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Wave propagation in concrete containing artificial distributed damage

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Abstract

The propagation of ultrasonic pulses through highly inhomogeneous mortar is discussed in this paper. The inhomogeneity is introduced by light plastic inclusions in different volume contents to simulate distributed damage. Wave propagation in such media becomes dispersive and therefore, although pulse velocity is influenced, other easily measured features are much more indicative of the inclusion content. These features can certainly improve characterization since they include information from the whole waveform and not only the leading edge.

Keywords: Mortar, inhomogeneity, scattering, wave propagation, mechanics of solids.

1. Introduction

Evaluation of concrete quality is a subject concentrating efforts of the engineering community for many decades. This is because the catastrophic failure or malfunction of civil infrastructure can lead to human casualties as well as high financial cost. Concerning specific macroscopic flaws, like bridge cracks, delaminations or ungrouted tendon ducts, accurate characterization is possible [1-3]. For distributed damage though, the traditionally used pulse velocity can provide only rough estimations [4] being quite “non-responsive” to damage to a large extent [5,6]. Despite its reduced sensitivity, pulse velocity has certain advantages. One is that it exhibits limited dependence on the length of propagation path, the type of transducers as well as the coupling conditions. Another, is that it can be measured using very simple equipment, without the need of delicate waveform analysis, and therefore, it has been used for more than fifty years. This leads to the next advantage which is the long-established, though rough, correlations with concrete strength. In many experimental works, compressive strength and pulse velocity were simultaneously studied, resulting in a variety of curves for strength estimation [7-12].

Nowadays, waveform acquisition is standard to most of the available equipment for ultrasonic testing. Therefore, the use of other simple features that draw information from the whole pulse is not hindered. The present paper aims to indicate some features that take advantage of the scattering parameters of the material, to characterize more accurately the material condition.

Experimental measurements were conducted in cementitious material containing small light inclusions to simulate distributed damage in different volume contents. It is seen that the inclusions influence pulse velocity but they have stronger influence on other parameters like the group velocity, the amplitude or the transmitted frequencies. The simulated damage has resulted in significant velocity dispersion (frequency dependence) as well as high attenuation for high frequencies [13,14] due to extensive scattering.

It should be kept in mind that even if pulse velocity or other features do not directly lead to the strength of the material, they can certainly indicate the most severely deteriorated part of a structure. This is also of great importance in a repair project, since this part can be treated accordingly (e.g. with a more dense pattern of cement or epoxy injection points) [1,15]. Considering that the repair actions aim to extend the service life of a structure for many years or even decades, the significance of this "relative" information becomes evident.

2. Wave propagation in concrete

Concrete is a highly inhomogeneous porous material, combining elastic (sand, aggregates) and viscoelastic phases (cement paste). The scale of distributed damage can be similar to that of constituent materials (e.g. aggregates). Therefore, it is difficult to distinguish between different mechanisms that influence the propagating wave. Although a globally accepted and accurate feature has not emerged (besides the rough estimations offered by pulse velocity), research in this field has substantially increased our understanding of wave propagation in cementitious materials. Lately, studies aimed to quantify the contribution of scattering and dissipation mechanisms in concrete, in relation to aggregates [16-22], entrapped air bubbles [23,24], porosity [25,26] or damage (actual or simulated) [14,27].

One important conclusion from the above mentioned studies concerning damage or air bubbles, is that the wave behavior depends strongly on scattering [13,14,24,25,27]. Scattering causes the elastic energy to propagate in directions which do not coincide with the incident wave. This has certain effects on the received waveforms. As will be seen, the pulse velocity measured by the first detectable disturbance of the wave is the least indicative feature of the internal condition.

The problem of wave scattering in heterogeneous media is scientifically intriguing as well as complicated. It is difficult to provide a general explanation for wave propagation in inhomogeneous media because each scattering problem is unique. The wave field depends on the mechanical properties of the matrix and the scatterers, the scatterers' shape, size, volume fraction as well as, their distribution in three-dimensional space and the propagating wavelength [28]. Each of the above parameters is crucial and largely affects the wave velocity, attenuation and frequency content [29-32]. Only after specific calculations of the scattering amplitude pattern it is possible to enlighten the wave propagation in a composite medium, considering usually spherical inclusions. What is certain though, is that the energy is attenuated and the frequencies downshifted [1,16-22,24,33] .

One simple, though general, explanation can be given as follows: Let us assume a sine cycle excitation introduced in a homogeneous material by a contact transducer. If one considers that the individual energy components travel through different parallel paths, they will have the same (or approximately same) transit time until the receiver. Therefore, they will compose a clear large cycle, as seen in Fig. 1(a). On the other hand, in an inhomogeneous material, scatterers will redirect the energy beams. For the components that will finally reach the receiver, the transit time will depend on the actual path traveled. Therefore, all the energy components will not arrive simultaneously but with different time delays, see Fig. 1(b). This results in much lower amplitude on the receiver, delay of the maximum peak, longer duration and therefore downshifting of the frequency content. However, the pulse velocity is not much affected since it is measured by the first arrival. In this case, the use of energy velocity measures, such as group velocity, that do not depend on the first arrival, but take into account the whole pulse can be very useful, as will be demonstrated.

In an actual situation when a wave impinges on a scatterer, the energy is redistributed to all directions, meaning that some energy is scattered also to the forward direction. Therefore, even after many encounters, it is possible that a small part of energy survives continuously scattered in the forward direction. This component may be weak but sufficient to trigger acquisition. Thus, focusing only on the first arrival will indicate no or limited deviation from the sound, homogeneous material. It can be said that the pulse velocity is characteristic of the fastest energy component (which travels through the shortest path), while it does not take into account the rest of the energy arrivals.

3. Experiment

The material used, was mortar of water to cement ratio 0.5 and sand to cement ratio 3 (by mass). The maximum sand grain was 3 mm and the shape of the specimens was cubic with side of 150 mm. The vinyl inclusions, used in this study, had shape of 15x15x0.5 mm. They were included in contents of 1%, 5% and 10% in the mortar matrix to produce specimens with different amount of “damage”. The specimens were cured in water for 28 days while the ultrasonic measurements were conducted after they dried. The inclusions did not show any tendency of conglomeration [13].

The through-the-thickness wave measurements were conducted with two piezoelectric broadband transducers, with response up to 1 MHz, placed on opposite sides of the cubes. The excitation was produced by a pulse generator introducing an electric spike with duration of 2 μs resulting in a broadband signal. The response was digitized with sampling rate of 10 MHz and a layer of silicone was applied between the sensors and the specimen's surface to ensure acoustic coupling. Measurements were repeated ten times at different points of the surface and the presented parameters come from their average. A similar experimental method (with resonant transducers) can be found in [13].

4. Results

In Fig. 2, the excitation, and the response through different materials are depicted. The waveform of mortar contains a strong and sharp cycle followed by weak later arrivals. Mortar with 1% vinyl exhibits a cycle of reduced amplitude, while for material with 10% inclusions, the first cycle is comparable to, or actually weaker than subsequent arrivals. This shows that inhomogeneity effectively diminishes the "coherent" energy, increasing the energy traveling through other longer paths. The only difference of the materials is their inclusion content; thus it is straightforward that interaction with vinyl is the reason for the later arrivals. One better way to visualize the later arrival of energy and the frequency downshift is the wavelet transform. Fig. 3 shows the wavelet transform of the waveforms of Fig. 2. For 0% inclusions (Fig. 3(a)), the higher frequencies approach 600 kHz, and after the initial burst, the energy is certainly lower. For the case of 1% (Fig. 3(b)) the high frequencies are compromised while significant arrivals appear up to 100 μs after the initial arrival. Finally, for the case of Fig. 3(c), which concerns mortar with 10% inclusions, the translation of energy is more evident. The energy content at 200 μs is stronger than the initial, showing that the forward scattered component is very weak. Additionally, frequencies above 250 kHz are completely cut off. It is noted that the mother wavelet, used for Fig. 3, is the Gabor wavelet and the transforms were conducted with software available on the internet [34].

4.1 Pulse Velocity

Despite the significant discrepancies between these individual waveforms, the examination of the wave onset reveals minor differences in pulse velocities, as seen in Fig. 4. Using the specific combination of pulser and transducers, the pulse velocity of material with 10% inclusions is decreased by only 3% compared to plain mortar, while the material with 1% inclusions exhibits practically the same velocity with plain mortar, namely 4000 m/s. It is mentioned that the typical error associated with the digitization sampling rate is 10 m/s, while the values are the average of ten different measurements on each specimen. Using any correlation from literature [7-12], the above velocity differences between different materials (within 120 m/s) would not reveal mentionable quality discrepancies. Therefore, it is seen that pulse velocity is not sensitive enough and even for material with as much as 10% of artificial damage, it reveals only slight differences.

4.2 Group Velocity

A feature that takes into account the later arrivals of a waveform is group velocity. In general, group velocity is a measure of the velocity with which the major part of energy propagates. There are different approaches for its calculation. Some researchers use the maximum peak of the waveforms (as opposed to the onset that is used for pulse velocity) [35]. Others create the signal envelope and use its maximum point [36]. Also, cross correlation between the “input” and “output” signals has been used [27]. The resulted time lag is characteristic of the transit time of the major part of energy and is also examined herein. The calculated values of group velocity are depicted again in Fig. 4 for different inclusion contents. This parameter is much more sensitive to damage, since the group velocity of material with 10% vinyl is decreased by 70% compared to the sound material's one, while even material with 1% inclusions exhibits group velocity slightly decreased compared to the plain mortar. This is a result of the longer duration of the first cycle as well as the delayed arrivals that move the energy of the received waveforms to later times. It is stated that the pulse and group velocities for plain mortar almost coincide (3992 m/s and 3951 m/s respectively), while as the inhomogeneity increases the discrepancies become more evident (see Fig. 4).

4.3 Energy

It is well established in concrete literature that energy parameters are more sensitive to damage than pulse velocity [14,37,38]. This can be observed also by the amplitude of the waveforms of Fig. 2. To quantify the difference, the absolute amplitude of the waveform was used, as well as the total energy, calculated by the area under the rectified signal envelope. The results are presented in Fig. 5. Both energy and amplitude decrease significantly with the inclusion content, even for the case of 1% inclusions. This loss of energy is mainly the combination of two reasons; One is, as mentioned earlier, the redirection of energy components that never reach the receiver. This is accompanied by the material damping that depends on the length of the wave path. Thus, its influence is smaller for the shortest path (typical for propagation in homogeneous material) and higher for longer paths (in scattering media). Therefore, the reduced energy is the result of scattering and dissipative mechanisms that attenuate more intensively the wave in inhomogeneous materials.

A way that has been used to quantify the delay of energy arrivals is the time centroid of the rectified waveforms [17]. Another is the accumulated wave amplitude. This has been used in surface crack depth measurements [39,40]. It is calculated by adding the absolute voltage of each point of the waveform to the previous. In Fig. 6(a) an example is depicted. Since the first cycle in plain mortar is strong, there is a rapid increase of accumulated amplitude for the first few microseconds. The inclination of the curve is subsequently decreased since the later arrivals are of lower amplitude. In Fig. 6(b), one can see the accumulated amplitude for different materials for the first 20 μs. The initial inclination is sensitive to "damage" since it decreases from 0.0021 μs^{-1} for plain mortar, to 0.0004 μs^{-1} for 10% inclusions, while for later times the slopes of the curves are almost similar. The duration of the first cycle for plain mortar is 4.3 μs. The energy arrived until that point for plain mortar, is 8% of the total received energy (see vertical dot line in Fig. 6(b)). For the material with 10% inclusions though, the energy up to the same moment is only 1.2% showing in another way that a smaller part of energy survives in the forward direction in strongly inhomogeneous media.

4.4 Central frequency

The introduced excitation contains strong frequency components at least within the band 50 kHz to 1 MHz. This leads to wavelengths, from 80 mm to 4 mm that can strongly interact with the vinyl inclusions of 15x15x0.5 mm. Therefore, except time domain, valuable information can be obtained by simple analysis in frequency domain. In Fig. 7(a) the fast Fourier transform (FFT) of typical signals from plain mortar and mortar with inclusions are depicted. The energy difference is evident, as it was already mentioned in the previous section. The other important feature is the downshift of the spectrum. The content at higher frequencies (e.g. above 200 kHz) is diminished more intensively than lower ones, as seen in Fig. 7(a). This leads to downshift of the frequency centroid, which is depicted in Fig. 7(b). The central frequency of 260 kHz for plain mortar decreases to 150 kHz for “damaged” mortar showing that this is another feature that can enhance the inhomogeneity characterization.

In order to compare the sensitivity of all the aforementioned parameters to the inclusion content, they are presented in a dimensionless form in Fig. 8. It is seen that all the studied features are more sensitive to damage (especially amplitude) than pulse velocity. These features depend on the length of the propagation path and therefore, they cannot offer global correlations with damage. They can be used however, in a case by case examination to characterize the most deteriorated part of a structure in order to select the adequate repair procedure.

5. Conclusions

In the present paper, wave propagation in mortar is studied. It is seen that inhomogeneity, in the form of small vinyl inclusions, has a certain effect on the received waveforms. Specifically, for the materials of this study, pulse velocity exhibits a 3% decrease, while other easily calculated features exhibit even 90% decrease in case the simulated damage content is high. From the above presented wave features, only pulse velocity can offer rough correlations with concrete strength. However, combined use of other features coming from time domain (like group velocity and amplitude) or frequency domain (centroid) can enhance characterization, indicating the most severely deteriorated part of a structure. These features do not require sophisticated analysis and are more sensitive to inhomogeneity since they include information from the whole pulse and not only the fastest wave path, which is characterized by pulse velocity.

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Figure Captions

Fig. 1 Wave composed by (a) synchronized and (b) non synchronized arrivals of the individual wave components.

Fig. 2 Waveforms after propagation through mortar with different inclusion contents. The excitation signal has been reduced to fit in the graph.

Fig. 3 Wavelet transform of waveforms from mortar with inclusion content a) 0%, b) 1%, c) 10%.

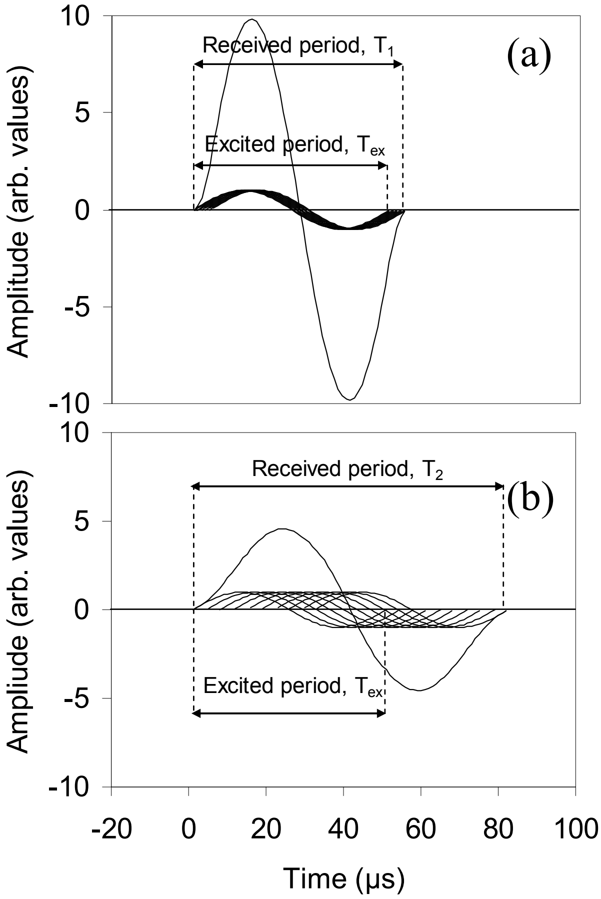
Fig. 4 Wave velocity for mortar with different inclusion content.

Fig. 5 Normalized energy parameters for mortar with different inclusion content.

Fig. 6 (a) Waveform and accumulated energy for plain mortar. (b) Accumulated energy for mortar with different content of inclusions.

Fig. 7 Frequency spectrum (a) and central frequency (b) for mortar with different inclusion content.

Fig. 8 Various normalized wave parameters vs. inclusion content.



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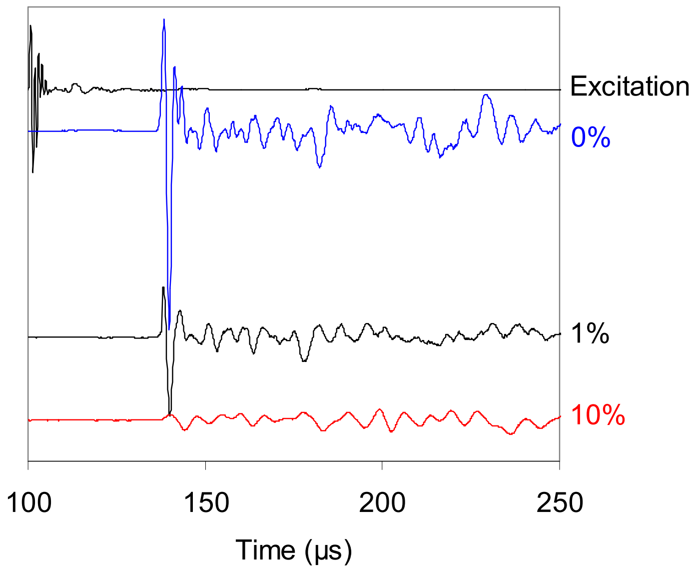

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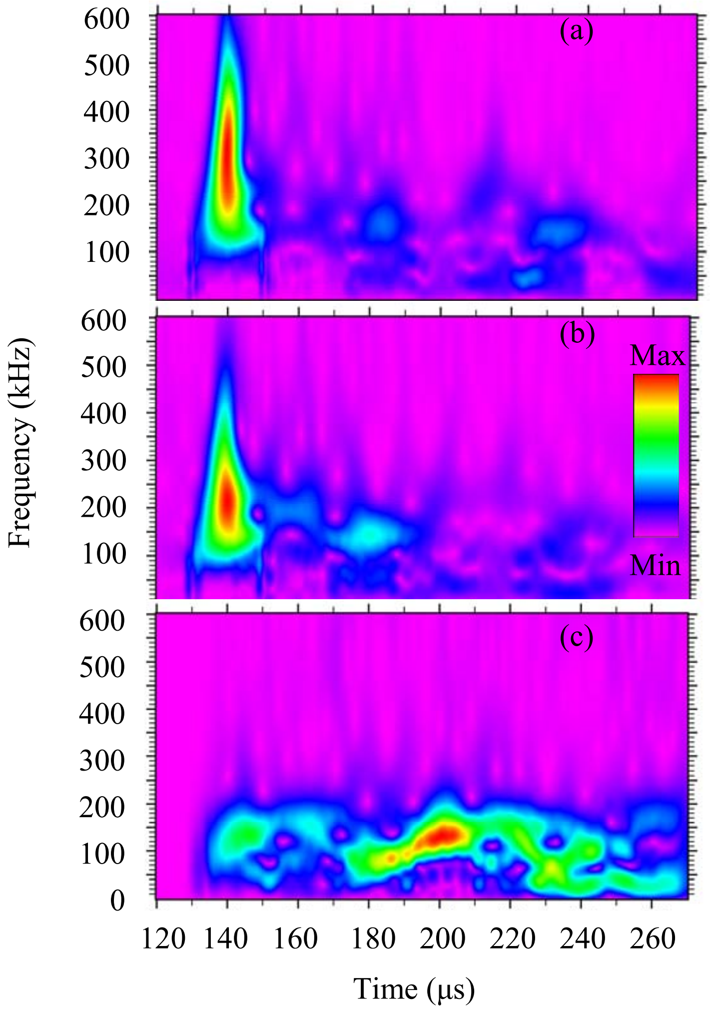

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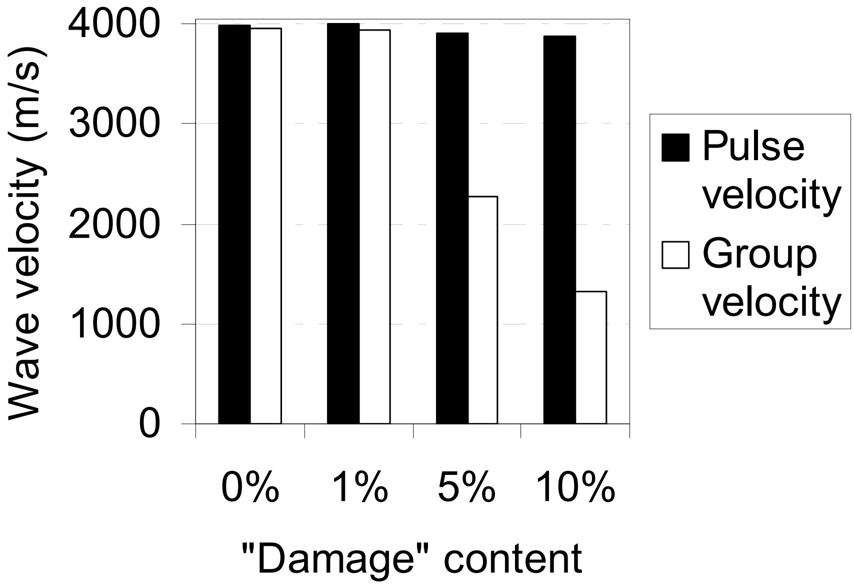
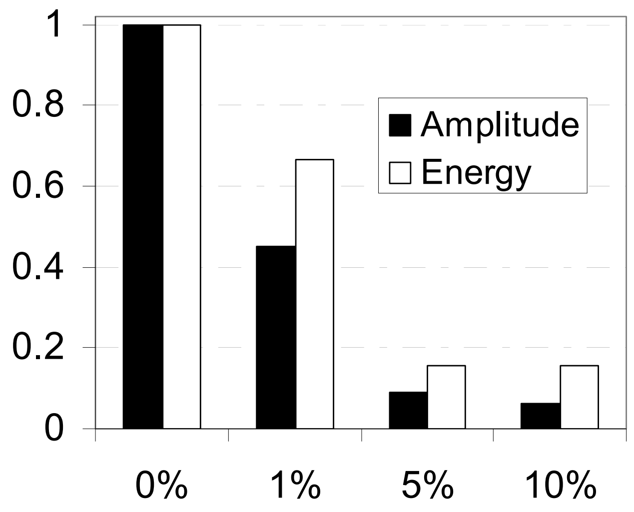


Fig. 4 Wave velocity for mortar with different inclusion content.



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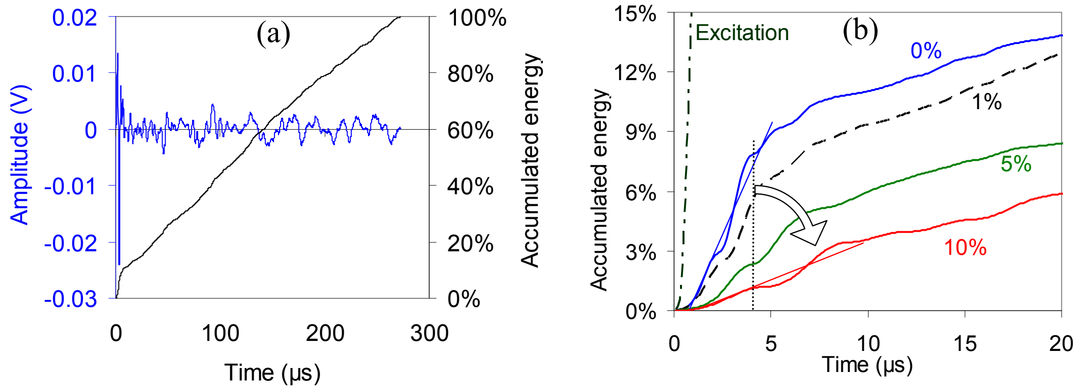

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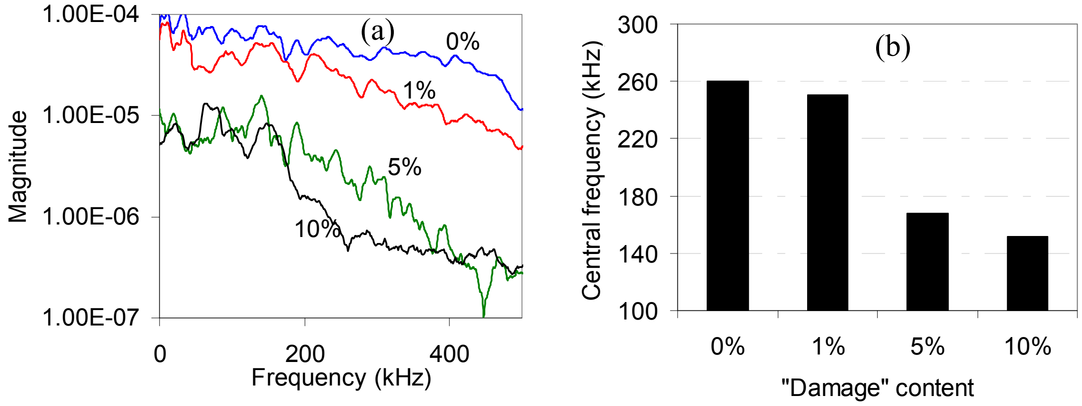

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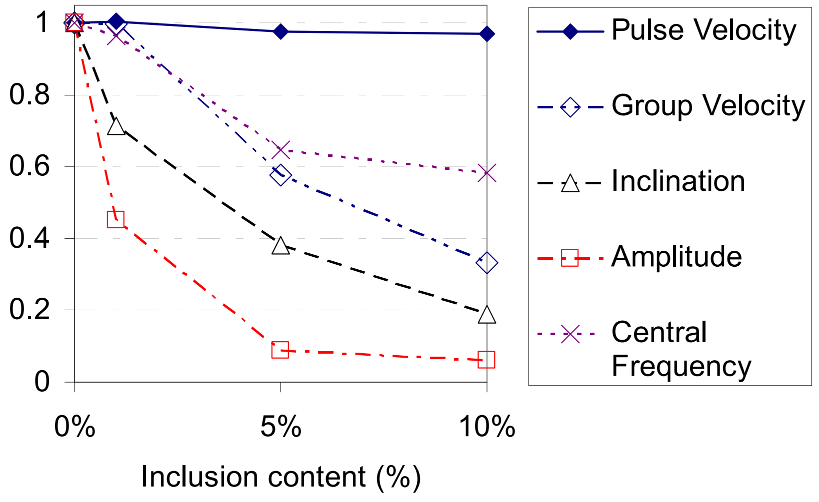

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