The Relationship between the Applied Torque and Stresses in Post-Tension Structures

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Abstract. This paper presents the non-destructive testing (NDT) method to determine the resultant stresses in mild steel bar usually employed in structures. The technique utilized ultrasonic pulse-echo that determined the wave velocity change due to torque applied between bolt and nut. Mild steel bar with nominal diameter of 19 and 25mm were used. The specimen was loaded by means of a torque wrench that gave the required amount of moment (~300Nm). This was carefully achieved manually. In order to measure the strain, strain gauges were employed. The direct strain gauge method gives the strain values. This strain is used to calculate the stress due to the applied load. The experiment had been carried out in a control environment with constant temperature. The relationship between torque-velocity, torque-strain and stress-strain is obtained and compared. The test results indicate that ultrasonic wave velocity decrease with the applied torque. This is due to degradation or loss of strength of the material. The potential of this NDT method to obtain structure quality and strength determination is discussed.

Introduction

Structures in general can be strengthened using different mechanism such as direct reinforcement, pre-stressed reinforcement, post-tensioning and etc. In pre-stress structures, a known stress is applied to the steel reinforcement members and thus the resulting stress in the structure is known. In post-tension structures, the tension is only applied after the beam or structure had been produced. The load is applied to the tendons inside the structure via bolts and nuts arrangement. Thus the resulting stress in the beam depends on the level of torque being applied to the nuts. This work investigates the relationship between the applied torque and the induced stresses in the bolts and nuts arrangement.

The ultrasonic stress measurement technique is based on the acoustoelastic effect [1]. The acoustoelasticity concepts originate from the interest in the measurement of third-order elastic constants (TOECs) in crystals. In 1953, Hughes and Kelly developed the theory of acoustoelasticity and used ultrasonic waves to determine these constants in crystals by varying the applied stress [2]. Ultrasonic wave propagating through an elastic material under stressed conditions change speed slightly due to the stress. In other word, acoustoelasticity is the term applied to changes in velocity or attenuation by applied or residual stress. This change is called an acoustoelastic effect, and the acoustoelastic technique can be applied to stress analysis of materials [3,4,5,6,7]. In practice, it is easier to measure velocity changes although velocity is a weak function of stress [8].

Yasui et. al. [9] studied on acoustoelastic measurement of axially loaded bolt with velocity ratio method. According to this study, acoustoelastic axial stress measurement method was proposed. This method employed longitudinal and transverse waves simultaneously by a combined longitudinal and shear wave mode transducer. The pulse-echo signals of both waves are digitally processed. The time resolution was enhanced. This velocity ratio method used the differences in the acoustoelastic coefficients of longitudinal and transverse waves. This method is highly practical since the value of axial load is calculated from the ratio of time of flight in a stressed and unstressed state. However, an extremely accurate time of flight measurement is required because ratio of transverse to longitudinal time changes only slightly with applied load. With this method, the axial load in short bolts used for automobile is estimated.

The ultrasonic velocities of both longitudinal and shear waves in solids can be expressed as a function of their density ρ , rigidity modulus G, and bulk modulus K, and can be written as

$v_l = \sqrt{\dfrac{K + \frac{4}{3}G}{\rho}}$ and $v_s = \sqrt{\dfrac{G}{\rho}}$ respectively.

The waves velocities can also be expressed in terms of the Lame' constants λ and μ , two elastic constants that described the behavior of the elastically isotropic solid, and can be written as $v_l = \sqrt{\dfrac{\lambda + 2\mu}{\rho}}$ and $v_s = \sqrt{\dfrac{\mu}{\rho}}$ respectively.

The work presented in this paper aims to understand the effect of torque on strain for mild steel bar. This was achieved primarily through the use of pulse-echo techniques where wave velocity and axial/lateral strain changes due to applied torque had been studied.

2. Materials and Methods

This work studied a type of mild steel bar used for reinforcement. Mild steel or low carbon steel is a type of carbon steels under category of carbon and alloy steels with carbon content less than 0.30%. This type of steel is suitable for sufficient strain to take effect since limited torque was manually loaded on specimen by using a torque wrench. Mild steel bar with nominal diameter of 19 and 25mm were used as the specimen for this work. With the same force applied longer specimen yields greater elongation and affects more on ultrasonic wave velocity. Since the accuracy of the applied stress is proportional to the effective length of the bar, the length of the mild steel bar was chosen to be 1.5m. The specimen had sufficient cross sectional area to place the transducer (10~16 mm in diameter). Both end faces of the mild steel bar are smooth and at right angle to the axis of the bar. This is to avoid errors and poor quality of the signal that is displayed on the ultrasonic instrument. Both ends of mild steel bar are threaded to fit the tightening nuts. The mild steel bar was fixed in the test rig where the tightening nut at one end applied the load and stretched the bar. The study was conducted on three physically identical specimens namely bar 1, 2 and 3 for each nominal diameter.

The axial tensile loading on the specimen was achieved by using a specially designed test rig (Figure 1) with two plates at the end of the column. This hollow rectangular column acted to resist buckling when compression force acted on it during the tensioning of specimen. The two plates were welded to each end of the column. Holes are drilled through the plates for placement of specimen through the test rig and also to sustain the nut during tightening. The plates were sufficiently thick to avoid deflection at the zone that was used for sustaining the nut. When the nut at one end of the specimen was tightened, the specimen is pulled and load is applied in the x-axis direction. Additional two small holes were drilled at the front plate and groove was made at the surface to place the strain gauge wires. Thus, the wire will not be damage due to the pressure from the nut on the plate. To introduce load to the specimen, torque wrench, ranging from 70 to 335Nm was used. A custom fabricate resin holder with rubber band was used to hold the transducer at the right position of specimen's cross sectional area. The rubber band ensured constant display of signal and eliminates errors due to the inconsistence pressure of transducer on the specimen.

3. Results and Discussions

Figure 2.1a showed axial strain and wave velocity versus applied torque for 19mm samples. The results showed that the ultrasonic wave velocity in unstressed condition for the 3 different bars were in the range of 5570~5588ms^{-1}. The ultrasonic wave velocity showed a linear drop of approximately 0.98% with applied torque ranging 70-240Nm. On the contrary, the strain increased in a parabolic trend from 0-1280 X 10^{-6}. Bar 3 showed lower ultrasonic wave velocity and rapid increase in strain compared to other bars. This is most probably due to the difference in metallurgical structures of bar 3.

Figure 2.1b showed axial strain and wave velocity versus applied torque for 25mm samples. The results showed that the ultrasonic wave velocity in unstressed condition for the 3 different bars were in the range of 5516~5623ms^{-1}. Bar 2 gave the highest wave velocity and lowest strain. The average drop of ultrasonic wave velocity was 1.02 % with applied load ranging 70-240Nm. Once again the strain increased in a parabolic trend from 0-708 X 10^{-6}. The lower increase in strain for bar 2 is also probably due to the differences in metallurgical structure compared to other bars. Although the wave velocity for all 3 bars decrease linearly with the applied load, the different ultrasonic wave velocity means each bar yields different metallurgical structure during production.

As an overall, both 19 and 25mm nominal diameter bars showed a trend of decreasing ultrasonic wave velocity with applied load. 25mm samples showed a significant variation in wave velocity compared to the 19mm samples due to the bigger dimension and less homogeneity. Smaller diameter bar showed a higher and consistent strain that indicate the effect of acoustoelastic is more obvious and homogeneous in smaller diameter bar.

Figure 2.2a showed lateral strain and wave velocities versus applied torque for 19mm bar. The lateral strain increased linearly with maximum value of 330 X 10^{-6} with bar 1 yields the lowest strain. Figure 2.2b showed lateral strain and wave velocities versus applied torque for 25mm samples. The lateral strain of both bars 2 and 3 increase with similar trend although the axial strain of bar 3 is similar with bar 1. In torsion, bar 1 showed a slow and sudden increased of lateral strain beyond 160Nm. Further investigation of 25mm diameter bar 1 was carried out and the result of 3 experiments revealed that the strain reading was inconsistent for torque below 160Nm (see figure 2.3). Although sufficient clamping had been applied, this inconsistencies is suspected to be due to the different resistant of bar during the experiments. All 25mm bars yield different ultrasonic wave velocity and decrease with applied load in a linear trend. The different in wave velocity might be due to the metallurgical difference in each bar.

If we plot the wave velocity versus axial and lateral strain, it is obvious that the wave velocity decrease linearly with the lateral strain but parabolic with the axial strain for both the 19 and 25mm bar (figure 2.4a and 2.4b respectively). Based on these figures, with a known dimension namely the length and diameter of the bar, the lateral and axial strain can be predicted from the measured velocity using the acceptable correlation (R^2>0.97) given in the figures. This is a very practical method since structures might have difference strength after installation on site after a period of time where strain gauge method is not applicable in this case. The difference in the microstructure shall be confirmed by using scanning electron microscope (SEM). The Young's Modulus and Poisson's Ratio shall be obtained for each bar to confirm and verify the differences obtain in the experiment. Furthermore, an error analysis such as Failure Mode Effect Analysis (FMEA) will be conducted to determine the sources of possible errors that may affect the results.

4. Conclusions

By correlating the applied torque to strain and wave velocity, a relation between axial and lateral strain with wave velocity can be obtained. The test results indicate that wave velocity decreases with the applied torque. This is due to degradation or loss of strength of the material. Since a wide range of wave velocity was obtained from 25mm samples, difference in metallurgical structure is expected for 25mm samples. By correlating wave velocity and strain one can easily predict the strength of structures in situ based on the wave velocity where usage of strain gauges is impractical for post tension structures. Future work will include the scanning electron microscopy (SEM), density of material, Young's Modulus and Poisson's Ratio by conventional method as well as ultrasound pulse-echo method.

References

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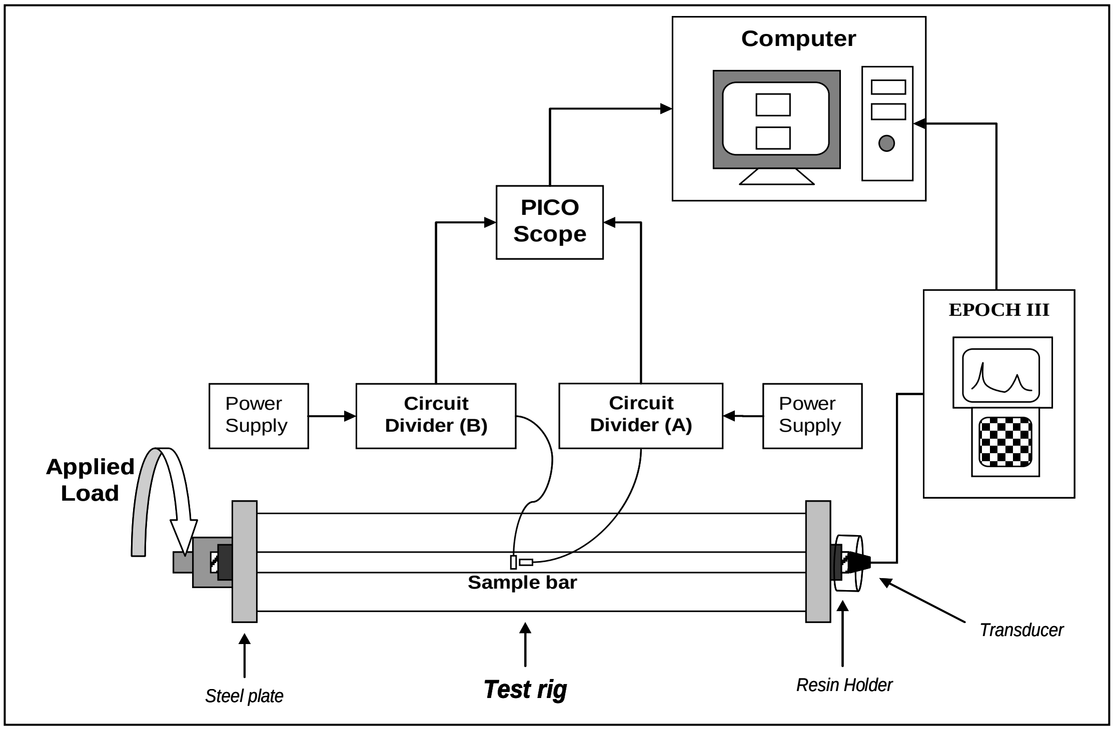

Figure 1: Experimental set up to conduct the study

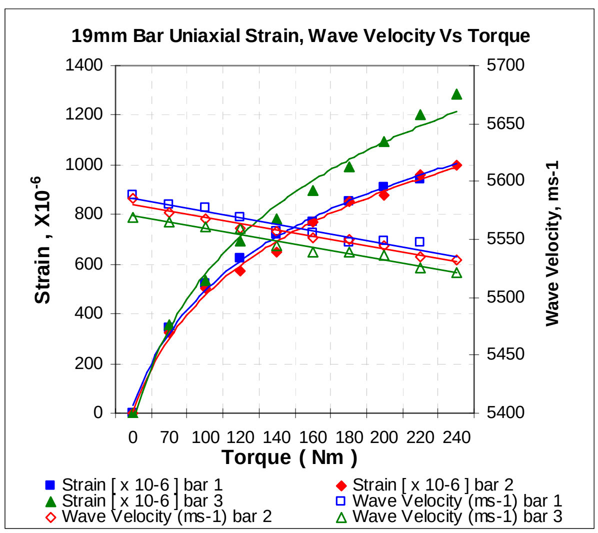

Figure 2.1a: 19mm bar axial strain and wave velocity versus torque

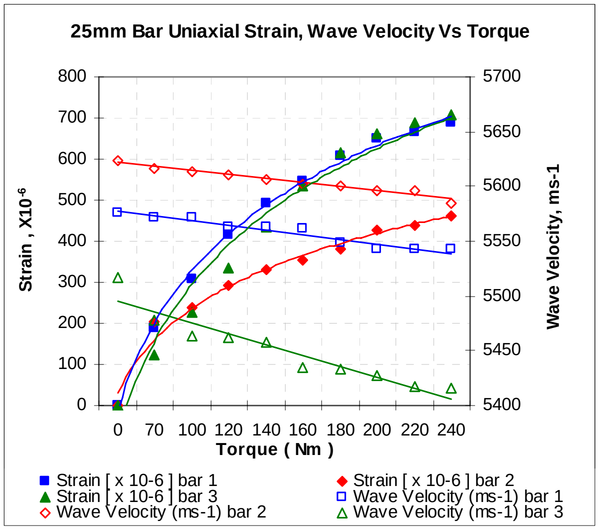

Figure 2.1b: 25mm bar axial strain and wave velocity versus torque

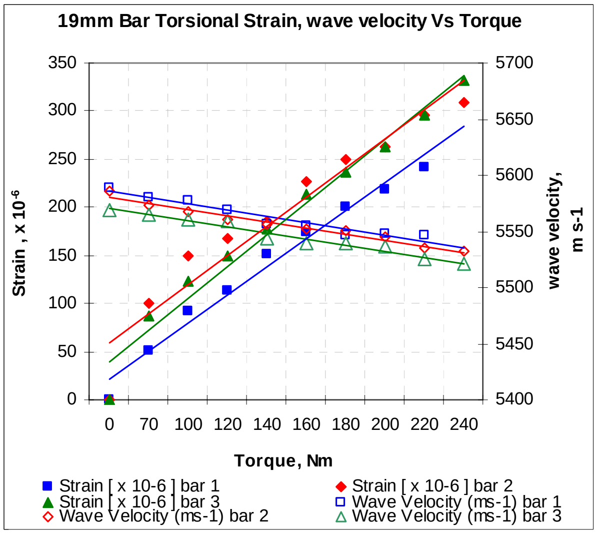

Figure 2.2a: 19mm bar Torsional strain and wave velocity versus torque

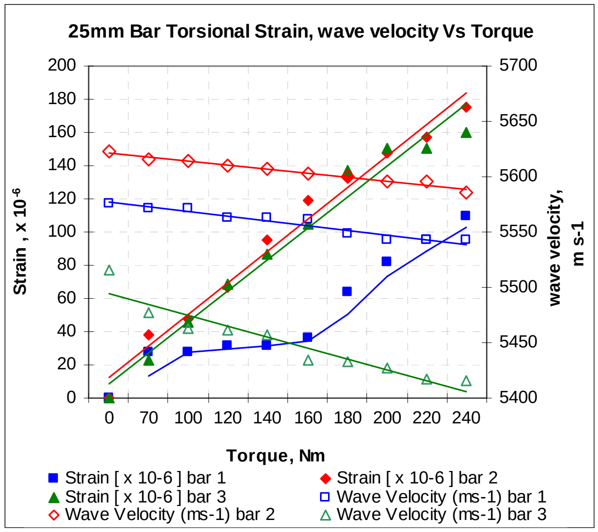

Figure 2.2b: 25mm bar Torsional strain and wave velocity versus torque

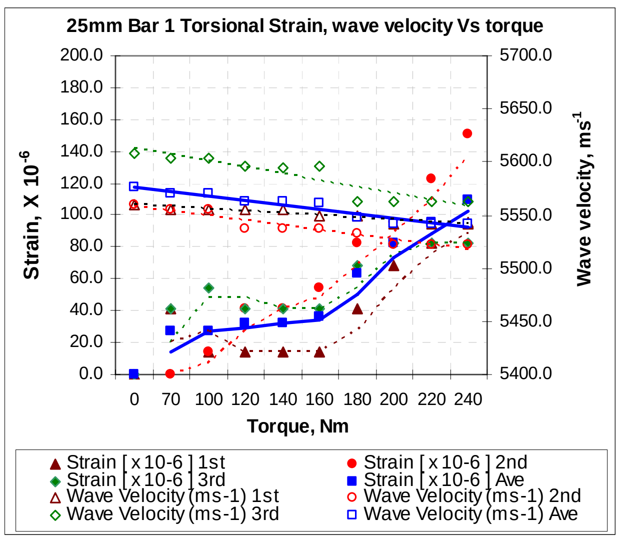

Figure 2.3: 25mm bar 1 Torsional strain and wave velocity versus torque