure 2: The components of the forward flexible coupling

This figure is an assemblage of photographs of the individual components of a forward flexible coupling.
The forward flexplate had fractured at one of the boltholes provided to attach the flexible coupling to the main rotor gearbox yoke. Flexplate fracture resulted in the lateral displacement of the forward end of the drive shaft, see figures 3 to 5.

**Figure 3: Main rotor gearbox drive components in the wreckage of VH-MIB**

a) Note that the flexplate remained attached to the yoke by one bolt
Figure 4: Components of the forward flexible coupling, VH-MIB

Figure 5: Forward face of the flexplate, forward flexible coupling, VH-MIB
Classification of fracture mechanism

The fracture surface features are consistent with incremental crack growth, in response to local alternating stresses – fatigue. The fracture surface features are shown in figure 6.

Fatigue cracking initiated first at the side of the bolt hole, closest to the outer edge of the flexplate, from a region of localised wear damage. Crack growth extended toward the outer edge of the flexplate more rapidly along the forward surface of the plate. The plane of crack growth displayed a distinct curvature towards the rear surface of the plate.

Following crack growth through the outer ligament of the plate, fatigue cracking initiated at the opposite side of the bolt hole, with crack growth progressing down the arm of the flexplate.

**Figure 6: Flexplate fracture surfaces**

a) The curvature of plane of crack growth extending from the outer side of the hole and the region of wear damage at the surface of the hole (arrowed) are evident in this photograph

b) Fatigue progression marks can be seen in the region near the end of the fatigue crack (arrowed)
Final fracture and disconnection from the main rotor gearbox yoke occurred by net section yielding as crack growth from the inner surface of the bolt hole neared the edge of the flexplate arm, see figure 7. The rate of fatigue crack growth could not be determined with certainty, however, the general features of the fatigue fracture surfaces indicate that crack growth was slow and occurred over the period of more than a few flights.

A composite photograph showing the location and orientation of the fatigue fracture paths is shown in figure 8.

**Figure 7: Region of final fracture**

The region of final fracture through net section yielding is arrowed

**Figure 8: Schematic showing the location and orientation of the fracture paths**

The fracture paths were traced from the flexplate recovered from VH-MIB and superimposed on an intact flexplate
No crack growth or wear damage was observed at the three remaining boltholes.

2.3 Intermediate Flex Plate

The intermediate flexible coupling was found intact but extensively deformed, see figure 9.

**Figure 9: Comparison between an intact intermediate flexplate and the intermediate flexplate recovered from VH-MIB**

a) Intact intermediate flexplate and clutch assembly

b) The intermediate flexplate recovered from VH-MIB
2.4 **Tail Rotor Blades**

Both tail rotor blades had fractured in the region where the blade structure joins the blade root fitting. Both blades displayed extensive trailing edge buckling at this location indicating that each blade had been subjected to a rearward, in-plane, bending load. Blade fracture followed the buckling of the blades.

The leading edge of both blades had been deformed locally by contact with unidentified bodies or structure.

*Figure 10: Views of the tail rotor at the accident site*

The inset shows an intact R22 tail rotor for comparison purposes.
One tail rotor blade (s/n 12609E) was found in close proximity to the helicopter wreckage, see figure 11. The leading edge of this blade had been damaged at its midspan location, see figures 12 and 13. The other tail rotor blade (s/n 12601E) was found subsequently, approximately 70 m from the wreckage site. The leading edge of this blade had been damaged near the blade tip, see figures 14 and 15.

In addition, both blades exhibited tip abrasion from ground contact. Small fragments of rocky material were found embedded in the abrasions.

**Figure 11: Tail rotor blade found close to the helicopter wreckage, s/n 12609E**
Figure 12: Blade s/n 12609E
Figure 13: Blade 12609E, leading edge damage and tip abrasions
Figure 14: Blade s/n 12601E
Figure 15: Blade 12601E, leading edge damage and tip abrasions
2.5 Recorded evidence

Maintenance and flight documentation established that the helicopter had been in service for a total time of 506 hours. The last 100 hourly maintenance actions had been conducted on 12 May 2004, after 476.1 hours total time in service. The maintenance documentation contained an entry that indicated adjustments had been made to the intermediate flexible coupling in the drivetrain on 2 July 2003 after 198.2 hours total time in service – “shimming was adjusted to within limits”.

No data, which would have assisted in the analysis of the flexplate failure, was recorded electronically.
The examination of the main rotor and tail rotor drive components recovered from the helicopter wreckage established that the flexplate in the forward flexible coupling fractured as a result of the propagation of a fatigue crack at one of the bolted connections between the plate and main rotor gearbox yoke. Final fracture of the flexplate occurred during operation and not as a result of the collision with the ground. No crack growth or wear damage was observed at the three remaining bolt holes.

In contrast, the fracture of both tail rotor blades could be attributed to substantial leading edge impact with unknown objects and tip contact with the ground.

### 3.1 Forward Flexplate Fracture Control

The safe operation of the Robinson R22 helicopter depends on maintaining the integrity of the main rotor and tail rotor drive train during each flight. Torque from the engine is transmitted along a single load path to both rotors, no redundant load paths are provided. The flexible coupling in the main rotor drive train is a critical structural feature of the drive train.

The threat of coupling failure to flight safety is managed by flexplate replacement after a prescribed period of time, and correct assembly during manufacture and maintenance.

The coupling is required to have sufficient strength to transmit the torque created during all phases of helicopter operation within the designed operational limits. It is also required to have enough strength to resist the initiation and growth of fatigue cracks under the local alternating stress state created by repeated torque application and repeated flexing of the plate during helicopter operation within the designed operational limits.

In general terms, fatigue cracking occurs in response to an exposure of a loading environment that creates alternating local stresses in a component. Crack initiation is dependent on the number and magnitude of the local alternating stress cycles. There is an inverse relationship between stress cycle magnitude and number of stress cycles to fatigue failure.

An event tree diagram showing the relationship between events and factors which result in flexplate fracture at one of the connection bolt holes is shown in figure 16.

The threat of fracture from a single load application is controlled by the sizing of components, the selection of materials with sufficient tensile strength and fracture toughness.

The threat of fatigue failure in the case of components subjected to many alternating loading cycles, for the duration of its expected life, is controlled by limiting the magnitude of the local stresses developed at the bolt hole during operation to a value below the fatigue limit for the component. The fatigue limit for a component is a function of alloy strength, surface finish and detailed geometry, and in the case of the flexplate, the presence of bonded reinforcement.
The region surrounding each bolt hole is reinforced by adhesively bonded reinforcing plates. The magnitude of stress created at the edge of the bolt hole during helicopter operation is affected by the presence of the bonded reinforcing plates. Flexplate fracture control depends on limiting the magnitude of the local stresses at the flexplate bolt holes.

**Figure 16: Event tree diagram for flexplate fracture at a bolt hole**
The occurrence of fatigue cracking initiating at a flexplate bolthole represents a failure of the flexplate fracture control plan. For a component subjected to many alternating loading cycles during operation, fatigue fracture represents a failure to limit the magnitude of local alternating stresses at the bolt hole.

The magnitude of local stresses at a flexplate bolt hole is affected by the magnitude of the applied loads or a change in the flexplate structure around the bolt hole. These relationships are shown schematically in figure 17.

**Figure 17: Relationship of factors leading to fatigue crack initiation at a flexplate bolt hole**

The loads applied to the forward flexible coupling are those derived from drive shaft torque and coupling flexure. If the magnitude of the loads applied to the flexible coupling was excessive then flexplate failure may occur at locations other than the bolt holes. If the bolt holes were the critical failure location for excessive loads then damage in the form of crack growth and/or wear damage would be expected at each bolt hole. No crack growth or wear damage was noted at any of the remaining three bolt holes in the flexplate.

The nature of fatigue cracking in the lug surrounding the bolt hole indicates that there has been a change in the structure of the flexplate at this location. It is apparent that the reinforcing plates have become disbonded during helicopter operation. An estimate of the operational time period for disbonding to occur cannot be made from the physical evidence.

The features of crack path curvature across the thickness of the flexplate and more rapid extension of the cracking along the flexplate forward face (figures. 18 and 19) indicate that the local stresses responsible for crack growth were created by out-of-plane flexure of the flexplate within the bolted joint.
If the bolt hole reinforcing plates had remained bonded then the local stiffening of the flexplate provided by the bonded reinforcement would prevent flexure in the immediate vicinity of the bolt hole.

The prevention of movement within the bolted joint, with consequent reinforcing plate disbonding and flexplate fatigue cracking, is dependent on the creation of an adequate clamping force in the bolted joint.

**Figure 18: Schematic showing the orientation of fatigue crack paths with respect to the flexplate geometry**

This schematic was created by tracing the fracture paths on the fractured flexplate and superimposing them on a photograph of an intact flexplate. Fatigue cracking initiated and extended under the reinforcing plates.

**Figure 19: Photomacrograph showing the curvature of the fatigue crack path across the thickness of the flexplate**
4.1 Bolted Joint Assembly Issues

The primary goal in the assembly of bolted joints in the flexible couplings is to create a clamping force that prevents movement between the joint elements.

The requirement to be able to adjust the longitudinal location of the clutch assembly through the incorporation of spacers in the flexible coupling bolted joints creates a degree of complexity in joint assembly through the need to consider bolt grip length, washer thickness and placement.

4.1.1 Bolted joint clamping

The assembly instructions for the flexplate bolted joints require that each of the four bolted assemblies be tightened in accordance with the fastener torque requirements documented in the Robinson Model R22 Maintenance Manual, section 1.300. The 5/16 – 24 bolts used in bolted joints of the forward flexible coupling are required to be tightened by applying 240 in-lb of torque to the nut (this value includes the nut self-locking torque). In addition to tightening of the nut by applying the correct torque value and its designed self-locking qualities, the nut is secured by a secondary locking mechanism in the form of a stamped sheet steel nut (Palnut) tightened against the installed nut. This bolted joint assembly procedure is specified for all critical fasteners. The maintenance manual defines a critical fastener as one which, if removed or lost, would jeopardise the safe operation of the helicopter. The bolts in rotor drivetrain bolted joints are critical fasteners.

The instructions for assembling critical fasteners include a warning that at least two threads up to a maximum of four threads must be exposed beyond the end of the nut to allow the proper installation of the locking Palnut. The warning provides an alert that if more than four threads are exposed the nut may seat against the bolt shank and result in inadequate joint clamping.

4.1.2 Longitudinal adjustment of the clutch assembly

Correct operation of the rotor drive system is dependent on the correct alignment of the engine output sheave and the clutch assembly sheave. The procedures for establishing the longitudinal and lateral alignment of the sheaves in the drive system are detailed in section 7.230 of the Robinson R22 Maintenance Manual.

Lateral alignment is achieved by adjusting the length of the clutch lateral centring strut (a strut attached to the side of the clutch bearing assembly housing. Longitudinal alignment is achieved by adjusting the position of the engine and/or the clutch assembly.

The position of the engine is adjusted by adding or removing shims from each engine mount.

The position of the clutch assembly is adjusted by selecting the length of the yoke at the forward end of the drive shaft. Two sets of attachment holes are provided in the forward yoke to provide different lengths of driveshaft and two variants of the yoke are available with different attachment hole locations – part numbers A907-4 and A907-5. Further, fine, rearward adjustment is achieved by placing spacers (AN960-516L washers) between the forward flexplate (A947-1) and both arms of the forward
drive shaft yoke (A907-4 or 5) and/or the main rotor gear box yoke (A908). Alternatively, forward adjustment is achieved by removing previously installed spacers from between the flexplate and yokes.

The position of the intermediate flexplate is adjusted by including, or removing, spacer washers between the flexplate and yokes in response to changes in the position of the forward yoke and/or the inclusion or removal of spacers in the forward flexplate assembly.

### 4.1.3 Forward Flexplate Bolted joint component specification

A review of the diagrams showing the parts used in the forward flexplate bolted joints contained in the Maintenance Manual and the Illustrated Parts Catalogue (IPC) revealed a difference in the specification of parts in the bolted joints, see table 1.

Notes contained within the IPC explain that bolts of different grip lengths and washers of different thicknesses (half thickness (L) or full thickness) are used in the flexplate bolted joints to expose between two and four threads beyond the end of the nut.

**Table 1: A comparison between Maintenance Manual and Illustrated Parts Catalogue forward flexplate bolted joint component specification**

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Bolt: NAS 1305-5</td>
<td>Bolt: NAS 6605-6</td>
</tr>
<tr>
<td>Washer under bolt head: AN 960-516L</td>
<td>Washer under bolt head: NAS 1149 F0532P</td>
</tr>
<tr>
<td>Spacer washer AN 960-516L</td>
<td>Spacer washer not shown in diagram</td>
</tr>
<tr>
<td>Washer under nut: AN 960-516L</td>
<td>Washer under nut: NAS 1149 F0532P (or NAS 1149F0563P, as required to expose 2 to 4 threads)</td>
</tr>
<tr>
<td>Nut: NAS 679A5</td>
<td>Nut: MS 21042L5</td>
</tr>
<tr>
<td>Additional Locking nut: MS 27151-16 (Palnut)</td>
<td>Additional Locking nut: B330-16 (Palnut)</td>
</tr>
<tr>
<td>Flexplate: p/n A947-1</td>
<td>Flexplate: p/n A947-1</td>
</tr>
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</table>
Research into the designation of bolts, washers and nuts revealed that some of the differences could be explained by the use of superseded part numbers, while other differences were related to bolt length and washer thickness.  

The NAS 13(XX) bolt specification has been superseded by NAS 66(XX). Both specifications define the design and material to be; long thread, alloy steel (160 – 180 ksi tensile strength) Cadmium II plated. NAS 13 refers to a shear bolt while NAS 66 refers to a close tolerance bolt. The remaining three numbers refer to the bolt diameter and grip length (shank of the bolt between the head and start of the thread, the full cylindrical portion of the bolt).

\[ NAS\ 1305-5: \quad 13\ (\text{design\ and\ material}),\ 05\ (\text{diameter\ in\ 1/16\ inch\ increments – 5/16\ inch}),\ -5\ (\text{grip\ length\ in\ 1/16\ inch\ increments – 5/16\ inch}) \]

\[ NAS\ 6605-6: \quad 66\ (\text{design\ and\ material}),\ 05\ (\text{diameter\ in\ 1/16\ inch – 5/16\ inch, 24\ threads\ per\ inch}),\ -6\ (\text{grip\ length\ in\ 1/16\ inch\ increments – 6/16\ or\ 3/8\ inch}).\ \text{The\ thread\ length\ for\ 05\ bolts\ (NAS\ 13\ or\ 66)\ is\ 0.469\ inch.} \]

The AN 960 washer specification has been superseded by the NAS 1149 specification. AN960-516L is equivalent to NAS 1149 F 0532 P.

\[ NAS\ 1149\ F0532P: \quad 1149\ is\ the\ basic\ specification\ number,\ F\ is\ the\ material\ code\ (020\ Carbon\ steel – 55\ ksi\ minimum\ ultimate\ tensile\ strength),\ 05\ is\ the\ size,\ 5/16\ inch,\ 1/16\ inch\ increments,\ 32\ is\ the\ thickness\ in\ thousandths\ of\ an\ inch – 0.032\ inch\ (63\ indicates\ a\ thickness\ of\ 0.063\ inch),\ P\ indicates\ that\ the\ washer\ is\ cadmium\ plated\ per\ QQ-P-416,\ type\ II\ class\ 2\ (gold). \]

The NAS 679A5 locknut specification is equivalent to MS 21042L5. The MS 21042L5 is a stiff nut design manufactured from steel, plated with cadmium type II, coated with ‘black Moly’ and has a rated tensile strength of 160 ksi. Both MS27151-16 and B330-16 are specifications for stamped sheet steel locking nuts, known as Pal nuts.

The relationships between joint thickness, a combination of yoke flexplate, spacer and washers with a 5/16 inch grip length bolt (-5 bolt) and a 6/16 inch grip length bolt (-6 bolt) is summarised in figure 20.

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Figure 20: Schematic showing the relationship between various joint thicknesses and bolt grip length

The NAS 6605-6 bolt shown at the top of the figure was removed from one of the flexplate/drive shaft yoke bolted joints, VH-MIB (the bolt is blackened as a result of fire). The bolt shown at the bottom of the figure is a NAS 6605-5 bolt. The coloured blocks represent the thickness of the bolted joint components.

For bolted assemblies where no spacer is incorporated, the -5 bolt provides the appropriate positioning of the nut, adequate clearance from the thread runout and adequate number of threads to allow secondary locking nut installation, if a thin washer is installed under the nut. The use of a -6 bolt in this situation would require a thick washer under the nut to provide adequate clearance between the nut and thread runout.

For bolted assemblies where a spacer is incorporated the use of a -5 bolt will not provide an adequate number of threads for the installation of the secondary locking nut. In this case the use of the -6 bolt provides adequate clearance between the nut and thread runout and an adequate number of threads for the installation of the secondary locking nut.

4.1.4 Intermediate Flexplate Bolted Joint Component Specification

All four bolts used in the assembly of the intermediate flexible coupling (VH-MIB) were marked, NAS 6604-4. The NAS 6604-4 bolt is the longer of the two bolts (NAS 6604-4 and NAS 6604-3) specified in the Illustrated Parts Catalogue (IPC). A note in the IPC explains that the selection of bolt length is based on the requirement to
expose no more than four threads and no fewer than two threads beyond the end of the nut.

All four bolted joints comprised of:

- NAS 6604-4 bolt
- One thin washer between the bolt head and the flexplate bonded reinforcement
- One thin washer between the flexplate bonded reinforcement and the drive shaft yokes (this washer is the spacer washer)
- One thick washer between the drive yokes and nut
- One stiff nut and one Palnut.

Figure 21: An example of the positioning of washers and spacer washers in the intermediate flexible coupling, VH-MIB
4.2 **Bolted Joint at Flexplate Failure Location**

The bolt installed at the flexplate failure location remained in the main rotor gearbox yoke. The bolt, as recovered from the helicopter wreckage, is shown in figure 21. It is evident, from an examination of the exposed threads and the residues remaining on the threads from the effects of fire, that the nut had not been moved following the accident, see figure 22.

**Figure 22: Bolt at flexplate failure location, as recovered from the wreckage**
The bolt installed at the failure location was a NAS 6605-6 bolt. One thin washer had been installed under the head of the bolt and one thin washer had been installed between the nut and main rotor gear box yoke. No more than four threads were exposed beyond the end of the nut. The nut face remained clear of the bolt thread runout, see figure 23. No secondary locking nut was present. However it is possible that the secondary locking nut was dislodged as the drive shaft flailed about during the failure sequence. Photographs of the wreckage show that the bolt installed in the other arm of the main rotor gear box yoke still had a secondary locking nut fitted. This bolt was not available for analysis.

Figure 23: Threads exposed beyond the end of the nut, four-quadrant view showing the entire circumference of the bolt

Figure 24: Location of the nut face with respect to the bolt thread runout
The two adhesively bonded flexplate reinforcing plates remained on the bolt between the washer under the bolt head and the main rotor gear box yoke. The gap between the two plates was greater than the thickness of the flexplate. The gap was measured by a digital vernier calliper and found to be 0.0855 inch (this measurement was checked by using a feeler gauge). The flexplate thickness is 0.0630 inch.

Examination of the bolt grip length revealed that extensive fretting wear had occurred around the entire circumference of the bolt, in the region adjacent to the flexplate, the regions adjacent to the reinforcing plates, see figures. 24 and 25. Fretting wear was also evident on the washer surface adjacent to the bolt head.

This type and degree of wear damage is indicative of coupling operation with no clamping force in the bolted joint.

**Figure 25: Fretting wear on the bolt grip length**

![Fretting wear images]

- a) region adjacent to the flexplate
- b) region adjacent to reinforcing plate next to the yoke
- c) region adjacent to reinforcing plate near bolt head
- d) washer surface under bolt head
4.2.1 Position of the nut with respect to the bolt thread

The threaded section of the bolt installed at the flexplate failure location was sectioned longitudinally in order to examine the witness marks created between the nut and bolt thread flanks during tightening. These marks can be used to determine how far the nut had been advanced along the bolt thread during assembly.

**Figure 27: Longitudinal sectioning of the nut using a fine diamond saw**
Following sectioning, one half of the nut was removed while the other half was left undisturbed to show the relationship between the nut and bolt threads, see figure 28. It is evident that the nut would have been capable of being advanced, at least, a distance of the thread pitch before interfering with the bolt thread runout. It is also evident that there is no defect in either thread that would have prevented the further advancement of the nut.

**Figure 28: The sectioned nut in the ‘as recovered’ position**

A characteristic feature of the nut thread is the tapered truncation of the leading threads. This feature is evident in figure 28 and is shown in more detail in figure 29. This feature affects the contact area between the nut and bolt threads and provides an indicator of the maximum extent to which the nut had been advanced along the bolt thread during assembly. Detailed observations of the thread contact marks were conducted with light and scanning electron microscopy see figures 30 to 34. Similar
observations were made for a bolt removed from one of the intact bolted joints in the flexible coupling.

Figure 29: Detailed views showing the nature of the nut thread

a) scanning electron micrograph, view from the bearing face of the nut

b) scanning electron micrograph at higher magnification, view of the loaded flanks of the thread (arrowed)
Figure 30: An overview of the threaded region of the bolt at the flexplate failure location examined by scanning electron microscopy for evidence of nut/bolt thread contact.

Scanning electron micrographs at higher magnification, of the regions arrowed, are shown in figures 31 to 34.
Figure 31: Flank of bolt thread loaded as a result of tightening, bolt at flexplate failure location - region 1

This is the first full thread from the thread runout, no nut thread contact marks are evident

Figure 32: Flank of bolt thread loaded as a result of tightening, bolt at flexplate failure location - region 2

Evidence of nut thread contact is present in the band delineated by arrows
Figure 33: Flank of bolt thread loaded as a result of tightening, bolt at flexplate failure location - region 3

Evidence of nut thread contact is present in the band delineated by arrows

Figure 34: Flank of bolt thread loaded as a result of tightening, bolt at flexplate failure location - region 4

Evidence of nut thread contact is present in the band delineated by arrows; note the width of the contact band increases in a manner consistent with the tapering truncation of the nut thread
Figure 35: An overview of the threaded region of a bolt from one of the intact bolted joints in the flexible coupling, examined by scanning electron microscopy for evidence of nut/bolt thread contact

For the purposes of this investigation, this bolt, one of two bolts used to assemble the flexplate to the drive shaft yoke, was identified as bolt 2.

Scanning electron micrographs at higher magnification, of the regions arrowed, are shown in figures 36 to 38.
Figure 36: Flank of bolt thread loaded as a result of tightening, flexplate to drive yoke bolt - region 1

First thread from bolt thread runout, no evidence of nut threat contact is evident

Figure 37: Flank of bolt thread loaded as a result of tightening, flexplate to drive yoke bolt - region 2

Evidence of nut thread contact is present in the band delineated by arrows
Evidence of nut thread contact is present in the band delineated by arrows

The nature of thread contact marks observed on the bolt thread, bolt from an intact joint, was similar to the nature of the marks observed on the bolt thread, bolt at flexplate failure location. The effect of nut thread truncation was evident through the increasing width of the band of contact marks and, significantly, the maximum position of nut advancement was similar, no thread contact was observed on the thread closest to the bolt thread runout.

Removal of the nut from the bolt at the failure location allowed the full extent of fretting wear on the bolt grip length and washers to be observed (figures 39 and 40).
Figure 39: The bolt at the flexplate failure location

The extent of wear around the entire circumference is shown in two photographs, with the bolt rotated 180° between each photograph.

Figure 40: Fretting wear on the washers in contact with the bolt head and nut face
(bolt assembly at the flexplate failure location)

The washer in contact with the bolt head is shown on the left. The washer in contact with the nut face is shown on the right.
4.2.2 Summary

It is apparent that the lack of clamping force in the bolted joint at the flexplate failure location is due to a mismatch between joint thickness, bolt grip length and nut position.

The use of the longer grip length, NAS 6605-6, bolt with a joint assembly that has only thin washers under the bolt head and nut, and no spacer between the flexplate and yoke does not provide adequate clearance between the nut and thread runout if the nut is tightened against the washer. Correct positioning of a tightened nut would require the inclusion of two thin washers or one thick washer between the nut and yoke, see figure 41.

The positioning of the nut on the bolt thread is consistent with the requirement to expose no more than four threads and no less the two threads.

Correct positioning of the nut with respect to the number of exposed threads on a longer grip length bolt (-6), coupled with a joint which has no spacer and has a single thin washer under the bolt head and the nut, will leave a gap in the bolted joint and provide no joint clamping, see figure 41.

**Figure 41: Schematic showing the relationship between joint thickness, bolt grip length and nut position**

The coloured blocks represent the thickness of joint components.
Examination of the two bolted joints between the flexplate and drive shaft yoke revealed that the longer grip length bolt (NAS 6605-6) had been installed. However, a notable difference between these joints and the joint at the failure location was the presence of two thin washers under the nut, see figure 42. No bolt grip length fretting wear had occurred on either bolt. The separation of the bolt hole reinforcing plates in these two locations may be attributed to the effects of post impact fire.

Figure 42: The bolted joints between the flexplate and drive shaft yoke

a) The flexplate attached to the drive shaft yoke, ‘as received’

b) Bolt 1  c) Bolt 2
4.2.3 **Forward flexible coupling factory assembly**

The assembly records for VH-MIB (ship s/n 3357M) reveal that the flexible coupling bolted joints comprised a NAS -6 bolt with thin washers placed under the bolt head and under the nut, and a spacer washer between the flexplate and yokes. This configuration is in accord with the standard build drawings for the forward flexible coupling.

An independent review\(^2\) of the assembly of the forward flexible coupling also revealed that in instances where a spacer washer is not installed a thick washer is placed under the nut to provide the correct joint thickness for the commonly used NAS -6 bolt. Photographs of this joint configuration are shown in figure 43.

**Figure 43: Photographs of a factory assembled forward flexible coupling bolted joint with no spacer washer installed**

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\(^2\) National Transportation Safety Board (NTSB) investigator, ATSB accredited representative
CONCLUSIONS

The fracture of the flexplate was caused by the initiation and growth of a fatigue crack from one of the four boltholes provided to allow the assembly of the forward flexible coupling.

The occurrence of fatigue crack initiation at a flexplate bolthole and subsequent growth to fracture represents a failure of the flexplate fracture control plan. For a component subjected to many alternating loading cycles during operation, fatigue fracture represents a failure to limit the magnitude of local alternating stresses at the bolthole.

Normally, the magnitude of alternating stresses in the vicinity of the bolthole is limited to a level that does not allow fatigue crack initiation by the presence of adhesively bonded reinforcing plates. The nature of fatigue cracking in the lug surrounding the bolt hole, crack path curvature across the thickness of the flexplate and more rapid extension of the cracking along the flexplate forward face, indicates that the adhesively bonded reinforcing plates have become disbonded during helicopter operation, allowing out-of-plane flexure of the flexplate within the bolted joint.

Examination of the bolt installed at the failure location revealed that extensive fretting wear had occurred around the entire circumference of the bolt, in the region adjacent to the flexplate and the regions adjacent to the reinforcing plates. Fretting wear was also evident on the washer surface adjacent to the bolt head. This type and degree of wear damage is indicative of operation with no clamping force in the bolted joint.

It is apparent that the looseness in the bolted joint at the flexplate failure location is due to a mismatch between joint thickness (thin washers under the bolt head and nut, and no spacer washer between the yoke and flexplate), bolt grip length, and nut position. Tightening to achieve effective clamping would have required the nut to be advanced along the bolt thread to a position which exceeded the specified thread run-out clearance.

Examination of contact marks on the bolt thread created during nut tightening indicated that the nut, installed on the bolt at the flexplate failure location, had not been advanced any further along the nut thread than its recovered position.

There were differences between the selection of washer thickness and placement in the bolted joint at the failure location (NAS -6 bolt) and the remaining two intact bolted joints in the flexible coupling (NAS -6 bolt), the standard practice of washer selection during factory assembly using a NAS -6 bolt, and the manufacturer’s assembly records for the helicopter (ship s/n 3357M).

The remaining two intact bolted joints differed from the bolt at the failure location by the inclusion of two thin washers under the nut instead of one.

An independent review of flexible coupling assembly practices revealed that, in cases of the absence of a spacer washer a thick washer is included under the nut when a NAS -6 bolt is used.
A review of the manufacturer’s build-sheets for the forward flexible coupling (ship s/n 3357M) revealed that NAS-6 bolts were used and a spacer washer had been included in each bolted joint and one thin washer had been installed under the nut.

These differences indicate that it is likely that the joint had been disassembled and reassembled at some time after initial assembly in the factory.