

Article

Failure Analysis of a Rear-Sprocket Mounting (Nap Gear) Bolt in a 145 cc Motorcycle

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Abstract.

Rear-sprocket mounting bolts, referred to in this study as nap gear bolts, transmit torque from the rear sprocket assembly to the wheel hub through the damper/bushing interface and may experience repeated transverse shear and bending loads. This study investigates the fracture of a rear-sprocket mounting (nap gear) bolt from a 145 cc motorcycle to determine its material characteristics, fracture mechanism, and mechanical cause of failure. The investigation combined macro-fractographic observation, spark-emission chemical composition testing, optical metallography, Vickers microhardness testing, and finite element analysis of a three-dimensional bolt model. The measured chemistry was consistent with the SAE 1015 low-carbon steel composition range, with 0.137 wt.% C and a ferrite-pearlite microstructure; however, the grade designation is reported as a chemical-consistency assessment rather than a mill-certified material identification. No abnormal microstructural difference or surface-hardening layer was observed between the failed and intact bolts. The hardness values were 179-190 HV0.5 for the failed bolt and 169-183 HV0.5 for the intact bolt. Fractography identified a proposed crack-initiation region, a crack-propagation region with beachmark-like macroscopic features, and a final-fracture region. Finite element analysis predicted a local maximum stress intensity, defined as the difference between the maximum and minimum principal stresses, of 529.6 MPa at the fracture location; the corresponding maximum shear stress was 264.8 MPa. The failure is therefore attributed to fatigue initiated at a stress-concentrated region, while the available evidence does not indicate that material selection or gross metallurgical abnormality was the primary cause.

Keywords: Failure analysis; fatigue fracture; rear-sprocket mounting bolt; low-carbon steel; finite element analysis

INTRODUCTION

Failure analysis is a systematic engineering approach used to identify the physical mechanism and root cause of component damage, and to formulate corrective actions that reduce recurrence. In mechanical components, this approach generally combines service-history review, visual and fractographic examination, chemical composition analysis, metallography, hardness testing, and stress evaluation so that material, manufacturing, assembly, and operating factors can be distinguished objectively [1], [2], [3], [4].

Threaded fasteners are critical elements in machinery and vehicle assemblies because they provide clamping and load-transfer capability while allowing disassembly for maintenance. However, bolted joints are sensitive to preload loss, transverse vibration, friction variation, eccentric loading, hole clearance, and local stress concentration; these factors can promote self-loosening, fretting, cyclic bending, or shear-dominated failure even when the nominal bolt material satisfies its specification [5], [6], [7], [8], [9], [10].

In a motorcycle rear-wheel drivetrain, engine torque is transmitted from the rear sprocket to the wheel hub through rear-sprocket mounting bolts and damper/bushing elements. In this study, the local term nap gear bolt is defined as a rear-sprocket mounting bolt: a torque-coupling fastener located between the sprocket assembly and the wheel hub. The bolt is subjected to repeated acceleration-deceleration cycles, chain-pull fluctuation, road-induced vibration, and occasional impact loading. Under these conditions, fatigue fracture is plausible because cracks can initiate at highly stressed surface locations and propagate progressively before final rapid fracture occurs [11], [12], [13], [14], [15].

A robust diagnosis of bolt fatigue requires correlation between fracture morphology, material condition, and mechanical loading. Crack initiation zones, beachmark-like propagation regions, and final fracture areas are typical macroscopic indicators of fatigue, while metallography and microhardness testing are needed to verify whether abnormal microstructure, surface hardening, heat-treatment inconsistency, or local strengthening differences contributed to the failure [16], [17], [18], [19], [20], [21], [22], [23]. Numerical analysis can further confirm whether the observed fracture location corresponds to the predicted stress concentration under the assumed loading condition [24], [25], [26], [27].

Previous investigations have reported bolt failures caused by fatigue, excessive tightening, preload degradation, stress concentration, corrosion-assisted cracking, and interactions between service loading and material condition in various engineering applications [28], [29], [30], [31], [32], [33]. Nevertheless, documented failure-analysis cases for motorcycle rear-sprocket mounting (nap gear) bolts remain limited, particularly for low-carbon steel bolts

operating as sprocket-to-hub torque-transfer elements. This study therefore aims to determine the failure mechanism of a fractured rear-sprocket mounting (nap gear) bolt from a 145 cc motorcycle by integrating macro-fractography, chemical composition testing, metallography, Vickers microhardness measurement, and finite element analysis.

METHODS

Specimen and Failure-Analysis Procedure

The investigated component was a fractured rear-sprocket mounting (nap gear) bolt from a 145 cc motorcycle. A visually intact bolt from the same rear-sprocket assembly was used as a comparative specimen for metallographic and hardness evaluation. The failure-analysis workflow comprised component identification, visual and macro-fractographic examination, chemical composition testing, metallographic preparation, Vickers microhardness testing, and finite element analysis.

Macro-fractographic observation was performed on the fracture surface at low magnification to identify the fracture origin, crack-growth region, final fracture region, and fracture orientation. Chemical composition was measured using spark atomic emission spectrometry following ASTM E415 for carbon and low-alloy steels [19]. Metallographic specimens were cut from the region near the fracture surface, mounted in resin, ground using abrasive papers up to 2000 grit, polished, and etched following standard metallographic preparation principles [34]. Optical microscopy was then used to compare the failed bolt and the intact reference bolt.

Vickers microhardness testing was performed on the failed and intact bolts using a 4.903 N load (HV0.5) and 15 s dwell time, consistent with the Vickers microindentation hardness testing principle [18]. Six indentations were taken from the diameter center toward the outer surface at an approximate spacing of 0.7 mm.



Figure 1. Failed rear-sprocket mounting (nap gear) bolt and nut used as the failure-analysis specimen.

Finite Element Loading Condition

Finite element analysis was performed using a three-dimensional model of the rear-sprocket mounting (nap gear) bolt. The material was represented by reference mechanical properties for low-carbon steel chemically consistent with SAE 1015. The model was used as a static stress-location assessment rather than a complete bolted-joint simulation. The reference material properties used in the analysis are summarized in Table 1.

Table 1. Reference mechanical properties for low-carbon steel chemically consistent with SAE 1015 used in the finite element model

Property	Value
Tensile strength	385 MPa
Yield strength	325 MPa
Shear modulus	80,000 MPa
Poisson's ratio	0.29
Elastic modulus	205,000 MPa

The input load was obtained from a theoretical torque-transfer calculation for the 145 cc motorcycle drivetrain. The maximum engine torque was transmitted through the first-gear ratio and final drive, resulting in an estimated rear-sprocket torque of 445.498 N m. Using a sprocket moment arm of 0.048 m, the resultant tangential force was 9270 N. Under the nominal analysis assumption of four identical, fully engaged bolts located at the same pitch radius, the force was equally divided among the four bolts, giving 2317.5 N per bolt. This equal-sharing assumption provides a baseline static load case; possible unequal sharing due to clearance, preload variation, damper/bushing degradation, or joint loosening was not included and is considered a limitation of the model.

The three-dimensional model represented the bolt shank and the head-to-shank transition corresponding to the observed fracture location. The nominal shank diameter was approximately 7.0 mm, inferred from the 3.5 mm radial extent of the microhardness traverse. The detailed native FEA project file was not available with the source manuscript; therefore, the exact solver element formulation, mesh size, total element count, and mesh-convergence record cannot be verified from the supplied material and must be completed from the original simulation before resubmission. The hub/nut support was idealized as a fixed boundary over the corresponding contact region, while the 2317.5 N tangential load was applied in the torque-transfer direction. Explicit frictional contact, bolt preload, and clearance were not reported in the original model and should be stated explicitly once verified. The stress output reported in this study is stress intensity, defined as the difference between the maximum and minimum principal stresses ($\sigma_1 - \sigma_3$), and the associated maximum shear stress is one half of this value according to the Tresca relation.

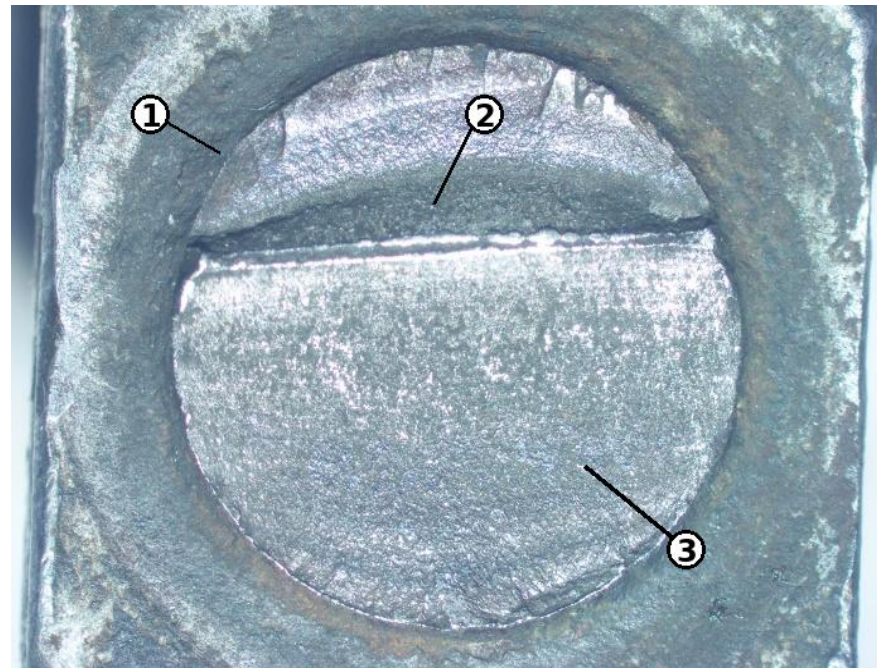
Table 2. Finite element model definition, loading assumptions, and structural acceptance criterion.

Parameter	Model definition / assumption
Model geometry	Bolt shank and head-to-shank transition represented; nominal shank diameter approximately 7.0 mm, inferred from the 3.5 mm radial microhardness traverse.
Element type	exact solid-element formulation used by the solver.
Mesh	global/local mesh size and total element number.
Mesh convergence	report at least three mesh levels and the stress change at the critical region; use a defined convergence threshold.
Material model	Linear-elastic low-carbon steel properties chemically consistent with SAE 1015 (Table 1).
Contact assumption	The original manuscript represented interfaces through load/support surfaces. Confirm whether frictional contact, bolt preload, and clearance were omitted in the native model.
Boundary condition	Fixed support at the hub/nut-support contact region, as described in the original loading model.
Applied load	Tangential force of 2317.5 N applied in the torque-transfer direction.
Bolt load share	9270 N resultant sprocket force divided equally among four identical, fully engaged bolts at the same pitch radius; used as a nominal baseline case.
Stress criterion	Stress intensity = $\sigma_1 - \sigma_3$; maximum shear stress = $0.5(\sigma_1 - \sigma_3)$, compared with the Tresca shear-yield estimate $S_y/2$

RESULT AND DISCUSSION

Fractographic Observation

Low-magnification macro-fractographic examination showed that the fracture plane was generally perpendicular to the longitudinal axis of the bolt. This orientation is consistent with combined transverse shear and bending during torque transfer. As shown in Figure 2, the fracture surface was divided into a proposed crack-initiation region, a crack-propagation region, and a final-fracture region. The broad macroscopic boundaries in the propagation region are described cautiously as beachmark-like features; the low-magnification observation does not provide direct microscopic evidence of fatigue striations.



1 = crack initiation; 2 = crack propagation zone; 3 = final fracture zone

Figure 2. Macro-fractographic features of the failed bolt: crack initiation, crack propagation zone, and final fracture zone

The proposed crack origin was located at the outer surface and the crack propagated toward the central region. This pattern is consistent with two-way bending fatigue, in which the highest alternating tensile stress occurs at the surface. The final-fracture region was relatively small compared with the propagation region, suggesting that a substantial portion of the cross-section had been weakened before final rapid fracture. Together, these macroscopic observations support fatigue as the most plausible failure mechanism, while the beachmark-like appearance is not interpreted as direct microscopic proof of fatigue striations.

Chemical Composition

The chemical composition result is presented in Table 3. The bolt contained 0.137 wt.% C, 0.473 wt.% Mn, 0.030 wt.% P, 0.011 wt.% S, and 99.09 wt.% Fe, with small amounts of additional elements. The measured C, Mn, P, and S values are within the composition limits for SAE 1015 carbon steel specified in SAE J403_202402 [35]. Therefore, the material is described as low-carbon steel chemically consistent with SAE 1015 rather than as a certified grade, because a mill certificate and production traceability were not available. The measured Si, Cr, Ni, Cu, and Al levels are treated as residual or minor elements commonly detected in commercial carbon steels. The Nb (0.088 wt.%) and Ti (0.048 wt.%) contents are not grade-defining constituents of SAE 1015; they may reflect residual or microalloy additions, but one spark-emission measurement alone cannot establish a deliberately microalloyed grade.

Table 3. Chemical composition of the rear-sprocket mounting (nap gear) bolt compared with SAE 1015 composition limits specified in SAE J403_202402 [35].

Element	Measured composition (wt.%)	SAE 1015 composition limits [35] (wt.%)
C	0.137	0.13-0.18
Si	0.045	-
Mn	0.473	0.30-0.60
P	0.030	0.040 max
S	0.011	0.050 max
Cr	0.047	-
Mo	<0.010	-
Ni	0.038	-
Cu	0.030	-
Al	0.037	-
Nb	0.088	-
Ti	0.048	-
Fe	99.09	-

Microstructure Analysis

Optical metallography showed that both the failed and intact bolts consisted of ferrite and pearlite, which is consistent with a hypoeutectoid low-carbon steel. The ferrite phase appeared as the lighter matrix, while pearlite appeared as the darker constituent. This morphology is consistent with the expected microstructure of plain carbon steel with approximately 0.15 wt.% carbon [20], [21], [22], [23].

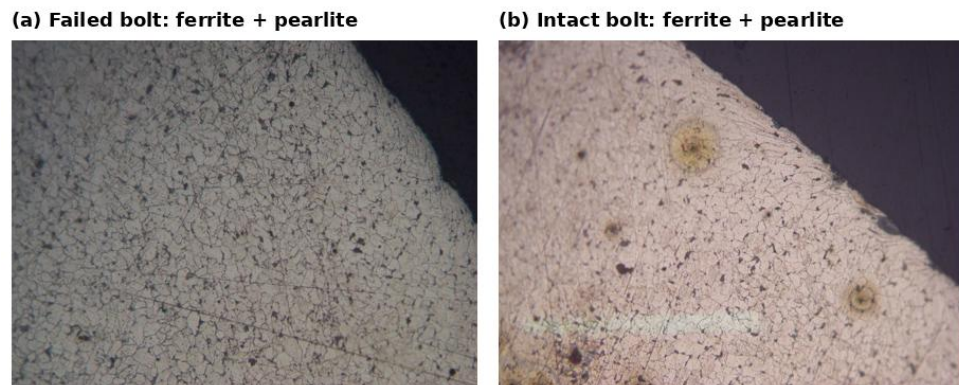


Figure 3. Optical microstructure comparison showing ferrite-pearlite morphology in the failed and intact rear-sprocket mounting (nap gear) bolts.

The microstructure near the surface was also comparable with that at the central region. This observation indicates that the bolts did not undergo a distinct surface-hardening treatment such as carburizing, induction hardening, or other case-hardening processes. Because both the failed and intact bolts had similar microstructures, the failure cannot be attributed primarily to an abnormal heat-treatment condition in the failed specimen.

Microhardness Distribution

The Vickers microhardness results are shown in Table 4 and Figure 5. The failed bolt showed hardness values ranging from 179 to 190 HV0.5, whereas the intact bolt ranged from 169 to 183 HV0.5. The average hardness of the failed bolt was 183.2 HV0.5 and that of the intact bolt was 174.3 HV0.5. Although the failed bolt was slightly harder, the difference was not sufficiently large to indicate a distinct material or heat-treatment condition.

Table 4. Vickers microhardness distribution from the center toward the outer surface.

Radius from centre (mm)	Failed bolt (HV0.5)	Intact bolt (HV0.5)
0	186	183
0.7	184	172
1.4	190	181
2.1	180	169
2.8	179	170
3.5	180	171
Average	183.2	174.3

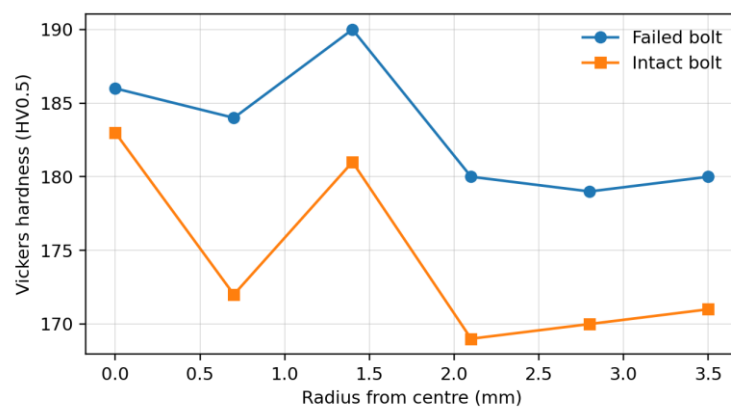


Figure 4. Vickers microhardness profile of the failed and intact rear-sprocket mounting (nap gear) bolts.

The hardness profile did not show a pronounced increase from the core to the outer surface. This result supports the metallographic observation that the bolts did not have a surface-hardened layer. The relatively higher hardness compared with common annealed or hot-rolled AISI 1015 values may be related to cold forming during bolt manufacturing, which can increase hardness by work hardening. The slightly higher hardness in the failed bolt may also be associated with localized strain hardening during cyclic loading before fracture, although this interpretation remains qualitative because the test points were taken after failure.

Finite Element Analysis and Failure Mechanism

The finite element model predicted a local stress concentration at the shank region adjacent to the head/contact interface, corresponding closely to the

observed fracture location. The maximum reported quantity was stress intensity, defined as the difference between the maximum and minimum principal stresses ($\sigma_1 - \sigma_3$), with a value of 529.6 MPa. This value is not reported as von Mises stress. The corresponding maximum shear stress was calculated from the Tresca relation as $\tau_{\max} = 0.5 (\sigma_1 - \sigma_3) = 264.8$ MPa. For the reference yield strength of 325 MPa, the Tresca shear-yield estimate was $S_y/2 = 162.5$ MPa; therefore, the local maximum shear stress exceeded the elastic shear-yield estimate under the nominal static load case.

The numerical result confirms that the observed fracture location was mechanically critical under the stated torque-transmission assumptions. However, the macroscopic fracture morphology indicates that the event was not a simple instantaneous overload. Instead, cyclic bending and shear likely initiated a crack at the outer surface, followed by stable crack propagation and final rapid fracture after the remaining section could no longer sustain the applied load. This interpretation is consistent with established fatigue-fracture theory and reported bolt-failure cases involving dynamic transverse loading [11], [15], [28], [32].

The current analysis does not establish the original trigger of crack initiation. Potential contributors include local stress concentration at the contact interface, joint loosening, unequal load sharing among the four bolts, damper/bushing degradation, impact loading from road irregularities, or assembly-related preload variation. These effects were not measured and were not explicitly represented in the static finite element model. Therefore, the most defensible conclusion is that the rear-sprocket mounting (nap gear) bolt failed by fatigue at a stress-concentrated region, while the available evidence does not indicate that material chemistry, gross metallurgical defect, or abnormal heat treatment was the primary cause.

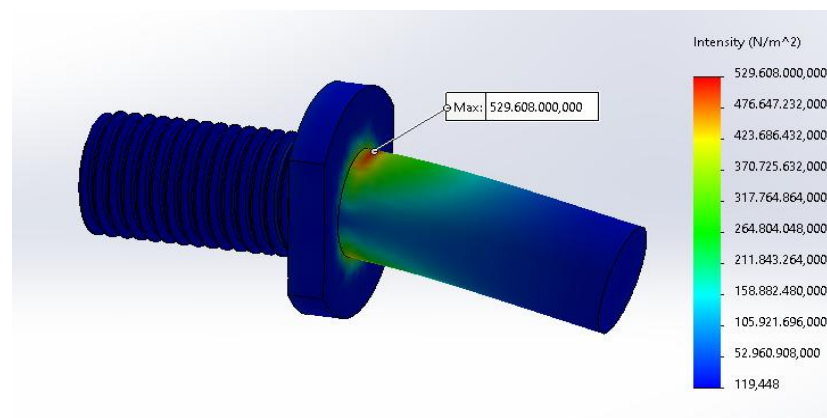


Figure 5. Finite element stress-intensity distribution showing local stress concentration near the fracture location.

CONCLUSION

The fractured rear-sprocket mounting (nap gear) bolt from the 145 cc motorcycle was a low-carbon steel chemically consistent with the SAE 1015 composition limits in SAE J403_202402, with 0.137 wt.% C and a ferrite-pearlite microstructure. Because material certification and mill traceability were not available, this description is a chemistry-based consistency assessment rather than a certified grade identification. The failed and intact bolts had comparable microstructures, and no distinct surface-hardened layer was detected. Therefore, the failure was not primarily associated with incorrect material selection or abnormal heat treatment. Low-magnification macro-fractographic observation identified a proposed crack-initiation region, a crack-propagation region with beachmark-like macroscopic features, and a final-fracture region. These features support fatigue under cyclic transverse loading and two-way bending, but they are not treated as direct microscopic evidence of fatigue striations. Vickers microhardness values were relatively uniform from the core to the surface, with averages of 183.2 HV0.5 for the failed bolt and 174.3 HV0.5 for the intact bolt. The slight difference in hardness did not indicate a decisive material discrepancy.

Finite element analysis predicted the highest stress intensity at the region where the actual fracture was observed. The reported stress intensity, defined as $\sigma_1 - \sigma_3$, was 529.6 MPa; the corresponding maximum shear stress was 264.8 MPa. This maximum shear stress exceeded the Tresca shear-yield estimate of 162.5 MPa derived from the 325 MPa reference yield strength. Within the stated modeling assumptions, the failure mechanism is best explained as fatigue crack initiation at a locally stress-concentrated region, followed by progressive crack propagation and final rapid fracture.

Future work should include direct evaluation of the damper/bushing condition, bolt preload, joint loosening, load sharing among bolts, road-impact loading, and experimental fatigue testing to quantify the actual service life and validate the finite element assumptions.

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