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Experimental characterization of ultrasonic nonlinearity in concrete under cyclic change of prestressing force using Nonlinear Resonant Ultrasonic Spectroscopy

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HIGHLIGHTS

- Prestressing force effects on decreasing the ultrasonic nonlinearity.
- Cyclic loading effects on increasing the ultrasonic nonlinearity.
- Sensitivity comparison of NRUS with UPV on measuring the ultrasonic nonlinearity.

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ABSTRACT

In this paper, an experimental study was conducted to investigate the effect of varying prestressing force on the nonlinearity of concrete. Prestressed concrete beams, which have been rarely studied in terms of ultrasonic nonlinearity, were prepared. When the prestressing force changes, the stress condition of the concrete inside the beam is affected. This leads to the generation of micro-cracks and a change of the mechanical properties, and as such it is necessary to introduce a nonlinear ultrasonic technique that sensitively reflects microstructural change. In the experiment, a repetitive prestressing load history, which includes maximum levels of 45%, 60%, and 75% based on the compressive strength, was designed to evaluate the effects of repetitive loading and different levels of loading on the nonlinearity. A comparison with the measured results of the linear ultrasonic method was also carried out to verify the stress-dependent change of nonlinearity induced by external loads. With the experimental results, the adopted technique is found to be more sensitive to damage then conventionally used ultrasonic method. As the investigation of the methodology is effective in prestressed concrete structures, the possibility of ultrasonic nonlinearity as an indicator of prestressing force is evaluated.

1. Introduction

Prestressed concrete (PSC) beams have been adopted in various infrastructures based on the strength of their cost-effectiveness, spatial savings, crack resistance, and possibility of use in long-span bridges. To increase the lower tensile strength, tendons in a sheath tube are strained by hydraulic pressure and jacked before cutting them. Therefore, the concrete in a PSC beam suffers pre-applied compressive stress and the beam can sustain higher tensile forces according to the self-weight and the external loads. However, there are various causes of reduced prestressing force such as elastic shortening, shrinkage, creep, and relaxation [1–4]. Under these effects, the structure loses its durability, which can lead to collapse of the entire structure. Meanwhile, when concrete is subjected to external loads, microstructural deterioration and change of mechanical characteristics occur. When a low level of load is applied, cracks on a micro-millimeter scale occur in the cement matrix and the aggregate area. As the load increases, the micro-cracks propagate and the bonding force between the interfacial zones weakens and macro-cracks occur. As the micro-cracks are formed, the concrete behaves nonlinearly and the ultrasonic characteristics are changed. Recently, studies on this phenomenon have been actively conducted. As a representative example, research is underway to estimate the compressive or tensile load history of concrete using coda wave [5]. This is done by determining acoustoelasticity, which shows the load-dependent characteristics of concrete. This is a technique that can detect characteristic changes

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due to micro-cracks in the initial state more sensitively compared to the conventional ultrasonic pulse velocity method [6–8].

Meanwhile, changes in ultrasonic characteristics, based on the nonlinear stress-strain relationship of a material, have been actively investigated using nonlinear ultrasonic methods, such as nonlinear ultrasonic spectroscopy, the higher harmonics, the time shift, etc. The above phenomenon began with the introduction of AKIRA HIKATA for the evaluation of aluminum in 1965. Zaitsev reported the nonlinear-modulation characteristics of a cracked glass specimen in 2006 [9,10]. Since the 2000s, methods using nonlinear characteristics of ultrasonic waves have been applied to evaluate concrete, which is a heterogeneous medium. Shah carried out experiments on harmonics generation with standard size concrete specimens, and a 150 mm cubic concrete specimen [11,12]. In addition, Neild measured the nonlinear vibration characteristics of a laboratory-scale concrete beam to assess the degree of damage, including the initial state, and reported that invisible micro-cracks can be detected [13]. The nonlinear vibration characteristics of concrete beams having a span size of 3000 mm have been verified through both experiments and numerical analyses, and the shift of the resonant frequency was analytically verified based on the results of the experiments [14,15]. Through the results of preceding studies, it is confirmed that it is possible to evaluate the nonlinear characteristic of concrete beams using the nonlinear ultrasonic method. Moreover, it would be meaningful to adopt this technique for prestressed beams in addition to RC beams.

In the present work, an experimental study was performed to characterize the ultrasonic nonlinearity of concrete due to the change of prestressing force in a PSC beam. By measuring the nonlinearity parameter, the effect of repetitive cyclic loads on ultrasonic nonlinearity and microstructural damage in concrete with change of the prestressing force was investigated. For this purpose, repetitive loads were applied and released up to certain level of compressive strength of concrete, and at each load level, the nonlinearity parameter was measured. In addition, the experimental results obtained by the linear ultrasonic method for the beam were compared to confirm the stress-dependent change of nonlinear characteristics induced by the external loads. With the experimental results, the effects of cyclic change of the prestressing force and the creation of micro-cracks were studied. Finally, the nonlinearity parameter was evaluated as a trial indicator for the change of prestressing force.

2. Experiment details

2.1. Beam preparation

The prestressed beam for the experiment was prepared in a factory, and the mix proportion is shown in Table 1, where W is water, C is cement, S is fine aggregate, G is coarse aggregate, and AD denotes the admixture. The maximum size of coarse aggregate particles is 25 mm and that of fine aggregate particles is 4 mm, with a water to cement ratio of 0.42 and admixture included at a rate of 2.81 kg/m^3. The beam is demolded after 24 h of steam curing and set for applying prestressing forces in the laboratory. After 28 days, by the ASTM C 39 test for five cubic samples, the compressive strength of the beam was measured as 30 MPa [16]. Fig. 1 provides a cross-sectional description of the beam. The dimensions of the beam are 240 mm in width, 1000 mm in height, and 3000 mm in length. This section is decided to reach higher internal stress and to prevent a shear failure. As the objective level of prestressing force is about 75% of the compressive strength, a 65 mm diameter sheath tube is inserted in the center of the upper and lower sections with 8 steel wires of 15.2 mm diameter. To avoid distortion and a shear failure, the anchorage zone is reinforced with closed stirrups. Using two hydraulic jacking machines at opposite ends of the beam, prestressing force is applied at the same intervals.

Table 1
Mixing proportion and compressive strength of beam.

W/C (%)	Unit Weight (kg/m3)					Strength (MPa)
	W	C	S	G	AD	
0.42	180	360	837	970	2.81	30.0

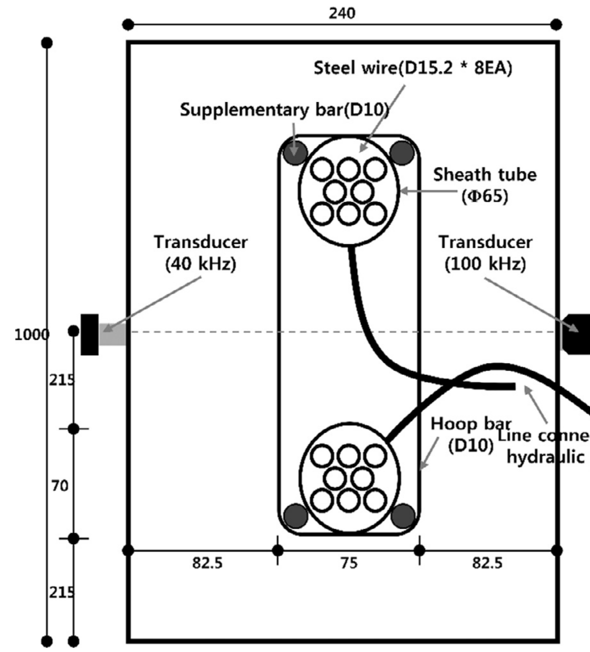

Fig. 1. Section description of the prestressed concrete beam.

2.2. Nonlinear Resonant Ultrasonic Spectroscopy (NRUS)

When the concrete is subjected to loads, the existing linear stress-strain relationship exhibits nonlinearity, which is closely related to the formation of micro-cracks in the concrete. In particular, when the external load is large enough that the level of stress generated in the concrete also becomes high, it is generally difficult to determine if the stress level is not sufficient [17].

$$\sigma = E\varepsilon \quad (1)$$

Equation (1) describes the existing linear stress-strain relationship and expresses the relationship between stress and strain through the linear elastic modulus E.

$$M(\varepsilon, \dot{\varepsilon}) = M_0\{1 - \alpha_h[\Delta\varepsilon + \varepsilon(t)\text{sign}(\dot{\varepsilon})] + \cdots\} \quad (2)$$

On the other hand, Eq. (2) is a one-dimensional relation expressing the nonlinear hysteretic behavior of concrete, M, where α_h is the value of the primary nonlinear factor according to the hysteresis to be measured in this technique. Also, $\Delta\varepsilon$ is the strain difference, where $\text{sign}(\varepsilon) = 1$ if $\varepsilon > 0$ and $\text{sign}(\varepsilon) = -1$ if $\varepsilon < 0$ [18]. When ultrasonic waves are passed through a medium having such nonlinear behavior, there are some characteristics where the measurement results are different from the initial incident wave. As a typical example of nonlinear ultrasonic characteristics, higher harmonics and resonance frequency shift can be generated and these characteristics are sufficiently sensitive that they can be affected by micro-cracks on the micrometer scale. Therefore, the nonlinear hysteretic behavior of concrete can be measured even if the stress