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OVERVIEW. This section accepts articles in the field of RMS (Reliability, Maintainability, and Supportability) that explain how one or more of these virtues have been altered. The scope of applications has no bounds and may include structures, electronics, propulsion, and systems. Successful and unsuccessful attempts to improve a product's reliability will be of great interest to some readers. Other readers will show interest in how improvements in maintainability, availability, and interchangeability were achieved. Spares handling, logistics, and case studies of improved access are of interest to all. Specific cases, such as an improvement in avionics system accessibility by inclusion of easy access structures, are the kinds of articles that are most welcome.

On the Reuse of Bolts Which Have Been Torqued to Yield

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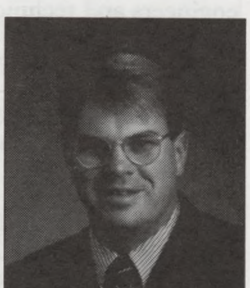
ABSTRACT. Bolts are torqued to yield in automotive engines to fasten aluminum alloy cylinder heads to cast iron cylinder blocks. This tightening method provides a reliable, even, and controllable clamping force that prevents warping of the soft cylinder head and ensures a leak-tight joint. It has one drawback: Since the bolts yield during engine assembly, they work harden even as their ultimate strength decreases. Upon reuse, yield stress more closely approaches ultimate strength. Fastener geometry and mechanical properties, now changed, supply changed joint-clamping force. For reasons such as these, Ford Motor Company recommends that bolts torqued to yield be replaced each time an engine is rebuilt. Cost savings, however, could be realized if engine remanufacturers could reuse these fasteners even once. In this article, reuse of SAE 10-mm cylinder head fasteners is simulated in the laboratory for a Ford 1.9-liter four-cylinder engine. Based on tensile test data of yielded bolts, recommendations are made discouraging their reuse.

BACKGROUND

During the past decade, aluminum alloy cylinder heads have seen increased use in automotive engines. Aluminum offers several advantages. First, the higher thermal conductivity of aluminum over that of the more conventionally used cast iron aids in rapid heat removal from areas of the engine having the highest temperatures. Second, its higher thermal diffusivity helps limit surface temperatures on internal head surfaces. Finally, its lighter weight increases vehicle fuel economy.

Unfortunately, engine designers must also deal with aluminum's disadvantages. Softer than cast iron, aluminum has a lower elastic modulus and yield stress. Aluminum heads must be well supported to avoid distortion during use. This is accomplished in two ways. First, even though the head is secured at discrete bolting locations, an elastically "soft" head gasket spreads the bolting forces across the joint sealing surfaces. Second, production and installation factors that affect clamping force are carefully controlled to minimize bolt-to-bolt variations. Bolts properly torqued to yield provide uniform clamping force.

Since the head has a higher thermal expansion coefficient than the bolts, the joint tightens as it is heated. A robust design (one able to withstand infrequent extreme operating conditions) can prevent leaking joints caused by occasional engine overheating. Even so, aluminum heads warp and joints loosen after extreme overheating. Nevertheless, a well-designed joint secured by bolts properly torqued to yield results in an effi-



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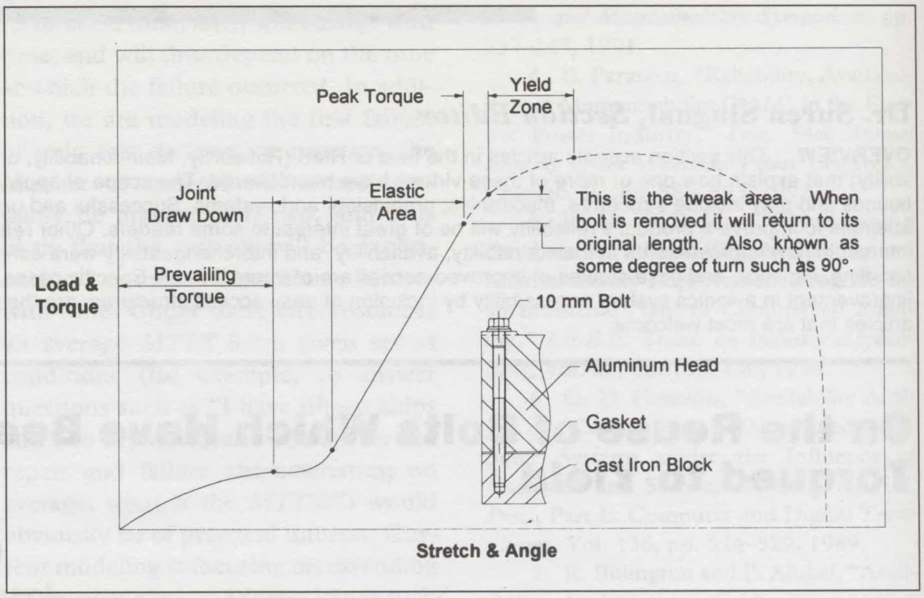
cient engine assembly that utilizes the unique properties of aluminum, cast iron and steel.

As the term implies, torque-to-its-yield fasteners are tightened until they yield.* Figure 1 [1] shows the relative relationship between bolt stretch and load for a bolted joint. It also shows that a properly designed joint using fasteners torqued to their yield prevents excessive loading caused by overtightening. Once yielded, the slope of the bolt stretch versus load curve drops, providing only small load variations for moderate variations in stretch. Bolting load can then be controlled fairly precisely utilizing conventional wrenching techniques. A fairly comprehensive treatment of torque-turn tightening of bolts and the control of bolting forces can be found in reference [2].

This precise control of bolting loads requires considerable engineering effort. Many factors affect the relationship between bolt torque, angular turn of the fastener, and clamping force. These factors include thread surface finish, lubricants, manufacturing tolerances, thread cleanliness, and washer surface characteristics. Torque/turn theory is sufficiently complex to preclude an entirely analytical solution. Instead, automotive manufacturers use sophisticated electronic equipment to simultaneously monitor bolt torque and rotation during assembly. The bolt has yielded when torque stops increasing while the bolt is still turning [3].

Lacking this special equipment, aftermarket rebuilders must rely on some combination of torquing and turning to control the load. The precise tightening procedure published in aftermarket manuals is determined after months of testing by automotive engineers and technicians.

FIGURE 1 Typical Bolt Turn vs. Load Curve (Adapted from [3])



DESIGN OF A TORQUE-TO-ITS YIELD BOLTED JOINT

Figure 1 displays the four important loading regions in torque-to-yield fastening of a joint: (1) prevailing torque, (2) joint draw-down area, (3) elastic area, and (4) yield zone.

The first three loading regions are found in all bolted joints, whether or not the fasteners are torqued to yield. The prevailing torque is the torque required to turn the bolt in the threaded hole before the bolt head contacts joint surfaces. The joint draw-down area is where mating joint surfaces are drawn into initial contact. The elastic or bolt stretch area is a zone where the bolt is stressed more than that required for initial contact, but is still within the elastic limit of the bolting material. Up to this point, if the bolts were loosened and the joint disassembled, there would be virtually no physical changes in fastener geometry or mechanical properties.

The fourth loading region, the yield zone, is the desired operating region for the torque-to-its-yield fastener. Once tightened into this region, the fastener has been plastically deformed both axially and torsionally. This deformation changes the geometry and the mechanical properties of the fastener. Stretching the fastener into the plastic range cold works the material. This initially raises the yield strength of the part while causing the ultimate strength to remain essentially constant. If the bolt is repeatedly stretched and relaxed, the yield strength eventually becomes infinitesimally close to the ultimate strength, and the part fails in brittle fracture [4].

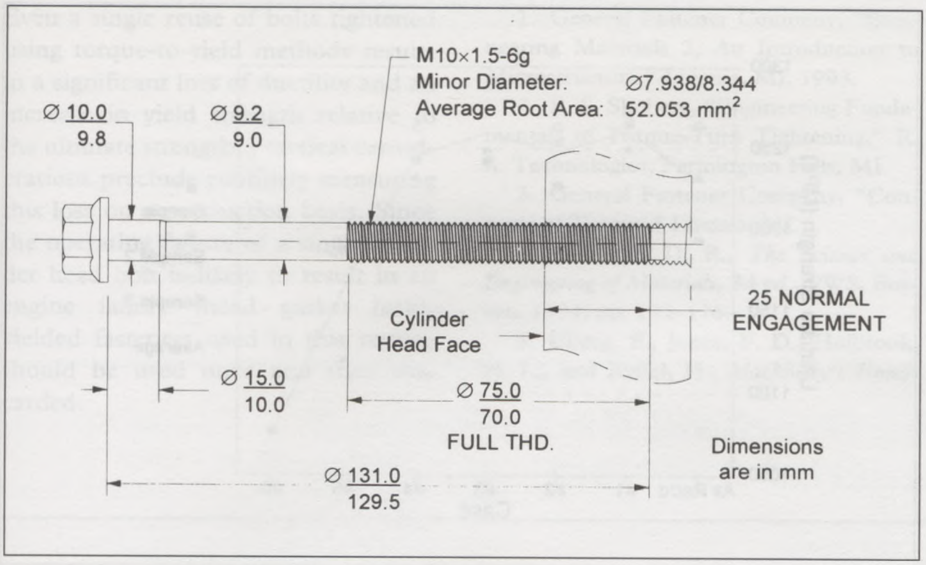
INVESTIGATION METHOD

To investigate fastener reusability, twenty-four M10 × 1.5-6g† fasteners (Motorcraft Part Number N804732-S100) were divided into eight groups of three. Figure 2 shows the bolt configuration [7]. One group, tested in the "as received" condition, served as a control. The seven remaining groups were identified with a case number, 1 through 7, which after testing would refer to the number of times that the bolts in that group were torqued. Thus, for example, a bolt from the case 3 group was torqued and relaxed a total of three times.

*At the outset, it is important to draw a distinction between a torque-to-yield bolt and a torque-to-its-yield bolt. A torque-to-yield bolt is specially designed to yield in the shank area. A torque-to-its-yield bolt, on the other hand, is a conventional bolt which is tightened using a special torque-to-yield method. It yields in the threaded area. This latter type is tested here.

†The thread designation is as follows for an M10 × 1.5-6g fastener: M refers to the thread profile. It features a 60° included angle thread form in accordance with American (ANSI B1.13M-1983) and International (ISO 68) standards. The 10 in this case refers to the basic major diameter of the thread in millimeters. The 1.5 refers to the pitch length in millimeters. The 6g refers to the allowance and tolerance grade (ANSI B1.13M-1983 or ISO 965/1) [5][6].

FIGURE 2 Configuration of Tested Bolt [7]



The engine cylinder block was simulated in the laboratory by a drilled and tapped piece of cast iron bar. The cylinder head was simulated by a cross-sectioned cylinder head from a Ford 1.9-liter engine. At assembly, the threads and head of each bolt were lubricated with a Grade SAE 30 motor oil to reduce friction and obtain uniform torque readings. Fasteners were relubricated before each subsequent torque sequence.

The torque procedure, in accordance with Ford overhaul specifications [8], was as follows:

1. Tighten each bolt in sequence to 44 ft-lb.
2. Loosen each bolt ½ turn (helps equalize surface contact stresses built up during initial draw-down).
3. Retorque each bolt to 44 ft-lb (fix bolt stress at or near yield).
4. Tighten each bolt, in sequence, 1/4 turn (add a small fixed amount of strain).
5. Tighten each bolt, again in sequence, an additional 1/4 turn (add a final small fixed amount of strain).

Once torqued, the joint was disassembled. A tensile test (to fracture) was then performed on each bolt using a Tinius-Olsen tensile test machine. When tensile testing the samples, every effort was made to duplicate the tensile conditions in the head and block. Special grips were made to interface the bolt with the tensile test machine. One grip was specially counterbored to receive the bolt head. The force at the bolt head was thus applied at the lip formed between the base and the shank of the bolt, just as in the real cylinder head. The other grip was threaded to receive the bolt. The bolt was threaded into its mating grip one inch deep to duplicate thread engagement in the engine block.

Tensile test data is summarized in Table 1. Stress values shown are based on the measured force divided by the average root diameter of an M10 × 1.5-6g external thread. No allowance is made for the fact that necking (area reduction) is occurring as the bolts yield. This data gives a *relative* comparison of the change in material properties as the bolt is successively retorqued. It does not indicate true bolt stress, as a standard tensile test specimen does, because the stress field through the grips and onto the threaded section is not uniform.

Similarly, elongation data gives a relative comparison of the change in material ductility. Elongation data is based on the total unsupported bolt length. This serves to greatly understate the elongation, since the elongation is almost certainly occurring exclusively in the threaded region of the bolt where the stress area is smaller.

RESULTS

From Table 1, the yield stress of the bolt increases an average of 8% through the fourth retorque (com-

TABLE 1 Experimental Results

	As Rec'd	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Samples: Failed/Total[a]	0/3	0/3	0/3	0/3	0/3	0/3	2/3	3/3
Yield Stress (MPa):								
Sample 1	983	1068	1077	1107	[b]	1102	1004	—
Sample 2	1090	1077	1090	1090	1137	1068	—	—
Sample 3	1068	1090	1098	1132	1141	1090	—	—
Average	1047	1078	1088	1109	1139	1087	1004	—
Ultimate Stress (MPa):								
Sample 1	1194	1265	1227	1242	1243	1188	1077	—
Sample 2	1232	1250	1254	1249	1232	1121	—	—
Sample 3	1265	1267	1263	1287	1262	1186	—	—
Average	1230	1261	1248	1259	1246	1165	1077	—
Relative Elongation (%):								
Sample 1	10.7	7.5	5.5	6.0	6.1	3.2	1.0	—
Sample 2	8.3	8.1	7.8	5.0	4.1	2.0	—	—
Sample 3	9.2	6.5	5.8	5.8	3.0	2.0	—	—
Average	9.4	7.3	6.4	5.6	4.4	2.4	1.0	—

[a] The first number denotes the number of samples that failed during torquing. The second number denotes the total number of samples tested.
[b] Unable to determine yield stress from tensile data.

pared to the "as received" bolt). Thereafter the yield stress drops an average of about 10% from this maximum value (engineering stress). The ultimate stress of the bolt remains relatively constant through the fourth retorque. Thereafter the ultimate stress drops an average of nearly 20% (Figure 3). The yield stress as a fraction of the ultimate stress increases with each successive retorque. The increase is nearly linear (Figure 4). The relative elongation drops significantly after the first torquing sequence. Necking of the fasteners was noticeable after the fastener had been tightened four times. This coincides with the drop in ultimate stress already noted.

This change in mechanical properties found during our testing procedures appears to be the reason why Ford recommends that fasteners torqued to yield be replaced with new ones each time the 1.9-liter engine is rebuilt.

FIGURE 3 Change in Ultimate Strength with Successive Reuse

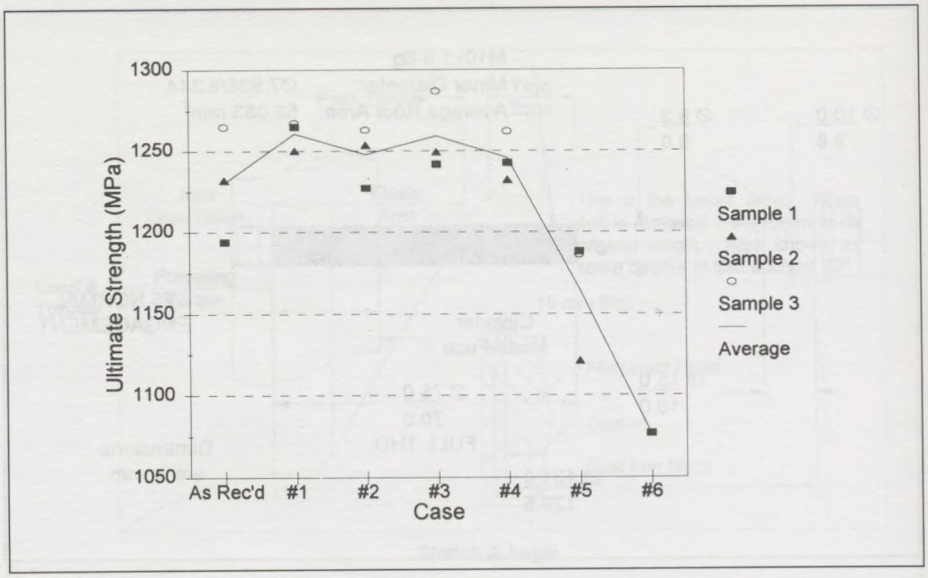
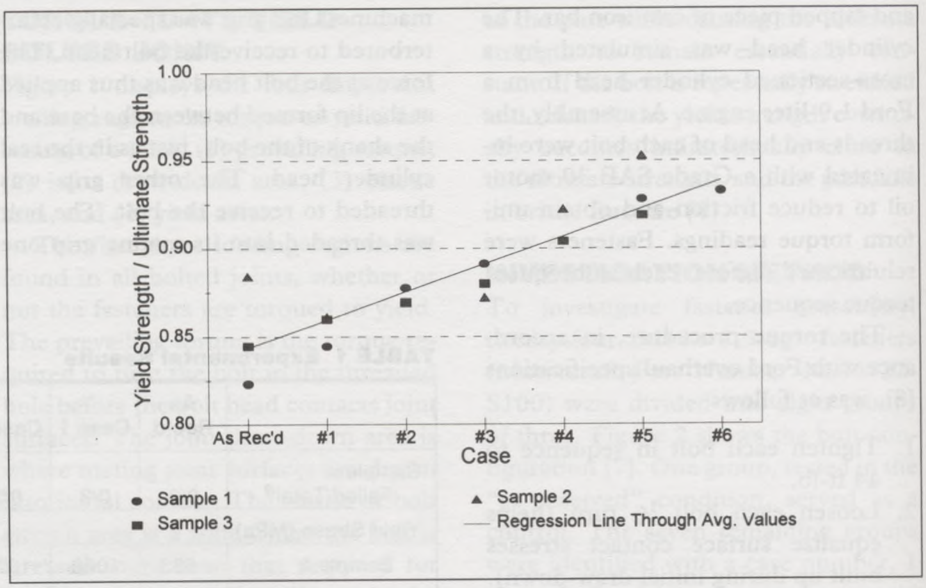


FIGURE 4 Change in 0.2% Yield Strength with Successive Reuse



DISCUSSION

Though those in the fastener industry would argue that a bolt removed from service after reaching its yield point should be automatically discarded and replaced, the question to be addressed in this study still is: Can a bolt that has been torqued to its yield be reused with a fairly high degree of confidence that it will secure the joint during subsequent operation? The data from these tests suggests that while reuse may be possible, reliability will suffer. Making this sacrifice on a head/block joint, where a single bolt failure is likely to result in failure of a customer's engine, would be imprudent and possibly negligent. For the reasons stated below, reuse of torque-to-yield fasteners is not recommended:

1. Fastener ductility suffers even after the first instance of tightening. This means that the bolting material's properties have deviated significantly from their original design values. The empirical data on which recommended tightening procedures have been based is of no use now—the joint characteristics have changed.
2. Production bolts invariably have large bolt-to-bolt length variation (5 mm in our case). This precludes measuring the bolt length after first use to determine how much elongation has in fact occurred. Without this information, the degree of yielding cannot be quantified, and acceptance criteria cannot be realistically determined.
3. Once fastener reuse is deemed acceptable, certain quality control issues become problematic. How can an engine rebuilder know for sure whether the head bolts on an engine have been reused before? Since the extent of yielding varies between one reused bolt and another, how can mixing of new and reused bolts be prevented and then verified to ensure that bolt tension is uniform and the reliability of the head/block seal is not compromised? How can the engine rebuilder assess the effect of engine thermal cycling on the already yielded bolts, especially when an engine's operating history is unknown? These questions have no clear-cut answers.

CONCLUSION

Even a single reuse of bolts tightened using torque-to-yield methods results in a significant loss of ductility and an increase in yield strength relative to the ultimate strength. Practical considerations preclude routinely measuring this loss on a production basis. Since the operating failure of a single cylinder head bolt is likely to result in an engine failure (head gasket leak), yielded fasteners used in this service should be used once and then discarded.

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