Determine the Fatigue behavior of engine damper caps screw bolt

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Abstract
In this paper, fatigue strength of the engine damper cap screw bolt is determined. Engine damper cap screw is critical fastener. Critical fastener is a term used to describe a cap screw that, upon failure, causes immediate engine shutdown or possible harm to person. So, determination of fatigue strength is important. S-N method is used for cap screw fatigue strength determination by testing number of samples at different alternating load keeping mean load constant. Alternating load is increased until cap screws begin to fail. But for measurement of axial load in fasteners, ultrasonic bolt gauging method is used. It has been observed that fatigue failure takes place on the thread of cap screw bolt due to high stress concentration on the thread.

Keywords: Caps screw bolt, Fatigue strength, Ultrasonic elongation, Preload.

1. Introduction

Generally pure static loading is rarely observed in engineering components or structures. The majority of structures are subjected to fluctuating or cyclic loads. There is difficulty to detect fatigue failure of bolts in complex system until a catastrophic fracture occurs, without warning [1]. In complex structure, it is difficult to determine the response analytically. Therefore, experimental, numerical or a combination of both methods are used for fatigue life evaluations. Nut and bolts are very important elements in automobiles and aerospace industries. They are used in large scale in modern car and aircraft and potential source of fatigue crack initiation. There are various parameters which are responsible for failure of bolts are thread root radius, low tightening force, material [2-6]. Bolts and nut are usually manufactured in either coarse or fine threads. Various researchers have studied experimentally the effect of thread pitch on fatigue life of bolts [7].

An ultrasonic method is used to measure tensile stress in high tension bolts after developing longitudinal and shear wave velocities. But main problem is the precision, how much tightening force is required in bolts. Insufficient or excessive tightening force is also the cause of bolted joint failure. There are various procedures to measure the bolt tension. The ultrasonic method is considered as a best method to measure elongation of bolts based on time of flight because it is easy to measure bolt tension with accuracy. However, before fastening ultrasonic method requires original length of the bolts and material constants such as young’s modulus to determine the actual tensile load from ultrasonic elongation of the bolts [8]. However, it is difficult to determine the fatigue behavior of a nut-loaded bolt due to complexity of the stress distribution. This complexity is present in the system. There are three causes for this: distribution of non-uniform load between the teeth of bolt and nut [9, 10], teeth generates the stress concentration [11] and due to presence of residual stresses (manufacturing process), stress field distorted [12, 13].

The effects of internal stresses were studied experimentally and numerically. Experimental evaluation is complex therefore scientist did more theoretical work [14, 15]. Experimental data are very limited [16]. But James–Anderson approach is very popular. It is used mostly [17, 18].

Earlier study was limited to stress analysis of the thread connectors [19-21].Later on using the finite element analysis; stress analysis of the thread root was studied. It gave the distribution laws of the stress concentration factors. The photo elastic stress-frozen technique was applied to determine the stress distributions both at the thread roots and on the screw flanks [22-23].Distribution of non-uniform load direct influence stress analysis of the connectors, especially in higher stress zone. Zhao [24] studied the behaviour of load distribution in a bolt-nut connector using the Virtual Contact Loading (VCL) method. Results obtained from VLC method was near to analytical and numerical solutions [25-26]. This method is based on mixed finite element and stress influence function methods. It has higher computational accuracy and efficiency [27]. In this paper fatigue strength of the cap screw bolt using S-N curve and failure location of bolt under fatigue testing has been studied.

2. Experimental Studies

- **Damper**

A damper is designed to reduce torsional vibrations by converting vibration energy into heat. For engine generally two types of engine damper is used. These are following

- ❖ Tuned, rubber (or elastomer) dampers
- ❖ Viscous fluid dampers

Engine dampers are normally effective at natural frequency of crank vibration and do not affect attached system vibrations. Sometimes damper are installed in other parts of driveline to add inertia and de-tune components.

- **Critical fastener**

Critical fastener is a term used to describe a cap screw that, upon failure, causes immediate engine shut down, mission disabling malfunction, or possible harm to person such as operators or bystanders. The critical fasteners are defined as cylinder head, main bearing cap, connecting rod, vibration damper and flywheel cap screws.

- **Damper cap screws**

The purpose of bolt is to clamp two or more parts together. The clamping load stretches or elongates the bolt, the load is obtained by twisting the nut until the bolt has elongated to the elastic limit. If the bolt does not loosen, this bolt tension remains as the preload or clamping force. This clamping force is called the pre-tension or bolt preload. It exists in the connection after the nut has been properly tightened no matter whether the external load P is exerted or not. When tightening, the mechanic should hold the bolt head stationary and twist the nut in this way the bolt shank should not bear the thread friction torque. During clamping, the clamping force which produces tension in the bolt induces compression in the members [28]. Damper cap screws are used to secure a vibration damper to crankshaft. Cap screws are subjected to vibration, fatigue and corrosive environment. Damper cap screw bolts mounting on engine has been shown in Figure 1.
Design of cap screw is an iterative process. The designer must balance preload requirement with acceptable alternating loads by adjusting grade selection and thread diameter. All cap screws must verify the preload, fatigue strength, torque requirement behavior and other attributes.

Technical specifications of the Damper cap screw bolt

Damper cap screws are used to secure a damper to the crankshaft. Details of the cap screw are given below [29]:

Type	: 12 point cap screw bolt
No. of cap screw	: 06 Nos.
Assembly torque	: 410 lb-ft
Nut factor	: 0.16 to 0.2
Mean dia	: 0.71
Length	: 4”
Grade	: 8
Thread	: ¾- 16 fine thread series UNF
Stress Area	: 0.373 inch^2
Thread per inch	: 16
Pitch	: 1/16 = 0.0625 inch
Proof Load	: 44800 lb
Tensile Strength (Min)	: 5600 lb

3. Evaluation of Mechanical Properties

Figure 2 shows the approach to determine the fatigue strength of cap screw bolt.

- **Material property evaluation requirements**

a. Surface hardness, Ultimate tensile strength was obtained prior to the fatigue test. Cap screws which were used in the evaluation. Those cap screws were not used as a fatigue test specimens.

b. Hardness of the shank is obtained through hardness tester.

c. Cap screws were tested to failure in tension, using the grip length or gage length and thread engagement of the intended fastener application.

d. Chemical analysis results obtained at the center of head after clean- up the surface

- **UTS (Ultimate tensile strength)**

Tension tests provide information on the strength and ductility of materials under uniaxial tensile stresses. To perform tensile test, SAE [29, 30] and ASTM [31] procedure has been adopted. Figure 3 shows the ultimate tensile machine (UTM) and cap screw with adopter. Details of the test procedure have been given below:

❖ The cap screw was inserted in the UTS machine with the test washer placed under the cap screw head.

❖ The test nut was assembled onto the cap screw by turning the cap screw head until the cap screw is seated against the hardened washer.

❖ Precaution was taken that a minimum of two threads protrude through the nut. Wedge grips were used for holding the specimen.

❖ Then the cap screw were continuously and uniformly tightened at a speed not to exceed 30 rpm with a torque-measuring device or equivalent means, until either the torque or the tension value, as required, was developed and both torque and tension readings were recorded.

❖ Axial loading was applied until failure.

❖ It was ensured that the cap screw shall not fracture before having withstood the minimum tensile load specified for the applicable size, thread series, grade and the failure location.

Table 1 shows the ultimate test results. Stress area, mean tensile strength and mean tensile stress is 0.373 $inch^2$, 71361 pound and 191315 $pound/inch^2$ respectively.

- **Chemical Analysis**

Chemical analysis was performed using spectrometer [32] and spectrometer has been shown in figure 4. Procedure for chemical analysis has been given below:

❖ Specimen was prepared for chemical analysis at the center of cap screw head by cleaning upper surface.

❖ A capacitor discharge was produced between the flat, ground surface of the disk specimen and a conically shaped electrode by spectrometer. The discharge was terminated at a predetermined intensity time integral of a selected iron line, or at a predetermined time, and the relative radiant energies of the analytical lines were recorded. The most sensitive lines of arsenic, boron, carbon, nitrogen, phosphorus, sulfur, and tin lie in the vacuum ultraviolet region. The absorption of the radiation by air in this region was overcome by evacuating the spectrometer and flushing the spark chamber with argon.

❖ Chemical composition for each element (C, Si, Mn, P, S, Cr, Mo, Ni) in percentage was noted. Chemical analysis results have been shown in table 2.

- **Hardness and Microstructure**

The Rockwell hardness test is an empirical indentation hardness test that can provide useful information about metallic materials. This information may correlate to tensile strength, wear resistance, ductility and other physical characteristics of metallic materials, and may be useful in quality control and selection of materials. Figure 5 shows the hardness tester and microscope for analysis of hardness and microstructure of cap screw respectively.

Test procedure has been described below:

❖ Placed the cap screw on hardness tester as per attached figure.

❖ Moved the indenter into contact with the test surface in a direction perpendicular to the surface.

❖ Measured the hardness of cap screw.

❖ Observed the microstructure of specimen at microscope.

Table 3 shows the hardness & microstructure test results of the cap screw.

- **Coating**

Cap screw bolts were coated with the zinc phosphate and oil coatings to provide a corrosion protection and a low & consistent friction coefficient. The most consistent preload is achieved with an as-received zinc phosphate and oil coating.

- **Minimum grade requirement**

Critical cap screws were used for dampers shall be grade 8 or above [29] for inch products or property class 10.9 or above [33] for metric products. Property class 12.9 fasteners are susceptible to stress corrosion cracking and are not recommended.

4. Determination of bolt pre-load

The purpose of the bolt was to clamp two or more parts together. The clamping load stretches or elongates the bolts; the load was obtained by twisting the nut until the bolt elongated to the elastic limit. When the bolt did not loosen, this bolt tension remains as the preload or clamping force. This clamping force is called the pre-tension or bolt preload. It exists in the connection after the nut has been properly tightened no matter whether the external load P is exerted or not. The preload is the force required to hold the joint together correctly. The preload cannot be calculated directly, but it can be estimated using available empirical data and then confirmed by measurements for the particular cap screw and joint.

- **Theoretical calculation of preload**

The relationship between the torque applied to a fastener and tension created from the resulting bolt elongation has been described below

$T = F.\ K.D$

Where T, K, D & F are torque, friction factor, bolt diameter and preload respectively. The K value can be thought of as summarization of anything and everything that affect the relationship between torque and preload. Table 4 gives brief list of some estimated K factors [34]. A K factor for zinc phosphate coated cap screws was assumed between 0.16 and 0.20 for approximate calculations of preload. Preload value of the damper cap screw has been shown in table 5.

- **Experimental measurement of preload**

In this work, axial load is measured by ultrasonic method using ultrasonic bolt gauge. Figure 6 shows the ultrasonic bolt gauge. The purpose of ultrasonic bolt gauging is to estimation of axial load in fasteners. The ultrasonic method of measuring the elongation of bolts based on time of flight to measure bolt tension with better accuracy. However, the ultrasonic method requires the original length of bolts and Young's modulus before fastening to determine the actual tensile load from ultrasonic elongation of the bolts [8].

The purpose of using ultrasonic bolt gage is to use ultrasonically measured elongation to determine cap screw preload. The cap screws are calibrated in a load frame to relate cap screw stretch (the ultrasonic elongation) to applied load. The cap screw stretches as torque is applied to joint. Using the ultrasonic length measurement, the stretch is related to preload through the cap screw calibration**.**

Before calibration, bolt gage were ground on top and bottom. Grinding improves connection between ultrasonic transducer to bolt. Preparation of the bolt surface has been shown in figure 7. After preparation of the cap screw bolt surface, cap screw bolt gage has been calibrated. Figure 8 shows the calibration set up. Length of the calibration bar is measured in this process. It is very necessary to makes sure that the bolt system is working properly. Initially ultrasonic length is measured before loading the bolt. Later on load is applied on bolt to measure ultrasonic elongation. Load and elongation were used to determine a calibration curve and load factor. Calibration of the damper capscrew bolt has been shown in Table 6 and Figure 9. After that, cap screw was installed on engine to mount damper with crankshaft. The cap screws were tightened in sequence. Torque all cap screw as per specification. Load (tension) was calculated for all stretch by multiplying the load factor, determined through calibration curve. Table 7 shows the value of preload using ultrasonic bolt gauge. 40651 lbf, average pre-load on cap screw bolts has been determined. Therefore 40,000 lbf, mean load has considered for fatigue test.

5. Fatigue testing

The purpose of the fatigue test is to make sure that a cap screw has adequate fatigue strength to survive in an engine environment under engine loading. Engine conditions are measured and duplicated in a tension-tension axial fatigue test.

- **Fatigue test procedure**

i. Mounted the screw bolt test fixture on closed loop servo hydraulic fatigue test system.
ii. Set gage length 64 mm.
iii. Set the load on the servo hydraulic fatigue test system.
iv. Cycle of the machine was set at approximately 15 Hz.
v. Maintained mean load 40000 lbs during testing & alternating load varying from 2000 lbs to 7500 lbs (Fatigue testing of samples should be at 2 to 4 times engine alternating load).
vi. Recorded the load and cycles to failure.
vii. Repeated above steps for all samples.

- **Fatigue test cycle**

In the conventional fatigue design, the fatigue limit was obtained at 10^7 number of stress cycle to determine the allowable stress level for design against high cycle fatigue.

Post test processing of the raw test data was used to obtain the estimate of the cap screw's mean fatigue strength, standard deviation, coefficient of variation of strength. These post test results can be used for comparison with a minimum fatigue test requirement .Table 8 shows the fatigue test results. Raw data can be effectively presented in an S-N plot and Goodman plot.

- **S-N Curve**

S-N curve for cap screw was determined using the alternating load. The load was increased until cap screw begin to fail.16 sample were tested to determine the shape of fatigue curve. The Data from this sample were analyzed using software and M.S. Excel. After drawn S-N curve, Endurance limit was determined. Figure 10 and 11 shows the S-N curve made using M.S. Excel and fatigue software respectively.

- ### Goodman diagram

Goodman diagram is a tool for estimating infinite fatigue life of a component undergoing mean and alternating load.

6. Results and discussion

Following observation is observed after analyzing the table 1, 2 & 3:

- Damper cap screw bolt can bear maximum tensile stress 191315 pound square inch before failure.
- It contains maximum amount of manganese. After that, chromium, nickel and carbon come in the row. Due to presence of high manganese hardenability, machinability and strength improves.
- Chromium and nickel improves toughness. Therefore bolt bears maximum distortion energy before fracture.
- The role of carbon is also very significant. Carbon increases the damping property. When fatigue load is applied, bolt dissipates more amount of energy to atmosphere. So life of the bolt increases.
- Bolt is very hard. Its hardness varies between 39-42 HRC.
- Tempered martensite structure is observed after seeing the bolt from microscope and thread rolling is done after heat treatment. Laps/cracks are absent at root or flanks of the threads.

Table 5 shows the pre-load calculations theoretically of the damper cap screw bolt. Preload is applied to hold the joint together correctly. The preload cannot be calculated directly, but it can be estimated using available empirical data and then confirmed by measurements for the particular cap screw and joint. Theoretical average value of the preload is 38737.8 pound. To measure the value of preload experimentally, ultrasonic method is used. Table 7 shows the value of preload using ultrasonic bolt gauge**.** 40651 pound average pre-load has been determined from ultrasonic bolt gauge. After calculating preload from both procedures, fatigue experiment has been performed. At the time of performing fatigue test, maximum and minimum load were changing but mean load was fixed. That was 40,000 pound. It was very near to average preload. Fatigue test results have been shown in table 8. When minimum and maximum load was 35,500 pound and 44,500 pound respectively, bolt was safe after passing 10000000 cycles. As soon as the value of maximum load reaches up to 45,000. Bolt fails at 7608380 cycles. Number of cycles decreases drastically after addition of 500 pound load in maximum load. S-N curve has been drawn using table 8 data in MS Excel sheet. Figure 10 shows the S-N curve. To validate table 8 data and S-N curve, fatigue software was used. Figure 11 shows the S-N curve by fatigue software. It is observed that bolt is safe, when alternating load is below 5000 pound.

Goodman line has been shown in figure 12.The Goodman line is used as criteria of failure when the component is subjected to mean stress as well as stress amplitude.

Conclusion

The fatigue strength of damper cap screw bolt is determined by S-N curve method. Data for S-N curve was generated on servo hydraulic fatigue test system by axial force controlled method. Fatigue strength of cap screw bolt is 4582 pound at mean load of 40000 pound.

The purpose of fatigue test is to make sure that a cap screw has adequate fatigue strength to survive in an engine environment under engine loading. Engine conditions are measured and duplicated in a tension-tension axial fatigue test.

Alternating load due to engine operation for particular damper cap screw bolt should be less than 4582 pound. For better design the alternating load should be half of fatigue strength. Goodman diagram plotted based on fatigue strength, mean load and ultimate tensile strength to find the Goodman diagram can be used for finding the design margin at different mean load & alternating load.

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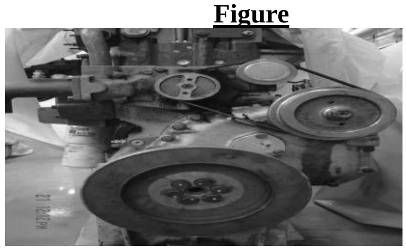
Figure



Crank Shaft Vibration Damper Cap screw Bolt

Figure 1: Cap Screw Bolt Mounting on Engine

Identify the component for fatigue strength-Damper screw bolt

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Mechanical material property evaluation

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Bolt pre load measurement

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Fatigue test setup and testing

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Creation of S-N curve

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Determination of fatigue strength

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Goodman diagram for analysis

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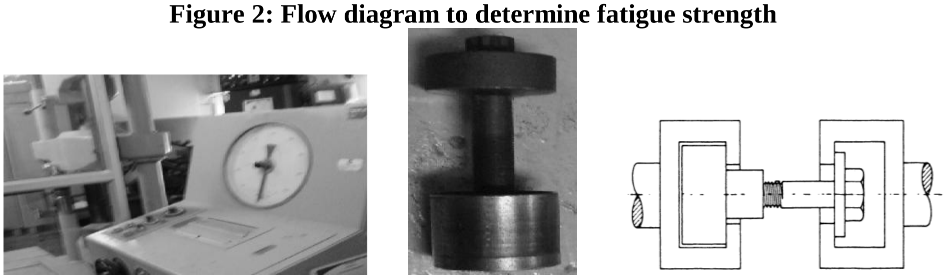
Results and Discussion

Figure 2: Flow diagram to determine fatigue strength



UTM Cap screw Cap screw with adopter

Figure 3: **Ultimate tensile testing machine and cap screw with adopter**

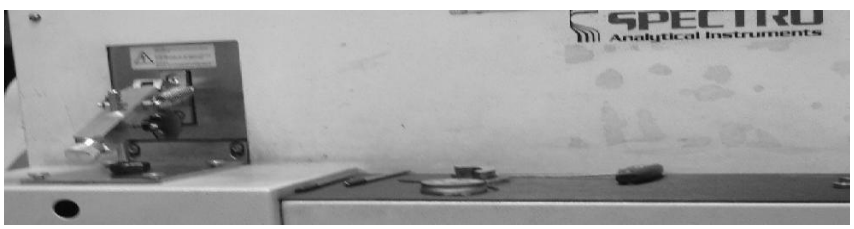


Figure 4: Spectrometer for chemical analysis

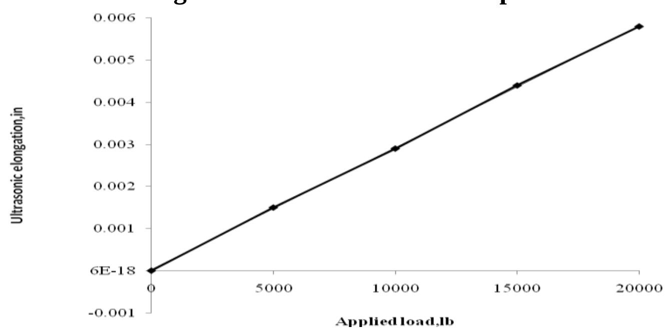
Hardness Tester Microscope

Figure 5: Hardness & Microstructure of cap screw

Figure 6: Ultrasonic bolt gage

Figure 7: Bolt Surface Preparation

Figure 8: Bolt Calibration setup



Load factor (slope) 3447784 Y-intercept 67.5 R^2 0.999857

Figure 9: Cap screw bolt calibration

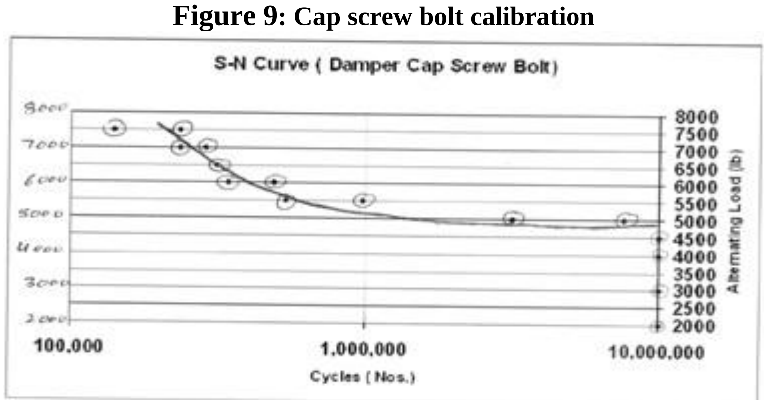


Figure 10: S-N Curve by MS Excel

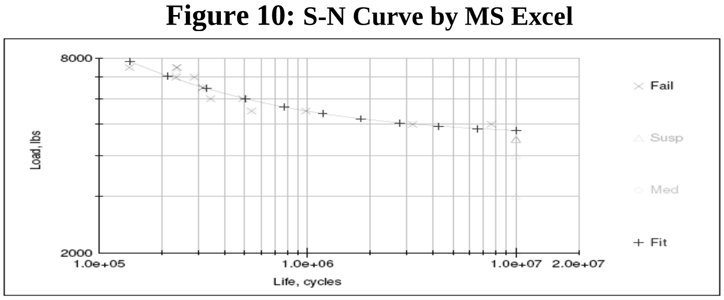


Figure 11: S-N Curve by fatigue software

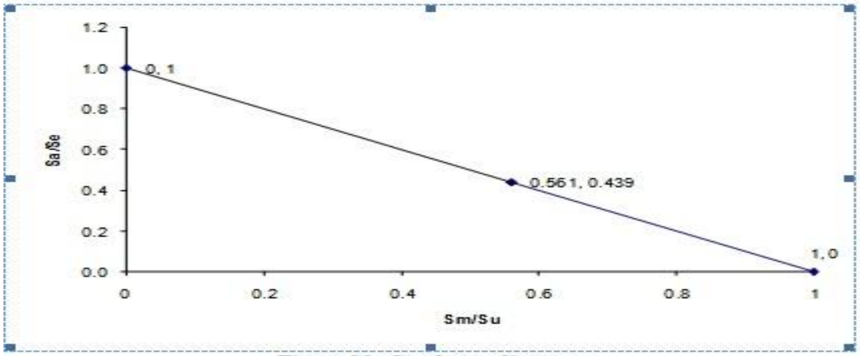


Figure 12: Goodman diagram

Table

Table 1: Ultimate tensile test results

Sr. No.	Sample	Failure Load (KN)	Failure Load (lb)	Failure Stress (Psi)
1	1	320	71939	192865
2	2	324	72838	195276
3	3	330	74187	198892
4	4	322	72388	194069
5	5	314	70590	189249
6	6	310	69691	186839
7	7	302	67892	182016
Average(UTS)		**318**	**71361**	**191315**

Table 2: Chemical Analysis results

Sr. No.	Element %	C	Si	Mn	P	S	Cr	Mo	Ni
1	Lot1	0.41	0.25	0.88	0.014	0.006	0.51	0.15	0.51
2	Lot1	0.4	0.26	0.85	0.02	-----	0.54	0.16	0.5
3	Lot1	0.38	0.15	0.73	0.017	0.01	0.58	0.19	-------
Standard	ASTM E415	0.37/ 0.44	0.15/ 0.35	0.70/ 1.05	0.035 max	0.04 max	0.35/ 0.65	0.15/ 0.25	0.35/ 0.75
Standard	SAE 8640	0.38/ 0.43	0.15/ 0.35	0.75/ 1.00	0.035 max	0.04 max	0.40/ 0.60	0.15/ 0.25	0.40/ 0.60

Table 3: Hardness & Microstructure test results

Sr. No.	Sample	Hardness	Microstructure
1	1	39-42 HRC	Fine tempered martensite. Cracks/laps are not observed at root/flanks of the threads. Decarburization
2	2	38-39 HRC	Tempered martensite. Thread rolling is done after heat treatment. Laps/cracks are absent at root or flanks of the threads.
3	3	38-40 HRC	Tempered martensite. Thread rolling is done after heat treatment. Laps/cracks are absent at root or flanks of the threads.

Table 4: K factors

Bolt Condition	K
Non-plated, black finish	0.20 ------ 0.30
Zinc-plated	0.17 ------ 0.22
Lubricated	0.12 ------ 0.16
Cadmium-plated	0.11 ------ 0.15

Table 5: Preload calculation –Damper cap screw

Assembly torque (T) lb.ft	410	410	410	410	410
Capscrew diameter (D_{in}) inch	0.71	0.71	0.71	0.71	0.71
Capscrew diameter (D),ft = D_{in}/12	0.0592	0.0592	0.0592	0.0592	0.0592
Nut factor (K), assume	0.16	0.17	0.18	0.19	0.20
Preload (P), lb = T/(D*K)	43309.9	40762.2	38497.7	36471.5	34647.9
Average Torque (lb.ft)	**38737.8**				

Table 6: Damper Capscrew bolt calibration

Sr. No.	Applied load, lb	Measured ultrasonic elongation, in
1	0	0.0000
2	5000	0.0015
3	10000	0.0029
4	15000	0.0044
5	20000	0.0058

Table 7: Torque tension test results

Torque = 400 lb.ft & Load factor = 3447784		
Cap Screw No.	**Stretch**	**Load**
1	0.0110	37960
2	0.0117	40339
3	0.0129	44476
4	0.0121	41718
5	0.0131	45166
6	0.0112	38615
7	0.0118	40684
8	0.0127	43787
9	0.0114	39305
10	0.0116	39994
11	0.0120	41373
12	0.0101	34823
13	0.0120	41373
14	0.0111	38270
15	0.0116	39994
16	0.0126	43442
17	0.0114	39305
18	0.0119	41029
19	0.0112	38615
20	0.0124	42753
Sample size	**Average stretch**	**Average load**
20	**0.0118**	**40651**
Std Dev = 2504, Min load = 34823 &Max load = 45166		

Table 8: Fatigue test results

Sample No.	**Mean load, (lbs)**	**Alternating load, (lbs)**	**Min load, (lbs)**	**Max load, (lbs)**	**Cycles to failure**	**status**
1	40000	2000	38000	42000	10000000	**Pass**
2	40000	3000	37000	43000	10000000	**Pass**
3	40000	4000	36000	44000	10000000	**Pass**
4	40000	4500	35500	44500	10000000	**Pass**
5	40000	5000	35000	45000	7608380	**Fail**
6	40000	5000	35000	45000	3190347	**Fail**
7	40000	5500	34500	45500	539646	**Fail**
8	40000	5500	34500	45500	982412	**Fail**
9	40000	6000	34000	46000	342895	**Fail**
10	40000	6000	34000	46000	490985	**Fail**
11	40000	6500	33500	46500	314736	**Fail**
12	40000	6500	33500	46500	314780	**Fail**
13	40000	7000	33000	47000	235024	**Fail**
14	40000	7000	33000	47000	286642	**Fail**
15	40000	7500	32500	47500	236327	**Fail**
16	40000	7500	32500	47500	140086	**Fail**