

Damage Identification using Torsional Wave Propagation for RC Pile Elements

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ABSTRACT: Wave propagation based tools have found increasing application in the area of Structural Health Monitoring. Wave propagation is a transient phase of dynamic response before the on-going wave and the in-coming wave superimpose over each other giving rise to a standing wave pattern. Whenever a wave encounters a changing impedance (force per unit velocity), due to change of stiffness or mass, a reflecting wave is generated with the total strain energy forked as reflected as well as refracted portions. The ratio of reflected wave to the incident wave is controlled by the impedance change and hence the damage magnitude and position could be quantified. Hence wave propagation mechanics comes in handy for damage detection and diagnosis. Dis-continuity (impedance mismatch) is induced in the pile by varying its cross section area along its length. Analytical simulations are performed using the ABAQUS on four different concrete piles under Pulse echo method. The effect of reduction of area (or increase of area) causes reduction in stiffness as well as mass and hence torsional impedance is not altered to a great extent. How a wave propagation based technique is able to identify the location and magnitude of defect is brought out. The wave scattering denotes both wave reflection (coming back to the source) and wave refraction (going away from source). Damage identification under conditions of uniform wave propagation is an easier task as compared to dispersive flexural wave propagation. The reason being that, until reflections from boundaries or damages are encountered the time duration of the transient pulse is preserved and the response is quiescent. Hence the elapsed time and the amplitude of the reflected pulse can be a simple indicator of the location and magnitude of the damage respectively. This paper deals with torsional wave propagation in concrete pile with structural dis-continuities.

KEYWORDS:Wave propagation, Structural health monitoring, Damage detection, ABAQUS, Transient pulse, Structural dis-continuities.

I INTRODUCTION

Structural Health Monitoring (SHM) is referred as the process of implementing damage detection methodologies and characterizing the current state of health of engineering structures. The damage is defined as changes to the material and/or geometric properties of a structural system, including changes to the boundary conditions and system connectivity, which in turn affect the system's performance. The SHM process involves observation of a system over time using periodically sampled dynamic response measurements from an array of sensors, the extraction of damage-sensitive features from these measurements, and the statistical analysis of these features so as to determine the current state of system health. Therefore health monitoring is a specific type of non-destructive evaluation techniques. It must allow the integrity of systems to be actively monitored during their operation and throughout their life.

Wave propagation based automatic SHM techniques and the warning and alert systems are widely adopted in aerospace and nuclear industry. These techniques are however, not in a matured state of development for civil structures and are

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evolving. Hence research in these areas is of paramount importance so that an automatic warning and alert system can be implemented for critical civil structures.

SHM technologies have emerged, for the last ten to fifteen years, creating an exciting new field within various branches of engineering. Academic conferences and scientific journals have been established during this time that specifically focuses on SHM.

Basics of Wave propagation

Wave propagation is a transient phase of dynamic response before the on-going wave and the in-coming wave superimpose over each other giving rise to a standing wave pattern. This dynamic phenomenon happens for structures of finite dimensions and the initial transient phase of response is well handled by wave propagation and the steady state response that follows this initial response is handled by classical structural dynamics.

For structures of infinite dimensions like water bodies, soil media and long bridges, the steady state response will be poorly defined. For these structures of long aspect ratios in-coming wave shall be totally damped out with only an on-going wave, generated from the vibration source. The only way in which such structures can be analysed is using wave propagation techniques.

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Dynamics analysis in structural engineering falls into two different classes, one involving low frequency loading and the other involving high frequency loading. Low frequency problems are categorized as Structural Dynamics problems while those involving high frequency loading fall into the category of Wave Propagation problems. In structural dynamics problems, the frequency content of the dynamic load is of the order of a few hundred hertz (Hz) and the designer will be mostly interested in the long-term (or steady-state) effects of the dynamic load on the structures. Hence, the first few normal modes and natural frequencies are sufficient to assess the performance of the structure. The phase information of the response is not critical here. Most of the dynamic problems in structures will fall into this category. On the other hand, for wave propagation problems, the frequency content of the input loading is very high (of the order of kilohertz (kHz) or higher) and hence, short-term effects (transient response) become very critical. Further, many higher order modes will participate in amplifying the dynamic response. Impact and blast-type of loading fall into this category. The multi-modal nature of wave propagation makes one parameter very important, and that is the phase information.

Dynamic analyses are traditionally performed using the conventional Finite Element Method (FEM). For wave propagation problems wherein the frequency content of the input is very high, many higher order vibrational modes participate in the motion. At these higher frequencies, the wavelengths are very small and hence to capture these modes effectively, FE meshes need to be very fine. This is due to the requirement that the element sizes should be of the same order as the wavelength of the signal. For larger mesh sizes, the element edges will act like a free boundary and start reflecting the initial responses from these element edges. A fine mesh, although ensuring accurate distribution of the inertia, also increases the computation cost enormously.

II. LITERATURE STUDY

Krawczuk Met.al [1] (2004) presents the method of analysis of the wave propagation process in cracked plates. For modelling the plate new type of finite spectral plate element with a crack was elaborated. It was assumed that the crack having an arbitrary length, depth and location was parallel to one side of the plate. Elastic behaviour of the plate at the crack location was considered as a line spring with a varying stiffness along the crack length. Zak A et.al [2] (2006) presents certain results of the analysis of in-plane elastic wave propagation in a composite panel. Numerical calculations are carried out for various orientations of reinforcing fibers within the panel as well as for various volume fractions of the fibres. It is shown that propagation of in-plane elastic waves in composite materials is a more complex phenomenon than in the case of isotropic materials. The velocities of the elastic waves and also the direction of

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propagation are functions of the fibre orientation and the relative volume fraction of the fibres. Ostachowicz W [3] (2008) brings together the principles, equations, and applications of damage modelling and elastic waves propagation, both traditional and state-of-the-art in a review form. It begins with the relevant fundamentals of damage modelling, derives the basic equations of fracture mechanics and elastic wave propagations, and covers advanced topics and applications of Lamb waves that are at the forefront of today's research. The results obtained indicate that the current approach is capable of detecting cracks and delamination of very small size, even in the presence of considerable measurement errors. The sections are filled with case studies, worked examples and exercises that make this paper an outstanding resource. Elastic pulse propagation in wires with circular cross-section was studied by Meitzler [4] (1961). Based on his observations of pulse distortion for pulses propagating in other modes, he concluded that the coupling between the various modes of propagation leads to pulse distortion.

III. DAMAGE DETECTION SCHEME

In general, there exist two methods of damage detection widely adopted in SHM with distributed PZT sensor networks. These include pitch-catch and pulse-echo. In pitch-catch configuration the damage is detected by analysing the signal transmitted from the actuating PZT to the receiving wafer. If the damage happens to be in wave path, the recorded signal will be altered with respect to the baseline. In contrast, pulse-echo method utilizes the reflection of the incident wave from damage in order to identify its possible location and severity. Usually the same wafer is used as an actuator and a receiver, which requires some switching circuits. This study employs the pitch-catch approach, since it is easy to implement in experimental studies.

Wave propagation Principles

A disturbance on a solid causes the entire body to respond by linear and angular accelerations. The applied force causes deformation in the solid body. Stress waves are generated, if the deformation is in elastic range and the applied force is rapid and changes with time, such as piezoelectric transducers or the collision of two solid bodies. Stress wave velocity in a solid depends upon the elastic properties and the density of the material from which it is composed. In an infinite elastic solid, the velocity of P wave is computed by the following equation

$$C_P = \sqrt{\frac{E(1-\nu)}{(1+\nu)(1-2\nu)\rho}} \quad (1)$$

Where E is the Young's modulus of Elasticity,
 C_P is the P wave velocity,
 ρ is the density and
 ν is the poisson's ratio.

In rod-shaped structures, where the diameter of the cylinder is much smaller than its length, $d \ll l$ the P wave velocity is slower than in an infinite elastic solid and is given by the following equation

$$C_P = \sqrt{\frac{E}{\rho}} \quad (2)$$

The shear wave velocity C_S , is calculated by the following equation

$$C_S = \sqrt{\frac{E}{2(1+\nu)\rho}} \quad (3)$$

The stress waves, which propagate into the object, undergo multiple reflections between the test surface and the internal defects of the opposite boundary of the test object. The path length of reflected P waves is twice the distance from the surface to the internal defect $2L$. Hence the travel time, t , between the successive arrivals of reflected P waves relies on the P wave velocity C_P , and is computed by the following equation

$$T = \frac{2L}{C_P} \quad (4)$$

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IV. MODEL FOR ANALYSIS

A simplified model of four beams namely Beam 1, Beam 2, Beam 3 and Beam 4 with cross sectional decrement and cross sectional enlargement at two locations have been analysed using the ABAQUS by using pulse echo method has been shown in the following figs. 1 - 4. In all the four models, each beam has a total length of 6 m.

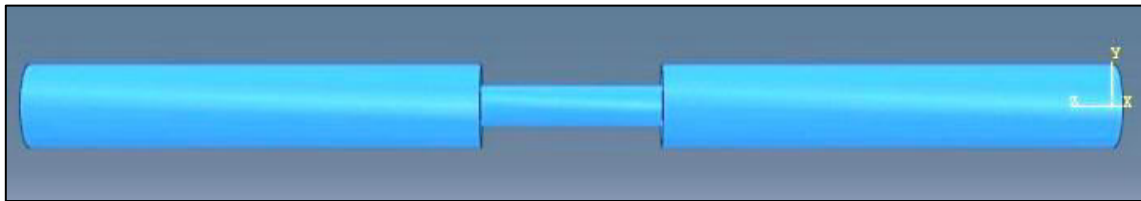


Fig.1 Beam1- Damaged symmetrically

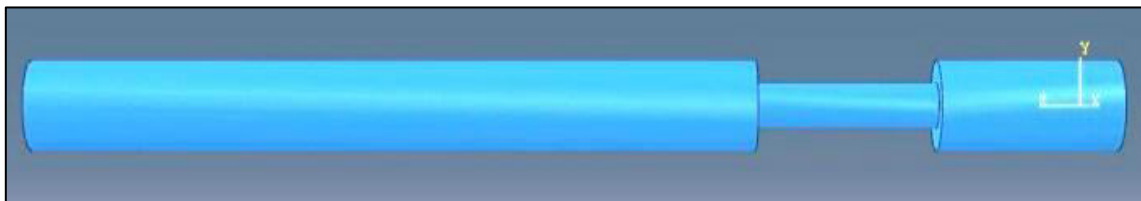


Fig.2 Beam2- Damaged unsymmetrically

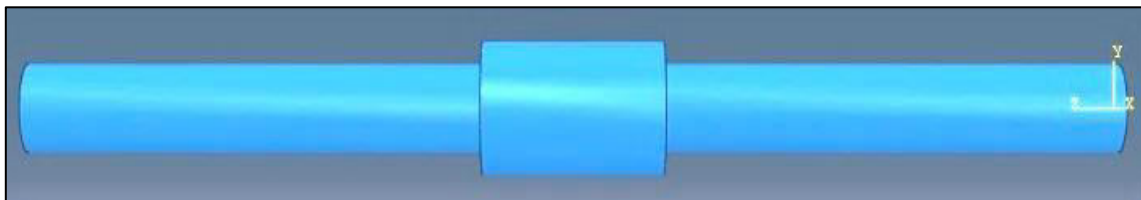


Fig.3 Beam3- Bulged symmetrically

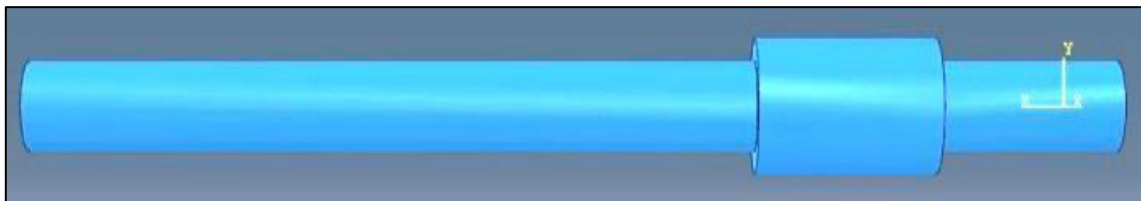


Fig.4 Beam4- Bulged unsymmetrically

The beams are modelled as such Beam 1 and 2 (Fig. 1 & 2) have a diameter of 200 mm along its length except at damaged portion of 1m length which has a diameter of 100mm (defect-reduced). The beam 3 and 4 (Fig. 3 & 4) has a diameter of 200 mm along its length except at the bulged portion which has a diameter of 300 mm (defect-bulged). In this model, the material property for M30 grade concrete is entered. The sensor which captures the wave velocity is located at the toe end of the pile element and the impact is given at the head of the pile element.

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Pulse Echo Method

In pulse echo method, the beam head is struck by an impact load, so that downward compressive wave is generated travelling with a wave speed "C". When this initial wave encounters a cross section change or concrete quality change at depth x, it generates an upward traveling wave which is observed at the beam top at a time equal to twice the distance of the cross section change from the top divided by the wave speed c ($2x/c$). The rest of the initial wave travels down to the beam toe and reflects. It is observed at the beam top at a time twice the beam length divided by wave speed ($2L/C$, L= beam length). Reductions in beam cross and concrete quality section generate tension upward traveling waves. From the known beam length and material the expected arrival time of beam toe reflect could be calculated. If the positive reflection is observed prior to the expected toe reflect time, the approximate defect location can be estimated from the assumed wave speed. The size of the defect can be estimated from the magnitude of the early reflection.

The input excitation which was given at the head of the pile element is shown in Fig.5.

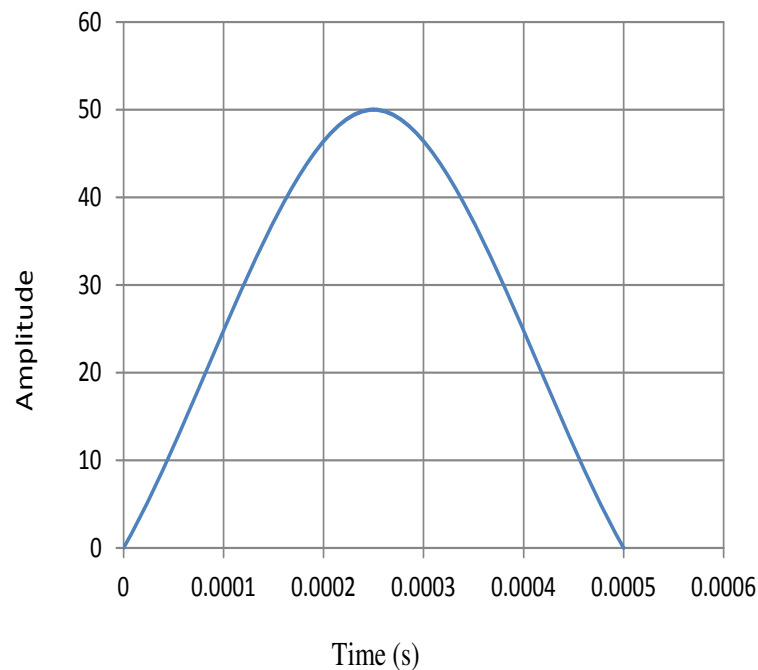


Fig.5 Input Excitation

V. RESULTS AND DISCUSSIONS

Analytical result obtained by Pulse echo method

When the impact load is given, it generates a compression wave travelling through the beam and reflects from beam tip and defects if any. Both stress wave inputs and reflections are measured as a function of time by an accelerometer put on the top of beam. For the quick and reliable assessment of the quality of the beam, graphs of velocity time is presented together for the whole duration of the test. The results obtained from the analytical investigations are presented below in Figs. 6 to 9. For all the beams the input excitation is given at the head.

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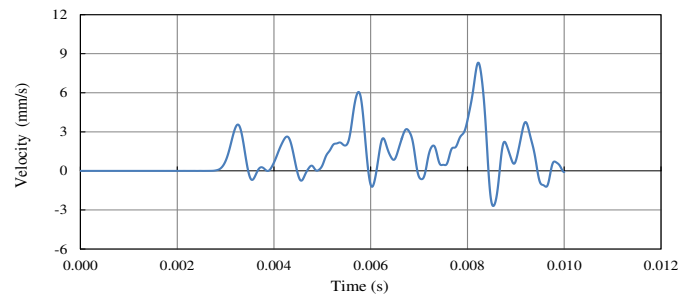


Fig.6 Output for beam 1

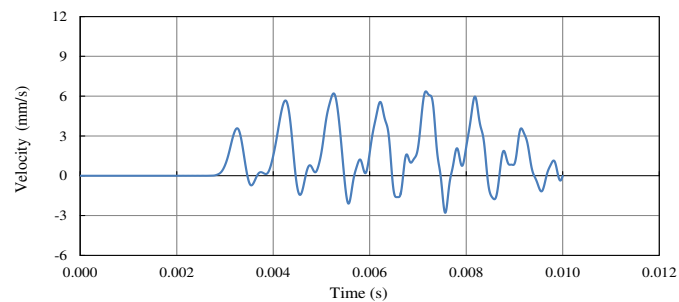


Fig.7 Output for beam 2

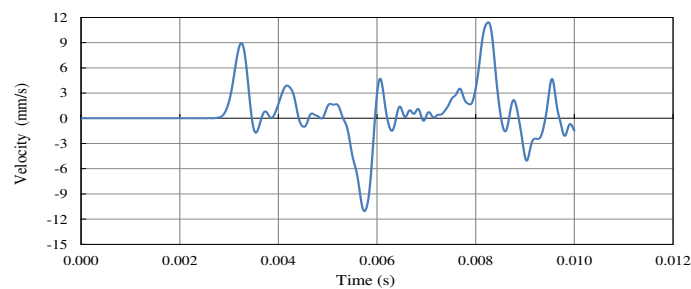


Fig.8 Output for beam 3

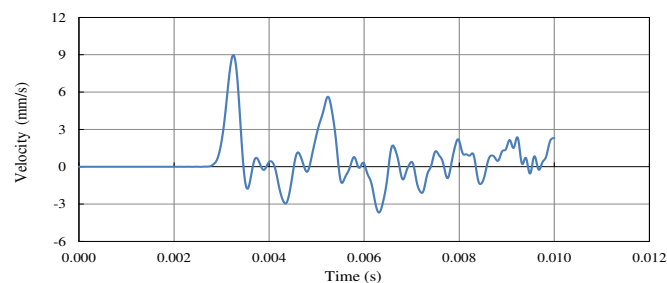


Fig.9 Output for beam 4

Formula used:

$$C = \frac{2L}{T}$$

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$$L = \frac{C T}{2}$$

‘L’ gives the length (m) (damage location and Head reflection)

‘C’ is the torsional wave velocity.

Case 1: Comparison between beam 1 and 2 (Symmetry damage and Un-symmetry damage).

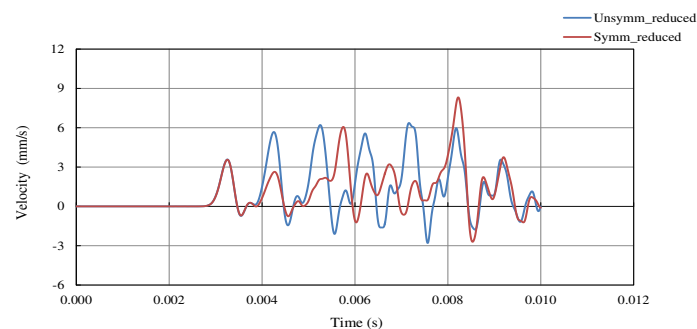


Fig.10 Comparison of Beam 1 and 2 – output

Case 2: Comparison between beam 3 and 4 (Symmetry bulged and Un-symmetry bulged).

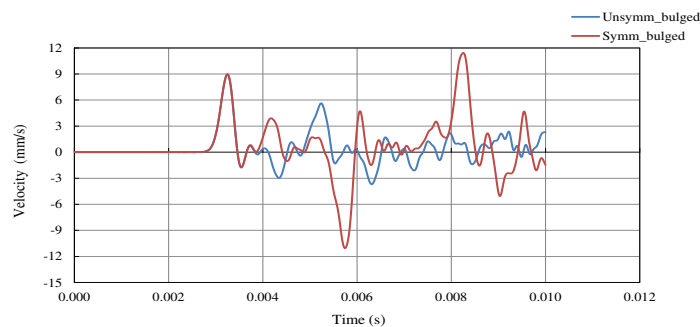


Fig.11 Comparison of Beam 3 and 4 – output

TABLE 1 Test Results for Beam 1 and 2 from pulse echo method

Specimen ID	Incident (ms)	Damage reflection (ms)	Location (m)	Head reflection (ms)	Location (m)
B1	2.75	5.1	2.559	8.23	5.970
B2	2.75	3.25	1.085	8.30	6.047

TABLE 2 Test Results for Beam 3 and 4 from pulse echo method

Specimen ID	Incident (ms)	Damage reflection (ms)	Location (m)	Head reflection (ms)	Location (m)
B3	2.75	5.08	2.537	8.26	6.0034
B4	2.75	3.25	1.085	8.28	6.025

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From the plot we can observe that the velocity profile of beam 2 and 4 is slightly elongated for the damage (reduced area and bulged area) located at 1m from the beam toe. For the beam 2 and 4, damage location is 1.085m instead of 1m. This is because the damage is located very near to the toe. i.e., when the reflected pulse from the toe reaches the defect which is nearer to the toe end, such that it could not identify the damage exactly at 1m. After a few milliseconds it identifies the discontinuity say at 1.085m. But for the beam 1 and 3, the damage reflection is good, say at approx. 2.5m. The head reflection is good for all the case because it is approximately 6m (beam length).

VI. SUMMARY AND CONCLUSIONS

The Analytical studies on torsional wave propagation in a concrete beam with induced structural discontinuities are discussed briefly. In the present work, pulse echo method is used to judge the integrity of the beam for discontinuities or defects. The results obtained from the analytical work are presented and discussed extensively. This paper presents a consolidated study on the mechanics of torsional wave propagation in an elastic medium. The investigation involves analytical study. Damage identification is essentially an inverse problem, wherein the damage needs to be detected using the measured input and output signals and previously updates system parameters. Towards studying the effects of uniform axial wave propagation in a prismatic member, with structural discontinuities, a series of four reinforced concrete beams are modelled with various imposed damages: reduction in cross-sectional area at mid-length and quarter length and Increase in cross-sectional area at mid-length and quarter length.

- There is a sign change in the reflected velocity pulse received from the bulged area (Fig.11), at a time difference which is exactly equal to the $2*L1/c$ where $L1$ is the distance from the toe of the beam to starting point of bulged area.
- No sign change is observed in the reflected acceleration pulse received from the reduced area (Fig.10). Here also, the time difference is equal to the $2*L1/c$ where $L1$ is the distance from the head of the beam to starting point of reduced area.
- Pulse shape being preserved in the reflected pulses in the un-damaged prismatic beam, coming out of the analytical study illustrates the phenomenon of uniform wave propagation.

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