Evaluation of concrete compressive strength in CFST column using ultrasonic bulk waves: A simulation study

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Abstract. Concrete filled steel tube (CFST) column has been used recently in a wide range because of the advantage of both steel and concrete materials. Evaluation and long-term monitoring of concrete compressive strength are not easy to achieve using destructive methods. In this study, CFST column is simulated to evaluate the concrete compressive strength using embedded and mounted piezoceramic sensors to transmit and receive ultrasonic bulk waves. The results showed a significant relationship between concrete compressive strength and the speed of the wave signals. These results can be utilized to characterize the concrete in-situ and monitor its material degradation permanently.

Keywords: Concrete filled steel tube; Ultrasonic bulk waves; Compressive strength

1. Introduction

Concrete-Filled Steel Tube (CFST) columns have been extensively used in many structures like high rise buildings, bridges, and off-shore platforms due to their load carrying capacity, improved ductility and economy in construction [1]. However, the steel covering the concrete core make the classical tests for concrete or visual inspection for damages of a difficult task. Ultrasonic waves have been employed for several decades in damage detection and material characterization. Non-destructive tests are among the main benefits of the ultrasonic waves. They have been used in different fields of construction to monitor structures against global and local defects [2-4].

Bin Xu et al [1] used Sweep sinusoidal signal with a frequency region from 500 Hz to 10 kHz to evaluate CFST column against debonding. They succeeded to detect artificial debonding using wavelet packet analysis. Shi Yan et al [5] employed a time reversal technique to evaluate the compactness of concrete in CFST columns. They used smart aggregate (SA) embedded inside the CFST column to transmit the required waves. Concrete voids that may arise due to shrinkage and/or inadequate compaction during concreting inside CFST column were studied by Wei Dong et al [6].

The heterogeneity of concrete causes some limitations in non-destructive testing (NDT) applied in concrete structures [7]. To avoid wave scattering, frequency of the transmitted wave should not exceed 100 kHz [8, 9]. The shear and longitudinal velocity equations relate between the material properties of concrete and acoustic properties of the wave. This can be found in Equations (1 & 2) below [9]:

\[ C_L^2 = \frac{\lambda + 2\mu}{\rho} \]  \hspace{1cm} (1)
\[ C_s^2 = \frac{\mu}{\rho} \]  

(2)

where \( \mu = E/(1 + \nu) \) and \( \lambda = E\nu/[(1 - 2\nu)(1 + \nu)] \) are Lamé constants, \( C_L \) is the longitudinal velocity, \( C_S \) is the shear velocity, \( E \) is the elastic modulus, \( \rho \) is the density, and \( \nu \) is Poisson’s ratio. According to the relation between wave speed and material properties, as stated in equations 1 & 2, the main objective of this research is to investigate the effect of concrete strength change on the wave speed used through the simulation process.

2. FE Method and Ultrasonic Wave Simulation

Convergence of numerical results is highly affected by the temporal and spatial resolution of the FE model [10]. The integration time step, \( \Delta t \), can be calculated through Equation (3).

\[ \Delta t = \frac{1}{20f_{\text{max}}} \]  

(3)

Where, \( f_{\text{max}} \) is the highest frequency of interest. The accuracy of the solution depends highly on the integration of the time step, \( \Delta t \). Spatially, the size of the elements is calculated according to Equation (4).

\[ l_e = \frac{\lambda_{\text{min}}}{20} \]  

(4)

Where \( l_e \) is the element length and \( \lambda_{\text{min}} \) is the shortest wavelength of interest. Using COMSOL software, the 2D geometric model of CFST column has been adapted to simulate the testing process by applying 40 kHz ultrasonic wave using PZT-5 piezoelectric sensors. The transmitter sensor was embedded inside the concrete whereas the receiver sensors have amounted on the steel encasement. Figure 1 shows the meshed column.

![Figure 1. CFST column meshed by COMSOL](image)

The wave signal employed in this simulation is composed of 10 volts, five cycles endowed with Hann window as shown in Figure 2.
The column dimensions were taken 3 m length 30 cm diameter with 3 mm steel encasement thickness. Concrete compressive strength was taken 20 to 45 MPa by an increment of 5 MPa. Concrete compressive strength was calculated in terms of modulus of elasticity using the Equation (4) [11].

\[ E_c = 4700\sqrt{f'c} \quad (4) \]

Where \( E_c \) is the modulus of elasticity of concrete and \( f'c \) is the concrete compressive strength.

3. Results and Discussion
The simulation process was conducted using COMSOL Multiphysics software and choosing a time-dependent study. Time of flight of the wave signal was chosen as \( 2 \times 10^{-4} \) sec. Results were saved in terms of wave amplitude (V). Figure 3 shows the wave signals captured from the receiver sensor nearest to the transmitter sensor for different concrete compressive strength values.
Figure 3. Wave signal amplitude for different concrete compressive strength, (a) wave signal amplitude for 20 MPa concrete compressive strength, (b) wave signal amplitude for 30 MPa concrete compressive strength, (c) wave signal amplitude for 40 MPa concrete compressive strength.

To compare the different wave signals captured for different concrete strength, Figure 4 has been created. Each wave signal has been recognised by different colour. A part of these curves has been zoomed in Figure 5 to compare precisely between the results. It can be noticed that the time of flight for the higher compressive strength value is less than that for the lower compressive strength. This leads to conclude that wave propagates faster in higher concrete compressive strength. This result is expected because usually higher compressive strength material has fewer voids and consequently the wave propagates faster.
Table 1. time of flight for captured wave signals.

| Compressive strength, MPa | Time, sec. | Relative change, % |
|---------------------------|------------|--------------------|
| 20                        | 1.18*10^-4 | -                  |
| 25                        | 1.12*10^-4 | 5.08               |
| 30                        | 1.09*10^-4 | 7.62               |
| 35                        | 1.07*10^-4 | 9.32               |
| 40                        | 1.05*10^-4 | 11.01              |
| 45                        | 1*10^-4    | 15.25              |
4. Conclusions
In this research, the concrete compressive strength of CFST column was investigated by employing wave speed in terms of time of flight of the wave signal. Results showed the direct relationship between the wave speed and concrete compressive strength. It has been concluded that the faster wave propagation means higher concrete compressive strength. This can be seen in the time of flight values for the different compressive strength, i.e. 20 and 45 MPa have a time of flight values as 0.000118 and 0.0001 second, respectively. This could contribute to the inspection of concrete in inaccessible areas.

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