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Monitoring of Post-tensioned Tendons using Ultrasonic Guided Waves

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ABSTRACT: There is an urgent need for developing a non-destructive evaluation technique to monitor the condition of post-tensioned tendons embedded in grout without any physical intervention with the structural concrete member. The problem of durability in prestressed concrete members is most prevalent in chloride induced corrosion of tendons. Traditional monitoring techniques such as half cell potential mapping etc. have encountered problems in such structures. These are electrochemical techniques which relate corrosion rate and extent through assessment on surrounding concrete medium. Standard non-destructive methods such as impact echo, georadar etc. fail because of large size and limited accessibility of civil engineering installations. None of the techniques concentrate on damage detection through direct measurements on embedded tendons. Hence, there is a need for non-intrusive, in-situ and real time monitoring system for grouted tendons in post tensioned concrete structures. This study introduces ultrasonic guided waves as a potentially effective method to monitor grouted post-tensioned tendons for corrosion induced damages. Longitudinal guided waves are used to monitor tendons embedded in grout with simulated corrosion defects. Corrosion is simulated as both as area reduction (notches) and delamination (debonding). Two ultrasonic techniques of pulse transmission and pulse echo are used to monitor the healthy and specimens with simulated damages. Time of flight measurement in pulse echo indicated the damage location accurately and the amplitude of received signal in both pulse echo and pulse transmission is a measure of extent of damage. Detection of corrosion damages in tendons using guided wave modes show a promising future to be developed into a full fledged monitoring system. It can very effectively relate to the state of tendon undergoing corrosion.

1 INTRODUCTION

Post-tensioning concrete combines the efficient use of high strength concrete and steel to increase load bearing capacity of concrete construction with durability. This technique is widely used for bridge constructions where steel tendons run through the ducts in grout after concrete has hardened. The tendons are tensioned to apply a compressive load on the surrounding concrete thus, increasing its tensile load capacity. The tendon ducts are filled with alkaline grout to protect the tendon from ingress of moisture and inhibit corrosion. These structures can be very durable, if properly constructed and maintained. But some recent bridge failures like Ynys-y-Gwas in UK (Woodward & Williams, 1988) have raised concern over duarabilty issues of these structures. If grouting is incomplete and poor, it leads to voids making way for moisture ingress and hence, corrosion. Process is further accelerated by the use of de-icing salts on roads in cold weather countries. This can be catastrophic for the tendons since failure of one tendon leads to transfer of load to other tendons which can initiate a chain reaction of failures leading to collapse of structure. Hence, it becomes essential to develop a non-intrusive damage monitoring technique for embedded tendons to detect and monitor its state without any active intervention with the structural member.

The embedded nature of tendons combined with with the fact that the tendons are located in ducts makes the inspection of individual tendons very difficult. There are many methods by which non-destructive evaluation (NDE) of tendons can be achieved like visual inspection, georadar, covermeter, radiography, remnant magnetism method, reflectrometrical impulse measurement, thermography, tomography etc. But none of these techniques can be suitably employed for the monitoring of corrosion induced damages in tendons in prestressed concrete structures. They only give an idea about the onset of corrosion and relate corrosion through the assessment of the effect of corrosion on surrounding concrete medium. Some methods give only partial results in accessible areas, but none allows a full assessment of the condition of an internal, post-tensioned and grouted tendon. At this time, the basic and practical method of carefully openeing and visually inspecting a tendonat a location where there is resonable doubt is still considered as a most reliable option in the field. Additionally these techniques require interpretation by an experienced engineer. Removing tendon for visual inspection is detrimental to the structure. Therefore, it is imperative to develop a non-intrusive technique for early detection of corrosion in tendons in grout/concrete. It is recommended in this study to use a ultrasonic guided wave approach for the same. Guided waves have the capability of testing over long distances with a sensitivity often greater than conventional non-destructive testing techniques, have the ability to test multilayered structures, and are relatively inexpensive due to simplicity and sensor cost. Furthermore, frequency and mode tuning can be utilized for evaluation of different types of deterioration or damage. The embedded tendon in grout can be excited at one end. The tendon acts as a waveguide that assists its propagation. The waves leak into grout and thus attenuate before reaching the receiver at the other end of reinforcement. Irregularities in the tendon profile surface from corrosion can also cause more attenuation from reflections, scattering and mode conversions.

Use of guided waves for inspection of individual tendons has been in existence for many years. Pulse echo method is used for inspection in which guided waves were excited at the free end of tendon exposed in the anchorage region. The waves are reflected from the defects and the position of defect can be calculated from reflection arrival time. The maximum inspection range is limited by the amount of attenuation the wave experiences as it propagates. Material damping and leakage of energy into surrounding grout are the major causes of attenuation which are highly dependant on mode properties at the frequency of excitation. But the recent discovery of high frequency, low leakage modes (Pavlakovic et al., 2001) having minimum attenuation have projected guided waves as a good NDT tool for embeddded tendons.

This study is an attempt to explore the effectiveness of high frequency ultrasonic longitudinal guided waves for damage detection in tendons embedded in grout with simulated corrosion defects. Defects are seeded as notches in the form of area reduction and delamination in tendons in grout. Ultrasonic pulse echo and pulse transmission techniques are used in combination to predict the presence, location and magnitude of notch very efficiently. Pulse transmission could successfully relate to delamination effect of corrosion. To appreciate the proposed methodology, a brief introduction of corrosion mechanism in tendons and its effect on post-tensioned members is discussed.

2 CORROSION IN POST-TENSIONED TENDONS

2.1 *Mechanism of corrosion*

Grout used in ducts of post-tensioned concrete bridges is alkaline and the alkalinity typically ranges from pH 12 and 13. Due to this alkaline environment, tendons are passivated by an iron oxide film (Fe_2O_3) that protects them. But the intrusion of chloride ions depassivates steel and is the most important factor in the corrosion of steel. Corrosion is basically an electrochemical process where the anode and the cathode are on the same steel bar. At the anode, iron atoms lose electrons to become iron ions (Fe^{++}). At the cathode, oxygen in the presence of water accepts electrons to form hydroxyl ions (OH^-).

Anodic Reaction:

$$Fe \rightarrow Fe^{2+} + 2e^- \tag{1}$$

Cathodic Reaction:

$$2e^- + H_2O + \frac{1}{2}O_2 \rightarrow 2OH^- \tag{2}$$

The hydroxyl ions react with the ferrous ions to form hydrated ferrous hydroxide called Rust.

$$Fe^{2+} + 2OH^- \rightarrow Fe(OH)_2 \tag{3}$$

$$4Fe(OH)_2 + O_2 + H_2O \rightarrow 4Fe(OH)_3 \tag{4}$$

$$Fe(OH)_3 \rightarrow Fe_2O_3.2H_2O \tag{5}$$

Hence, the manifestation of corrosion is in the formation of these corrosion products on the surface of the rebar. The steel-concrete interface is altered where rust is formed. The pressure caused by rust results in cracks in the concrete leading to debond (Sharma et al., 2010)

2.2 *Corrosion in prestressing steel*

The steel used in post-tensioned concrete is prone to corrosion attacks due to chloride induced corrosion, and theoretically would be susceptible to stress corrosion cracking (SCC) or hydrogen embrittlement (HE). Chloride-induced corrosion is the most common form of corrosion in pre-stressed concrete. It can be relatively quick and can localize to cause significant reductions in cross-sectional area. The concrete surface is stained due to the rust produced which also causes cracking and spalling. Pitting corrosion is very common in pre-stressed concrete structures and can be quite destructive due to the concentrated pits of corrosion causing large reductions in cross-sectional area with a small amount of overall metal loss. Cross-sectional geometry of the steel along with high strength and high tensile loadings make a post-tensioned structure a possible candidate for catastrophic failure if chlorides are allowed easy access to the strand. Proper grouting of the post-tensioning ducts is necessary for corrosion protection and bond transfer, but complete grouting can be difficult due to lack of visibility and access to all parts of the duct.

The grout injected into post-tensioned ducts serves a dual role of providing bonding between concrete and the pre-stressing steel as well as protecting the steel from corrosion. But segregation of cement and water may lead to accumulation of bleed water at high points in the tendon profile while the grout is still plastic. As grout sets, bleed water may also collect at intermediate points in very tall grout columns or on top of horizontal pre-stressing steel. This phenomenon can result in voids in the duct and anchorage area leading to possible corrosion of tendon. Post-tensioning cables tend to be inaccessible to visual inspection, so that corroding tendons may go unnoticed for long periods of time (Iyer et al., 2002).

Most researchers have simulated debond by artificially introducing a debond element at the interface. But distinguishing feature of chloride corrosion in tendons is pitting where crevices are formed in the bar leading to local loss of area. Thus, in addition to debond, chloride corrosion manifests itself in local weakening of the bar. This study investigates the effect of local loss of material and loss of bond on the propagation of ultrasonic guided waves in tendons in grout. Simulated pitting effects are created by notches on the surface of the bar in varying percentages of its crossectional area. Simulated debond is generated by wrapping a double sided tape of varying length on the tendon embedded in grout. Simulated corrosion samples are ultrasonically monitored in pulse echo and transmission modes using guided waves to estimate the suitability of simulation techniques.

3 MODELING OF GUIDED WAVES

Previous studies (Beard et al., 2001) have shown that in an isotropic cylinder, such as tendons, dispersion of the wave takes place due to complex effect of the boundaries and multiple modes are generated. Specific modes can be excited selectively by choosing a frequency bound. In this work a standard software Disperse (Pavlakovic et al., 1997) has been used to determine the modes. The tendon is modeled as a two layer axially symmetric system , consisting of a solid steel cylinder embedded in infinite expanse of cement grout. Material properties that were used for steel and grout respectively are: Young's Modulus: 217 GPa and 11.2 GPa, Poissons Ratio: 0.29 and 0.21 and Density: 7900 kg/m^3 and 1600 kg/m^3. At high frequencies, material damping is also a significant contributor of attenuation and hence is included in the model. Longitudinal and shear attenuation was taken to be 0.003 and 0.043 nepers/ wavelength respectively for steel and 0.008 and 0.100 nepers/ wavelength respectively for grout.

The most significant factor in selecting a suitable mode is minimising the attenuation in order to maximise the inspection range. Longitudinal waves having no angular displacements and exhibiting only radial and axial displacements are chosen. It is easier to invoke a strong longitudinal wave. They are produced in the strands by keeping compressional transducers parallel to the guiding configuration at the two ends of the strands. The different longitudinal modes are excited by varying the excitation frequencies. The selection of frequencies is done based on the phase velocity dispersion curves. They are validated by experimentally confirming the signal fidelity.

To simulate corrosion damage, pre-stressing steel strands of 12.7 mm external diameter and 1.2 m length embedded in grout are used and dispersion curves are plotted **(Fig.1**). The selection of frequencies for testing is done based on the phase velocity dispersion curves.For tendons embedded in grout. High frequency lowest attenuating modes with displacement profiles centered in the middle of bar are chosen to minimize leakage into surrounding grout.

L (0, 7) mode at 1 MHz is chosen for study since it shows a different pattern linking the plateau regions of all modes together to form a single mode that propagates close to the longitudinal bulk velocity of steel. It also corresponds to the points of minimum attenuation **(Fig. 1).** The use of low frequency mode such as L(0,1) is undesirable, because the long wavelength means that energy can travel in the beam or duct as a whole rather than tendon alone [12]. Hence, this mode is utilized for ultrasonic monitoring of tendons with simulated corrosion defects.

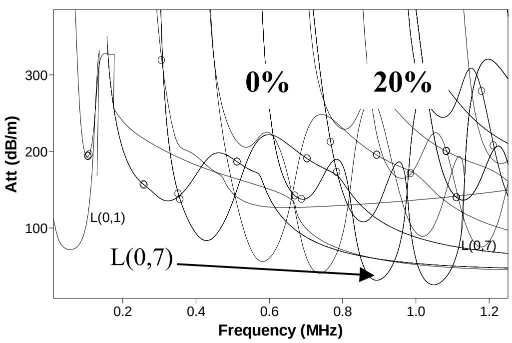


Fig.1: Attenuation dispersion curve for 12.7 mm tendon embedded in grout

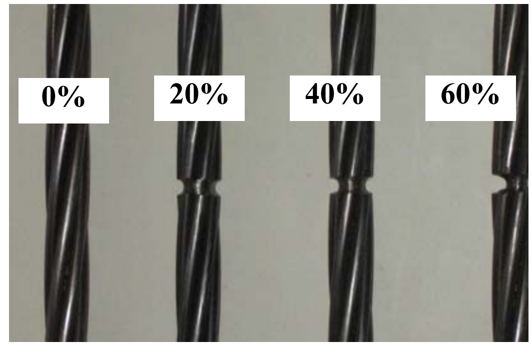


Fig. 2: Strands with 0%, 20%, 40% and 60% diameter reduction

4 SIMULATED DAMAGE STUDIES

4.1 Description of Experiment

To simulate corrosion damage, pre-stressing steel 7-wire strands of 12.7 mm external diameter and 1.2 m length are used for experiments. Cement grout with proportions of cement and standard sand as 1:1.5.is taken. The water cement ratio is kept as 0.45. Beam specimens of dimensions 150 mm x 150mm x 700mm with strand in the centre of crossection of the beam at the time of casting. The strand projected out by 250mm on each side of beam. Two sets of specimens were created to simulate pits and debonding. In one set of specimens, notches with symmetrical 0%, 20%, 40% and 60% diameter reduction are introduced in the middle of the bar before casting them in concrete **(Fig. 2)**. In another set of specimens, delamination is simulated by a wrapping a double sided tape on the tendon to different extents of 0%, 12.5%, 25%, 50%, and 75% representing different extents of debond and then embedded in grout **(Fig. 3a,b)**.

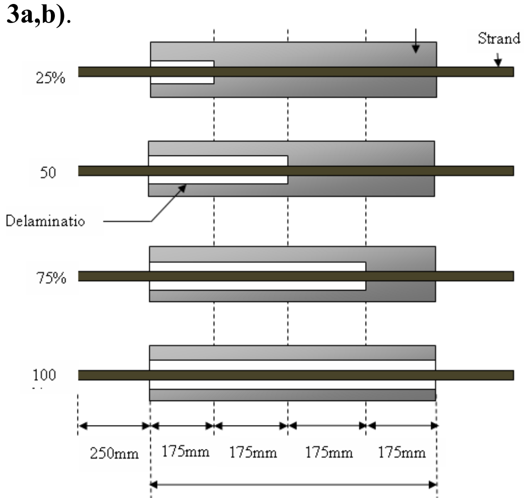


Fig. 3a: Strands in beams representing different extents of delamination

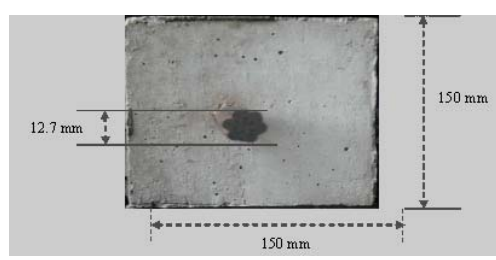


Fig. 3b: Cross-sections of beam with pre-stressing tendon

4.2 Experimental Set-Up Details

A standard ultrasonic testing system consisting of a pulser /receiver, transducers, and display devices is used (Sharma et al., 2010). The transducers were attached at the two ends of the bars by means of a holder and a coupling gel between the bar and the transducer. Driven by the pulser, the compressional transducer generates an ultrasonic pulse that propagates through the embedded bar in the form of longitudinal waves. The excitation signal consisted of a compressive spike pulse with duration ranging from 10-70 ns. The pulse transmitted at the other end of the tendon is recorded using a receiving transducer. In this study, contact transducers with central frequency of 1 MHz is used. The notch specimens are tested in pulse echo and transmission modes first in air and then after embedding them in concrete. The delamination specimens are ultrasonically monitored in the pulse transmission mode only. The debond specimens are monitored to relate the effect of extent of delamination on input pulse.The results were reported in the form of Voltage-time (V-t) curves.

5 RESULTS AND DISCUSSIONS

5.1 Simulated Notch Damages

5.1.1 Tendon testing in air

The notched tendons are tested in pulse echo and pulse transmission using L (0, 7) mode at a frequency of 1 MHz. Pulse echo records show a notch echo (NE) as well as the back wall echo (BWE) in tendon testing in air. In a healthy specimen, the peak is the BWE. In a notched specimen, the 1st peak is NE and the 2nd peak is BWE **(Fig. 4b)**. Appearance of NE indicates presence of the defect in the tendon in air. From the time of flight of NE, the location of the damage can be computed.The magnitude of damage can be directly related to the magnitude of the peak received after reflection from NE as well as BWE. It is observed that the amplitude of NE increased and that of BWE reduced with the increase in the notch dimensions **(Fig. 4).** As the magnitude of notch increased, more signal energy is reflected back from the notch and less of it travels to the back wall. Therefore, the peak-peak voltage amplitudes of NE's and BWE's can be related to the extent of damage. However, the NE peak did not rise perceptibly even at 20% damage. Thus, its discernibilty to small notches is not very high. This is due to the core seeking nature of the mode L (0, 7) used for testing. As the energy of the mode is concentrated at the centre of the bar, the mode is insensitive to surface irregularities.

In the pulse transmission testing with L (0,7) mode, the peaks observed **(Fig. 5)** are the transmitted peaks obtained after traveling length 'L' of embedded bar. The arrival time of the pulse is not affected by the presence of the notch. Thus, the notch location is not discernible through pulse transmission. However, studying the relative change in the amplitude of input pulse and the transmitted pulse (P/T-Notch), the severity of the damage can be calibrated. As the percent of damage increased from 0% to 60%, the magnitude of P/T reduces **(Fig. 5).** This is because as the notch dimensions increased, more energy is reflected back and less of it travels through the bar to reach the other end. Hence, relative signal attenuation of the transmitted pulse can relate to the extent of the notch in the tendon in air.

Thus, peak to peak voltage amplitudes of reflected and transmitted peaks in pulse echo and transmission methods respectively closely relate to the extent of damage. However, the attenuation of the peak is not linearly proportional to the extent of damage. This is due to the core seeking mode shape of L (0, 7) mode used.

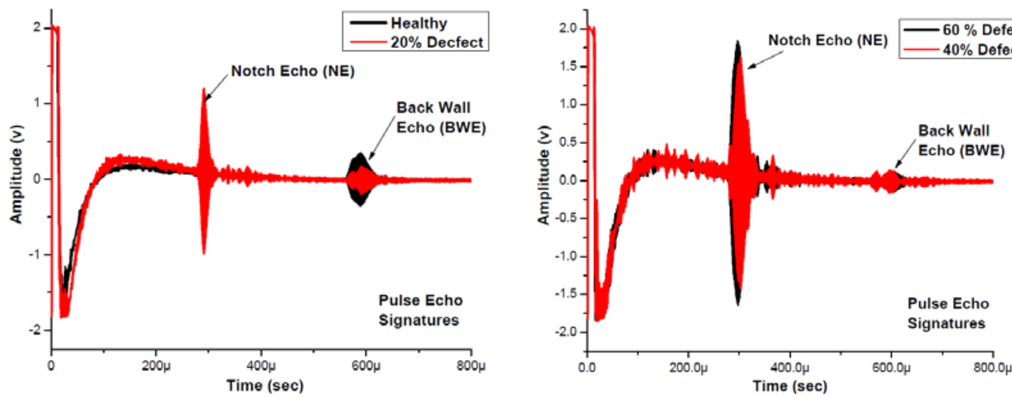


Fig. 4: Pulse Echo signatures (Notch at L/2)

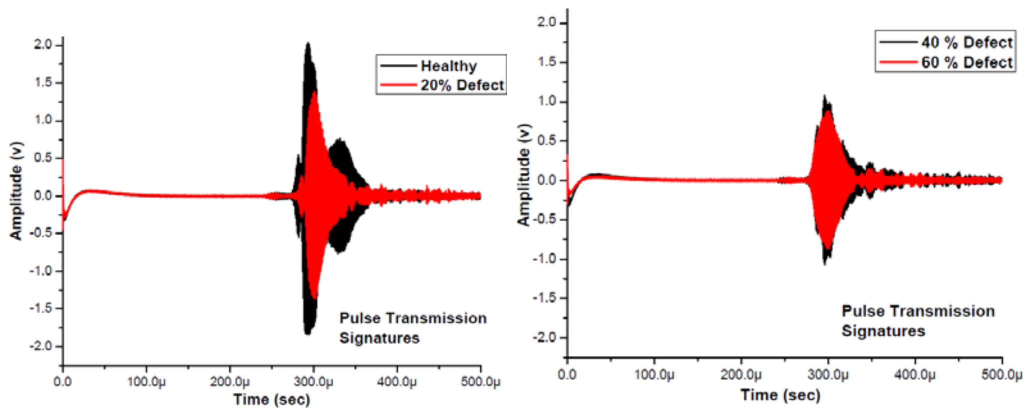


Fig. 5: Pulse Transmission signatures (Notch at L/2)

5.1.2 Tendon testing in grout

Tendon is embedded in grout and testing is carried out only in pulse transmission mode. This is because of the presence of attenuating concrete, leakage of energy takes place and hence no peaks are obtained in P/E. Also because of large surface area of tendons leakage further increases. Similar trends are observed in P/T testing of notched tendons in grout **(Fig. 6a)** Another significant observation from these graphs is the huge amount of signal attenuation experienced by the input pulse because of the presence of attenuating grout. Hence, it is signifies the importance of selection of an ideal low leakage modes for damage detection in embedded strands.

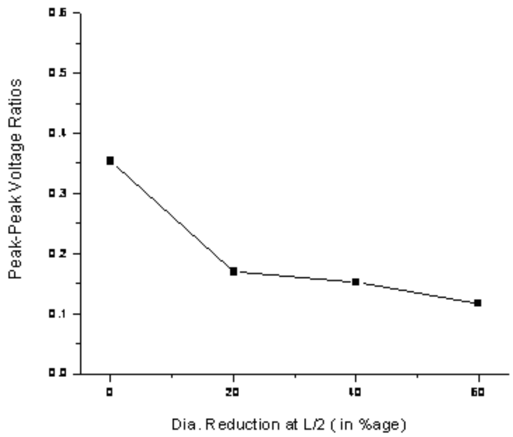
5.2 Simulated Debond Damages

In simulated debond specimens, L (0, 7) mode is used for testing in pulse transmission .As the percentage of delamination increases, the transmitted signal strength (P/T) keeps on rising **(Fig. 6b).** As the percentage of delamination between steel and concrete is increased from 0-100%, transmitted signal strength rises continuously since the amount of energy leaking into the surrounding concrete decreases with increase in percentage delamination. Hence, an increase in the input signal strength in pulse transmission can successfully relate to the presence as well as extent of delamination in tendons in grout.

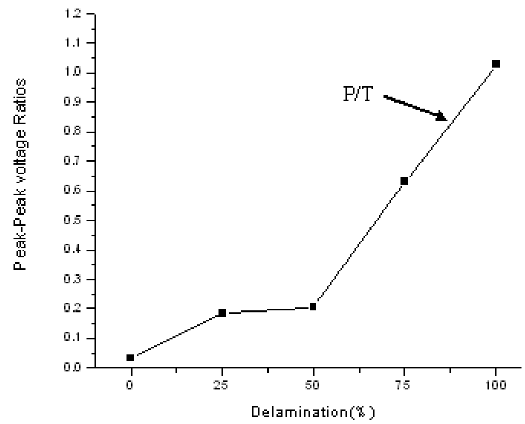
6 CONCLUSIONS

The methodology established in the study utilizing specific guided wave modes can be applied for in-situ monitoring of post-tensioned tendons embedded in grout. Following major conclusions are drawn from the study:

- Corrosion in tendons is simulated in the form of notches (area reduction) and delamination and is well picked up by high frequency guided wave modes.
- They not only indicates the presence of notch damage but also gives the exact location and magnitude of damage by efficient combination of the two ultrasonic monitoring techniques.
- Delamination marked by rise in signal strength rise is also well picked up by guided waves.



(a) Peak to peak voltage ratio trends of P/T with notched specimens



(b) Peak to peak voltage ratio trends of P/T with delamination specimens

Fig. 6: P/T trends in notched and delaminated specimens

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