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Quantitative Analysis of Big End Journal Form and Bolt Installation using Ultrasonic Time of Flight Measurements

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Abstract

Connecting rod bolts have the effect of compressing the bearing cap when preload is applied, placing the journal into an out of form state when exacting levels of torque are not exercised. In this paper, this effect has been highlighted by means of practical measurements and then simulated with FEA models.

A further study into ultrasonic velocity through torque to yield fasteners has highlighted as torque is increased, there is a coherent decrease in sound wave velocity. Testing also highlighted a change in Young's modulus during the elastic region, throwing animosity to the conventional linearity of Hooke's law.

Based on current literature, a relationship linking increased hardness to a reduction in ultrasonic velocity resulted in further testing that indicated as fasteners yield, the material locally strain hardens, causing a decrease in sound velocity in the heavily yielded region. It is then regarded that high frequency ultrasonic testing can identify localised micro structural changes due to strain hardening, giving a variation in Young's modulus during the elastic region when compared to the linearity of the conventional bulk tensile test that cannot identify such details.

Keywords: ultrasound, time of flight, connecting rod, big end journal form, bolt installation, load, torque

1 Introduction

Threaded fasteners are the fundamental method for creating a semi-permanent joint between two components, utilising the elastic force between the helical threads and bolt head when stretched. "Torque to yield" bolts are fasteners that are designed to be tightened into the plastic region of the material's properties, and then typically an angle of rotation to ensure they are well into yield. Fasteners will naturally relax and lose a small amount of tension over time with cyclic loading. Figure 1 highlights the advantage of tightening into the yield region, demonstrating how as a bolt relaxes, if in the flatter section of the force vs. stretch curve there is a lower loss of clamping force for the same level of relaxation.

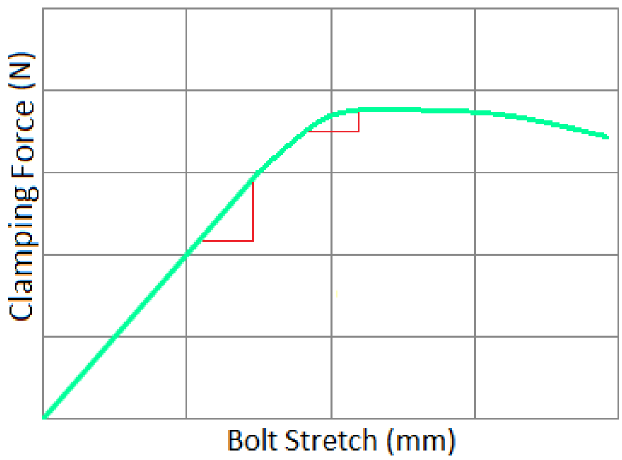

Figure 1 – Clamping force against bolt elongation, highlighting the difference in loss of clamping force dependent on the region of the force/elongation curve

The objective of this paper is to give an insight into the effects of connecting rod big end bore distortion due to the preload force from the bearing cap fasteners, and carry out an experimental analysis of the mechanical changes of a bolt in the pre and post stages of yield. Information on these particular connecting rod fasteners was not available and this provoked the experimental study into the behaviour of torque to yield fasteners demonstrated here. Having access to a large supply of new bolts allowed for consistent yield testing with new samples utilised for each test, opening the door to repeatable experimentation.

2 Testing

Testing was carried out on a Ford Sigma connecting rod (figure 2), using new torque to yield fasteners for each test.

Figure 2 – The Ford Sigma connecting rod assembly

The first employed tests were measurements of torque against fixed increments of angle of rotation, with bolt elongation recorded at each stage. Turning the bolts to over 900° of rotation well exceeded the operational torque but provided insight into the full range of the bolt's properties. Using figure 3**,** the yield point was estimated to be in the region of 40 Nm. Further testing of tightening and measuring elongation highlighted that when 40 Nm of torque was exceeded, the bolt did not return to its original length, clarifying this as the yield torque.

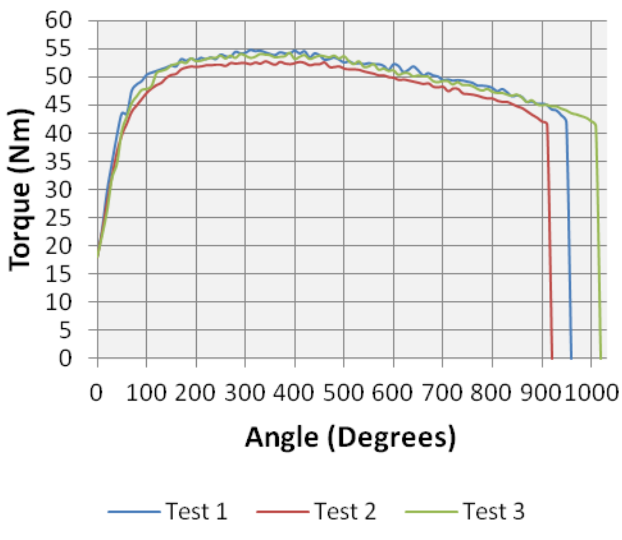

Figure 3 – Bolt torque against angle

By use of a CMM, detailed measurements of bore distortion were recorded, based on changes in diameter across three planes of the connecting rod big end journal (figure 4).

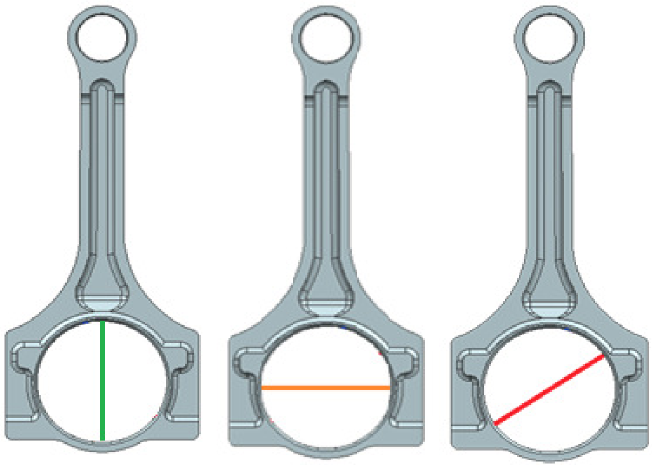

Figure 4 – A diagram highlighting the planes in which bore diameter was measured with the CMM

To correlate with practical measurements, an FEA model of the Ford Sigma connecting rod was also produced, simulating the bolt using RBE links (figure 5 and 6). Two load cases were set up, owing to opposing literature, stating differing cases for thread load distribution. The first views concluded that the majority of load is distributed across the first few engaged threads [1], decreasing in an exponential style pattern, and stating how the first 3 threads are all that is needed to develop the full load of a bolt [2] . The second view acknowledges the previous view, but regards that during yield, thread load distribution becomes much more even along the threads due to fastener deformation [3].

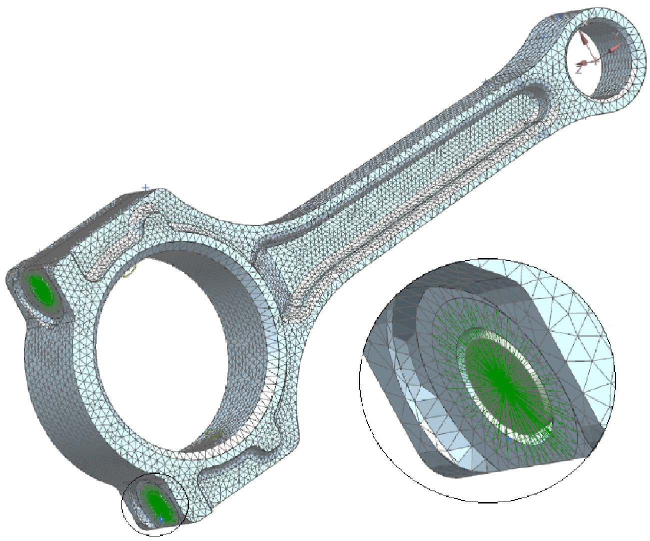

Figure 5 – Ford Sigma FEA model

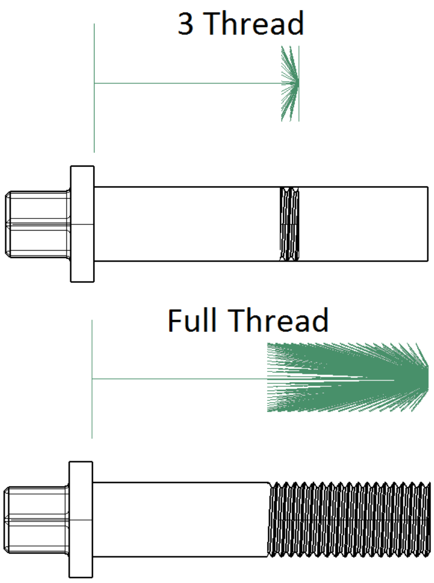

Figure 6 –full thread fastener models using RBE3s

The subsequent part of experimental testing involved using a Silverwing D-Scan 705 ultrasonic testing set, monitoring sound velocity through the fastener based on time-of-flight (*ToF*) measurements as torque was applied. This itself took lots of testing to set up a rig system and overcome testing issues before a solid test procedure was refined for implementation, such as machining the bolts flat (figure 7) and developing a repeatable physical length measuring technique.

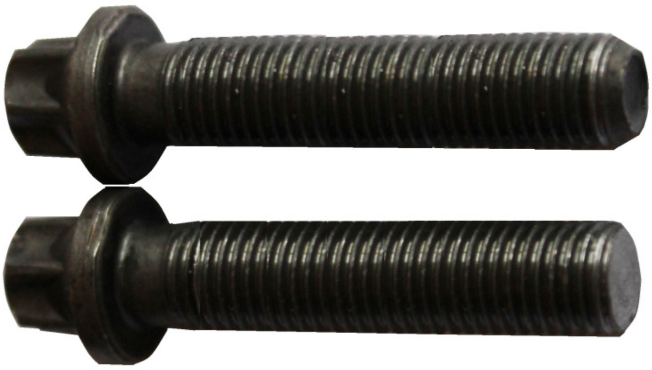

Figure 7 – Comparison between standard and machined bolts

In order to calculate the actual velocity, some equations had to be applied to extract the *ToF* based on using physical bolt length measurements. Initially, the UT set calculates distance based on,

$$d_{ULTRASONIC} = V_{PRE-SET} \times ToF \qquad (1)$$

By then knowing the pre-set velocity, the *ToF* was extracted by rearrangement of the known values,

$$ToF = \frac{d_{ULTRASONIC}}{V_{PRE-SET}} \quad (2)$$

From the now calculated *ToF*, by using the physically measured distance (length) of the bolt, the actual velocity was calculated.

$$V_{ACTUAL} = \frac{d_{PHYSICAL}}{ToF} \quad (3)$$

Once actual velocity measurements were calculated, values for Young's modulus were then determined based on rearrangement of the following equation,

$$V = \sqrt{\frac{E}{\rho}\left(\frac{1-\sigma}{(1+\sigma)(1-2\sigma)}\right)} \quad (4)$$

2 Experimental Results and Discussion

2.1 Bore Distortion

Using the FEA models simulating full thread pretension and first 3 thread engagement, based on the bolt elongation data obtained from practical experiments, pretension values were calculated in the elastic region where the Young's modulus is constant using the equation,

$$K = \frac{EA}{L} \times x \quad (5)$$

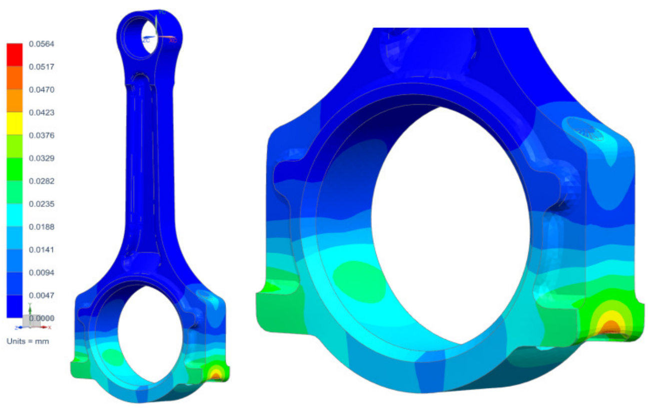

Figure 8 – The FEA model

Displacement measurements were then taken at 3 identical node locations from each load case for fair comparison against the 3 planes of measurements taken from the CMM testing (figure 9).

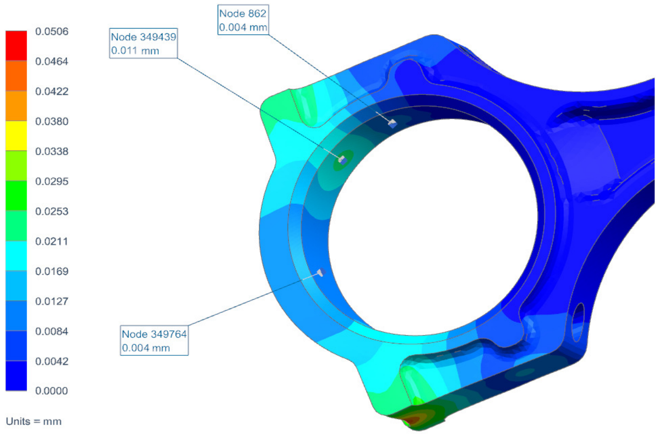

Figure 9 – One sample FEA model result

The results were then compared with the physically measured CMM results, and are presented as a % of accuracy in table 1.

		Accuracy as a % comparison					
		3 Threads			Full Threads		
Torque (Nm)	Force (N)	Diagonal Disp (%)	Lateral Disp (%)	Longitudinal Disp (%)	Diagonal Disp (%)	Lateral Disp (%)	Longitudinal Disp (%)
18	20366	-	-	-	-	-	-
23.00	25991	75	100	33	75	50	67
28.00	35015	92.5	67	60	82	50	100
33.00	41780	92.7	75	57	78.5	50	87.5

Table 1 – FEA result accuracy

It must be noted that viewing results as a percentage puts the distortion levels out of context, due to the level of microns involved. Every result is within a close range of microns. Overall, the combined accuracy of the full thread simulation was 72.46 % compared to the 3 thread accuracy of 71.11 %. Due to the marginal difference from these models, it is not possible to distinguish which thread load simulation most accurately represents real world load distribution. Further detailed work and modelling is required, but this exceeds the accuracy of the CMM machine used for measurements.

2.2 *Ultrasonic Velocity*

Figure 10 highlights the changes in velocity through the bolts as they are tightened, showing a clear pattern that the sound velocity reduces as torque increases. As torque increases, axial stress increases, and a greater reduction in velocity for a smaller increase in torque can be seen once the 40 Nm yield region of the fastener is reached. The variation on the starting velocity is due to the slight diversity in the bolt’s starting lengths after machining.

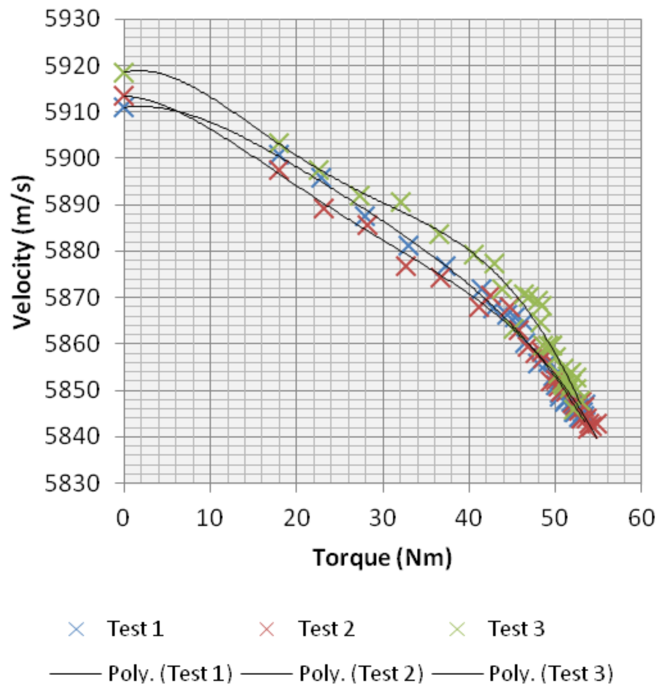

Figure 10 - Ultrasonic velocity against torque

Surprisingly, as figure 11 highlights, there is a gradual change in Young's modulus during the elastic region (up to 40 Nm), disagreeing with the fundamental rule of Hooke's law that indicates a constant value during the elastic region. The graph also displays a larger magnitude decrease in Young's modulus once the 40 Nm region has been met, again indicating the bolts yield point.

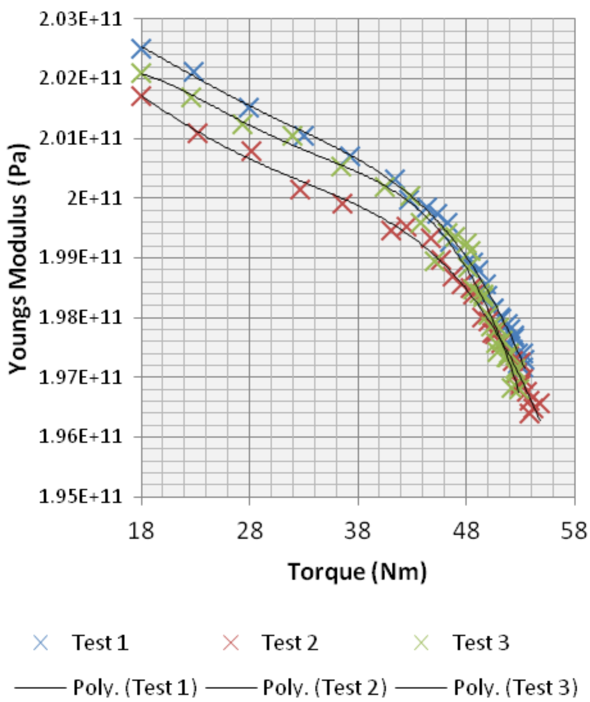

Figure 11 –Young's modulus against torque

Using equation (4) and knowing that calculated density is shown to reduce as torque increases, a result of the volume increasing as the bolt stretches; one would expect that the velocity would increase. The opposite has consistently been displayed with uncertainty as to the reasons.

Literature based research has drawn some potential theories. The first is a study comparing longitudinal velocity against hardness for steels.

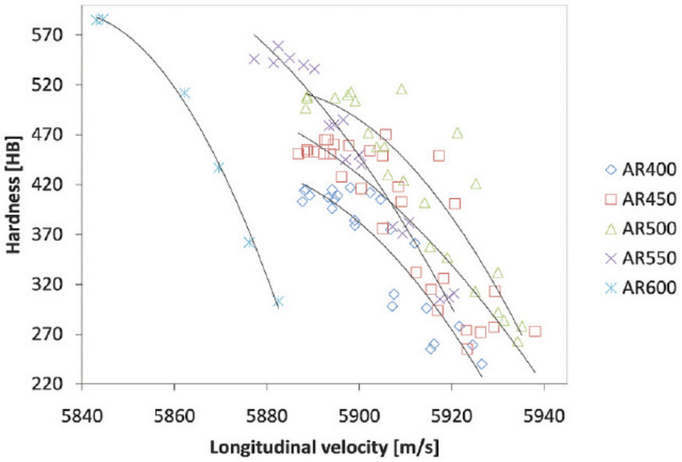

Figure 12 –Steel hardness Vs. longitudinal velocity (Lukomski and Stepinski, 2010)

The study highlights that increased hardness results in a reduction in ultrasonic velocity [4]. Another study highlights the effects of strain hardening with ultrasonic velocity, stating when a metal is strained it becomes harder, leading to the same conclusion of a reduction in ultrasonic velocity [5] (figure 13).

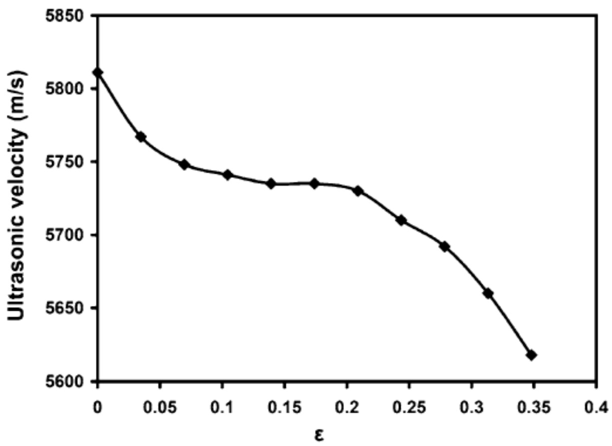

Figure 13 – Ultrasonic velocity Vs. Strain (Behjati et al, 2011)

The latter study suggests that the link between ultrasonic velocity reduction with hardness is due to a material micro structural change such as dislocations. This again agrees with further literature stating that reduction in ultrasonic velocity is an indication of loss of material strength or degradation [6].

A restriction in magnification did not allow microscopic inspection to display identifiable micro structural changes, therefore in the aim of linking hardness increase with strain and micro structural discontinuities; a hardness test was carried out on a sectioned and heavily yielded connecting rod bolt sample. The Rockwell hardness test was implemented in 6 locations (figure 14) and the associated results are found in figure 15.

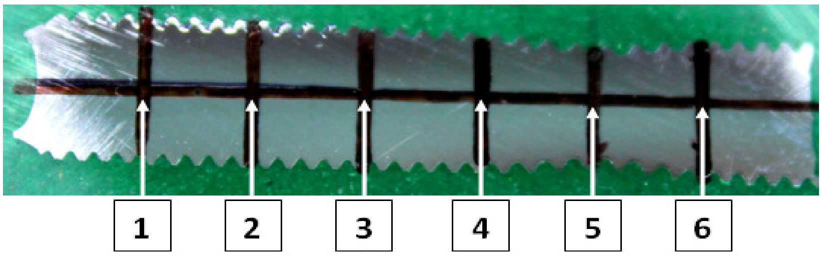

Figure 14 – Locations of the Rockwell hardness test

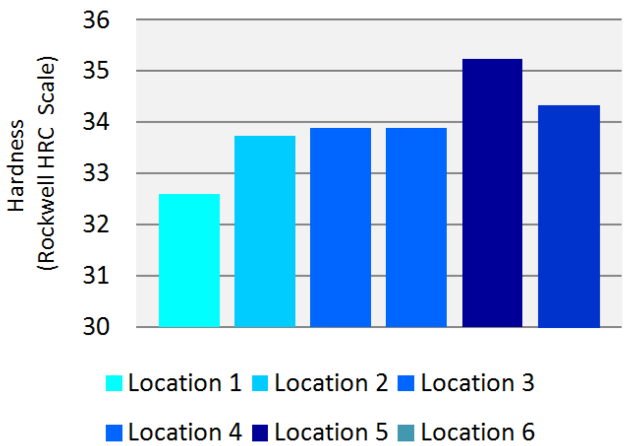

Figure 15 –Rockwell hardness test results

Location 5 is directly in the centre of the visually deformed part of the yielded bolt and has recorded the hardest area across the sample. Hardness can then be seen to reduce with distance away from this region, indicating that deformation has work hardened the bolt. This agrees with previous literature, exposing the ultrasonic velocity reduction with increased torque.

The final suggested ideology is with regard to the change in Young's modulus recorded using ultrasonic *ToF* measurement. Again, literature suggests that dislocations in the material lattice structure will lead to a reduction in Young's modulus, and it is felt that high frequency ultrasonic measurements are able to identify the localised micro structural variation in the stressed sample that a conventional bulk material tensile test is unable to establish.

3 Conclusions

This paper has brought forward a wide range of analytical and largely experimental approaches to evaluate connecting rod big end fasteners and the effects on the big end journal due to pretension. Some of the key findings are summarised below.

1. Torque against angle testing highlighted small-scale variations in fastener torque, a result of variations in coefficients of friction from one fastener to another.
2. CMM measurements highlighted how bolt pretension has an effect on big end journal form, indicating the potential for re-sizing after bolt replacement.
3. Correlation can be seen between physical distortion measurements and FEA predictions, but due to the micron scale of distortion, differences are minimal.
4. Ultrasonic testing highlighted a clear reduction in ultrasonic velocity as torque increased (axial stress increased).
5. An indication of the yield point can be identified by a larger magnitude of velocity reduction for an increase in torque.
6. Further testing has indicated a hardness increase in the localised yield region, agreeing with literature stating that an increase in hardness results in a decrease in ultrasonic velocity.

A change in Young's modulus has been identified in the elastic region using the ultrasonic testing method, highlighting discrepancy with the fundamental rule of Hooke's law based on tensile testing.

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