Evaluation of Fatigue Damage of Concrete using Impact Echo Method

by

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Dissertation submitted in partial fulfilment
of the requirements for the
Bachelor of Engineering (Hons)
Civil Engineering

December 2004

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Civil Engineering Programme
Universiti Teknologi PETRONAS
in partial fulfilment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
(CIVIL ENGINEERING)

Approved by,

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UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

December 2004

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

TAN CHAR AI

ACKNOWLEDGEMENT

I would like to take this opportunity to express my gratitude to several individuals that are highly indebted to throughout this final year project.

First of all I would like to express my highest gratitude to my Final Year Project supervisor, Dr. Victor R. Macam for the guidance and useful knowledge given to me from the start till the end of the project. I am very thankful for all the efforts and time he sacrifices in guiding me. I am also very fortunate to have worked with him.

I also wish to thank my colleague, En Rahim and civil engineering department technicians, Encik Johan and Encik Zaini, for assisting me during the laboratory works.

Last but not least, thanks to my family members and friends for their moral support towards me during the project. Their understanding and concern are much appreciated.

ABSTRACT

The impact echo technique is traditionally used to determine position of defects within concrete structures. Impact echo technique is non-destructive, non-intrusive, and cost and time efficient. In this paper, application of impact echo in assessing crack development n concrete structures subjected to cyclic load is discussed. Research work is carried out by performing impact echo test on concrete plain beam 150mm x 150mm x 750mm subjected to cyclic load. Mechanical stress wave is generated by striking the concrete surface with 7mm diameter steel ball. The reflected stress wave is then detected by accelerometer and displayed result in the form of amplitude-frequency waveform on the screen of an oscilloscope. The waveform recorded at certain interval of cyclic loading is analysed to estimate the crack development in concrete. It is found that impact echo result has a strong correlation with the concrete fatigue life. There is also a great potential of using Impact echo method to predict the remaining service life of a concrete structure subjected to cyclic load. However many parameters can affect the accuracy of impact echo result, more research need to be done and many conditions need to be taken into consideration when implementing this method in predicting the remaining service life of concrete structure.

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CHAPTER 1
INTRODUCTION

1.1 Background of Study

Impact-echo method is a non-destructive testing technique for flaws detection in concrete based on stress wave propagation. A team of researchers at the National Institute of Standards and Technological (formerly the National Bureau of Standards) initiated a study in 1983 that developed the rudimentary basis for this method. Subsequently, research carried out at Cornell University, under the direction of Dr. Mary Sansalone, has refined the theoretical basis of the method, extended its applications to a broad spectrum of problems and lead to the development of a field system[1].

Previously referred to as *pulse-echo method,* the technique has come to be called the *impact-echo method.* The name "impact-echo" was adopted to distinguish the technique from traditional ultrasonic pulse-echo techniques in which one piezoelectric transducer is used both to generate the stress pulse and to monitor reflections[2].

The technique involves tapping a steel sphere on the concrete surface, with a receiving transducer/accelerometer located near the striking point. The accelerometer acts as the receiver and the wave detected will be displayed on the screen of oscilloscope connected to it.

Impact-echo method is now well-known as an acoustic, non-destructive method for evaluating concrete and masonry structures. This method has been used for more than a decade. The commercialized impact-echo equipment available in the U.S market claimed itself to be effective in[3]:-

1. Measure thickness of concrete slab according to ASTM Standard C 1383-98a, including pavement, retaining walls, tunnel wall, etc;
2. Determine location, depth and extent of cracks, voids, delaminations, honeycombing and debonding in plain and reinforced structures, including plates (slabs, walls, decks, pavements), layered plates (including asphalt on concrete), columns and beams (round, square, rectangular), and hollow cylinders (pipes, tunnels, mineshaft liners, tanks).
3. Locate voids in subgrade beneath slabs and pavements;
4. Measure depth of surface-opening cracks;
5. Locate voids in the grouting in tendon ducts in post-tensioned structures;
6. Locate cracks, voids and other defects in masonry structures where brick or block units are bonded together by mortar.

Others non-destructive test that have been developed in concrete testing including rebound hammer, ultrasonic pulse velocity, photon radiation, acoustic emission, laser holography, probe penetration and etc. Each of these methods has its own advantages and disadvantages.

Studies about impact-echo method have been carried out world-widely; which includes studies about applications of impact echo for different types of structures, parameters that influenced the data quality, usage of different approaches to analyse the impact-echo signals and etc. But so far there is no literature published about the studies of using impact-echo test to predict the remaining service life of a concrete structure subjected to cyclic loading.

1.2 Problem Statement

Most of the built-up structures such as bridges, offshore structures, airport pavement, railway sleepers (ties) and etc are subjected to repeated application of loads each of which is lower than the collapse load of the structure. The repeated applications of load can cause collapse of the structure from a low of a few thousand cycles to a high of several million cycles.

Since these infrastructures are considered the lifelines of a nation it is imperative that collapse of these structures are prevented. Besides that, Public Work Department of Malaysia (PWD) has reported that some bridges in Malaysia have experienced premature deterioration. This means proper monitoring of their structural integrity is necessary to predict not only the remaining service life of the structure but also, to determine the time for implementing repair or upgrading works. The possibility of life and properties loss due to collapse of the structures can thus be prevented.

The performance of concrete varied with mix design, time/age, method of curing, method of compaction and many others factors. Concrete must be tested frequently to ensure its fitness and also to establish the safety of the concrete structure. The traditional method of evaluating concrete is to take a sample from the supply during placement (e.g. Concrete cubes, cylinders) or from the completed structure (e.g. coring, drilling). The samples are assumed to be the representative of the parent concrete; any uncertainty can be alleviated only by taking more samples. Besides that, coring method also causing destruction to the structure and required the closure of bridge to traffic. Therefore the method used to monitor the condition of bridge is still visual inspection.

Non destructive test methods are also non-obstructive. Bridges and roads need not to be closed to traffic for inspection and monitoring. Various non-destructive methods have been introduced, but destructive method is still widely used in Malaysia. Knowledge about the theory and application of NDT should be promoted in Malaysia.

1.3 Objectives

The objective of this study is to correlate the fatigue life of concrete with the result of an impact-echo test and to investigate the possibility of using impact-echo test to predict the remaining service life of a concrete structure subjected to cyclic load.

1.4 Scope of study

This research involves the evaluation of concrete damage subjected to cyclic load using impact echo method. The experimental program required the preparation of concrete samples in the form of cube and plain beam. After that cyclic load is imposed to the concrete samples using dynamic Universal Testing Machine, impact echo signal waveform is recorded at a certain interval of number of cycles.

After that the impact-echo result is carefully analyzed; to compare the waveforms obtained with the progress of cyclic loading until failure. In this research, the analysis is focused on the crack propagation; whereby the relative crack length is estimated from the impact echo result.

CHAPTER 2
LITERATURE REVIEW AND THEORY

2.1 Non-Destructive Test

In the past decades, a variety of semi-destructive and Non-destructive Testing (NDT) techniques have been tested to investigate concrete elements and structures, to evaluate their integrity and locate defects. Non invasive techniques such as NDT in most cases are a quicker and cheaper means of detecting defect in concrete structures than intrusive techniques. NDT also offers minimum activities/traffic disruption, and with coverage of large areas of the element[4].

Another important feature of NDT is that they permit re-testing at the same location so that changes with time can be monitored. The use of NDT leads to increased safety and allows better scheduling of construction, thus making it possible to progress faster and more economically.

However NDT by their nature do not readily provide definitive results in locating defects. The equipment must therefore be used and the results interpreted by personnel experienced both in the techniques and equipment being used and in the detection of the types of defect being investigated; whereby engineering judgement is necessary. NDT Equipment should also be calibrated against hard evidence provided by intrusive methods, and used in conjunction with other information to build up a picture of the condition of the structure[5].

Comparison among the popular NDT available in terms of cost and effectiveness for concrete bridge are tabulated in Table 2.1. Among these methods, *impact echo* is nowadays being promoted heavily in the USA.

TABLE 2.1

Comparison among the relative cost and effectiveness of selected NDT[5]

NDT	Cost	Effectiveness
Visual inspection	Low	Ineffective, since bridge rarely show distress before catastrophic failure.
Load Test	Relatively high	Ineffective procedure and dangerous as the structure could fail before any meaningful deflection is obtained.
Impact echo	Intermediate	Potentially useful in detecting voids in various masonry and concrete structures. But it is essential to ensure that impact frequency is sufficiently high to identify the defect.
Radiography	High	A high powered radiographic technique gives good image of voiding but requires closure of the bridge and may not be used in urban areas due to the risk of radiation.
Ultrasonic tomography	Intermediate	Promising method that could identify voids by producing a 2-D or 3-D image of the beam cross section.

2.2 Impact-Echo Method

Impact-echo is one of the prevailing NDT which involves tapping a hammer with metal tip or small steel sphere against a concrete surface, produces low frequency stress waves that propagate into the structure and are reflected by the flaws and/or external surfaces. The wavelengths of these stress waves are typically between 50mm and 2000mm, longer than the scale of natural inhomogeneous regions in concrete (aggregate, air bubbles, micro-cracks, etc). As a result they are only weakly attenuated, and propagate through concrete almost as though it were a homogeneous elastic medium. Multiple reflections of these waves within the structure excite local modes of vibration; resulting surface displacements are recorded by a transducer located adjacent to the impactor[1].

The piezoelectric crystal in the transducer produces a voltage proportional to displacement, and the resulting voltage-time signal (called a waveform) is digitized and displayed on the screen of the oscilloscope.

The principle of the impact-echo technique is illustrated in Fig.2.1 and Fig 2.2[6]. A transient stress wave is introduced into a test object by mechanical impact on the surface. The stress wave propagates into the object along spherical wave fronts as compressive wave (P-waves) and shear wave (S-waves). In addition, a surface wave (R-wave) travels along the surface away from the impact point. The P- and S- stress waves are reflected by internal interfaces or external boundaries.

The arrival of these reflected waves at the surface where the impact was generated produces displacements which are measured by a receiver. If the receiver is placed close to the impact point, the displacement waveform is dominated by the displacements caused by P-wave arrivals. The displacement waveform can be used to determine the travel time, t, from the initiation of the wave to the arrival of the first P-wave reflection. If the P-wave speed, *Cp*, in the test object is known, the distance, *T*, to the reflecting interface can be determined.

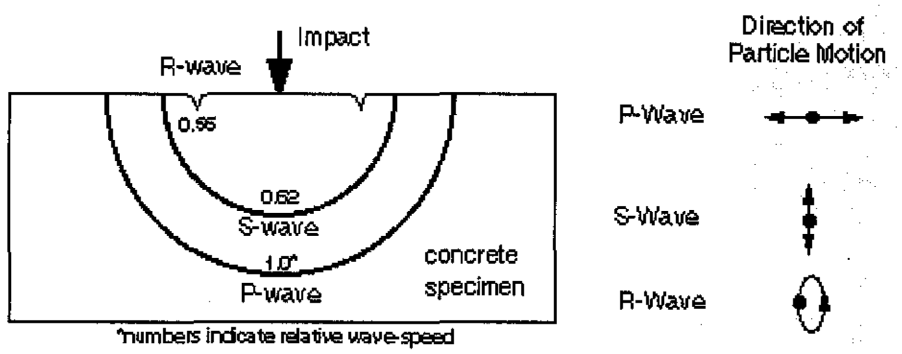


FIGURE 2.1

Propagation of Stress Waves due to Impact [6]

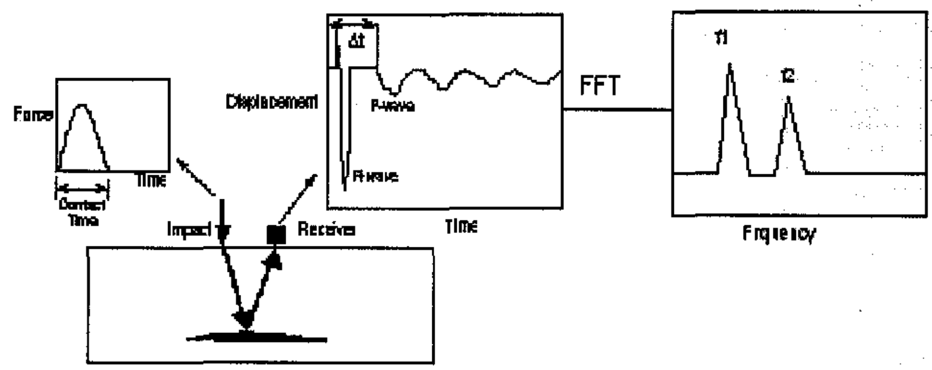


FIGURE 2.2

How Impactor and Receiver works[6]

A typical commercial impact-echo test system is shown in figure 2.3. The major components are a cylindrical handheld transducer unit, a set of spherical impactor and a portable computer. The computer is installed with high speed data acquisition system and a software program that controls and monitors the test and displays the result in numerical and graphical form.

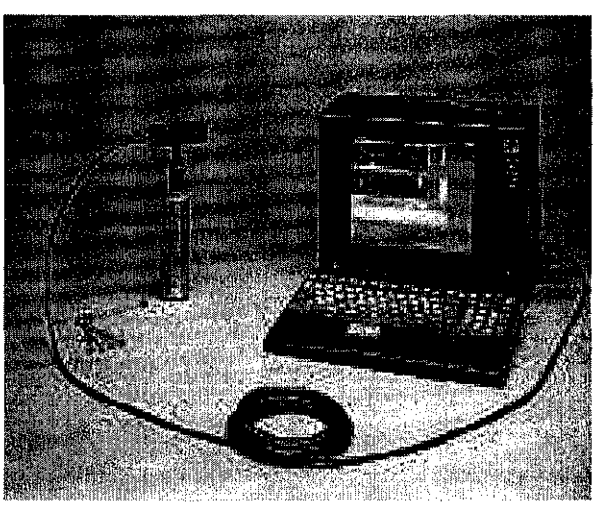


FIGURE 2.3

Typical commercial impact-echo systems

2.3 Wave Theory

Wave Propagation Velocity

The velocity of propagation of stress waves through infinite elastic media is a function of the material properties of the media, and depends upon the elastic modulus of the material, E, Poisson's ratio, ν, and the material density, ρ. In an infinite elastic solid, the compressive wave velocity, v_p , is given by the equation[7]:

$$V_p = \sqrt{\frac{E(1-\nu)}{p(1+\nu)(1-2\nu)}}$$

The wave propagation velocity of shear waves, V_s, is expressed by the following equation:

$$V_s = \sqrt{\frac{G}{p}}$$

where G is the shear modulus given by the following equation:

$$G = \sqrt{\frac{E}{2(1-\nu)}}$$

Values of shear wave velocity in many elastic solids are generally slightly less than half the compression wave velocity. For a Poisson's ratio of 0.2 to 0.3, a typical range in concrete, the shear wave velocity is 0.61 to 0.54 times the compression wave velocity traveling through an infinite medium.

Rayleigh surface wave particle motion is two-dimensional: the particles follow an elliptical path in a vertical plane parallel to the direction of propagation. The influence of the Rayleigh wave decreases rapidly with depth. The propagation velocity of Rayleigh waves, V_R, can be determined from the following approximation:

$$V_R = \frac{0.862 + 1.14\nu}{1+\nu} v_s$$

As poisson's ratio, ν, varies from 0 to 0.5, the Rayleigh wave velocity increases from $0.862v_s$ to $0.955v_s$.

The compression wave velocity in good quality concrete is often taken in practice to be 4000 m/s. Typical compressive wave velocities in concrete may range from 3500 m/s to 4500 m/s, depending upon the age, condition, and composition of the concrete. For poor quality concrete, the propagation velocity reduces to 2000 m/s to 3000 m/s for honeycombed concrete, soil inclusions, gravel, sand, and mud, so that the presence of these defects or extraneous materials is obvious when evaluating the results of NDT.

Wave Reflection and Transmission

When a wave strikes an obstacle, or comes to the end of the medium it is travelling in, at least a part of the wave is reflected. For example: we can see that water waves reflect off of a rock or the side of a swimming pool. Another example is that we can hear a shout reflected from a distant cliff-which we call an "*echo*".

For reflection of a two or three dimensional plane, as shown in Fig 2.4, the angle that the incoming or *incident wave* makes with the reflecting surface is equal to the angle made by the reflected wave. This is the *law of reflection: the angle of reflection equals the angle of incidence.*

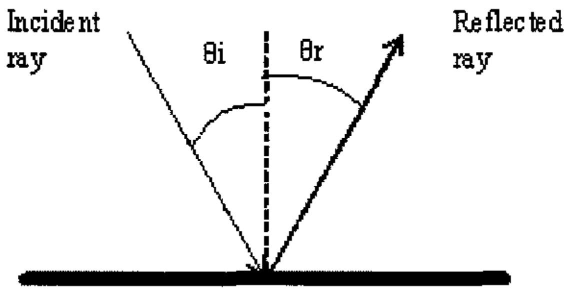


FIGURE 2.4

Law of reflection

Wave Refraction

When any wave strikes a boundary, some of the energy is reflected and some is transmitted or absorbed. When a two- or three dimensional wave travelling in one medium crosses a boundary medium where its velocity is different, the transmitted wave may move in a different direction than the incident wave. This phenomenon is known as *refraction*.

If the velocity of the wave in medium 2 is less then in medium 1, the direction of the wave bends so it travels more nearly perpendicular to the boundary. That is, the angle of refraction, θr is less than the angle of incidence, θi. If the wave travels into a medium where it can move faster, it will bend in the opposite way, $\theta r > \theta i$.

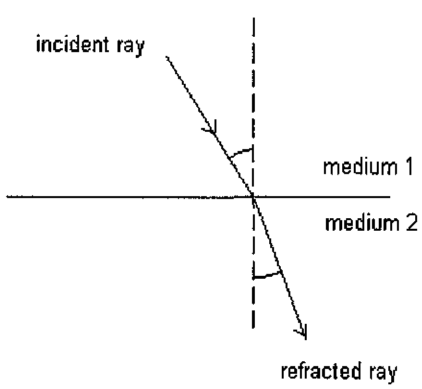


FIGURE 2.5
Wave refraction

Wave Diffraction

Wave spread as they travel, and when they encounter an obstacle they bend around it somewhat and pass into the region behind. This phenomenon is called *diffraction*. The amount of diffraction depends on the wavelength of the wave and on the size of the obstacles. If the wavelength is much larger than the object, the wave bends around them almost as if they are not there. For larger objects, there is more of a "shadow" region behind the obstacle where the waves may penetrate a little.

2.4 Signal Analysis Method

The principle of frequency analysis is illustrated in Fig. 2.3, which shows a solid plate of thickness T subjected to an impact-echo test[1].

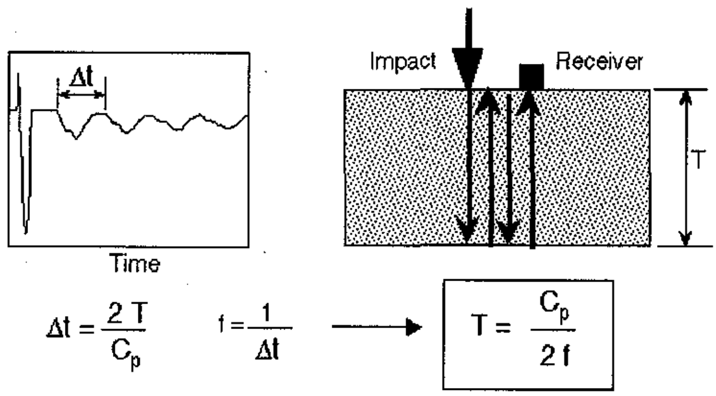


FIGURE 2.6
Signal Analysis Method

The P-wave generated by the impact propagates back and forth between the top and bottom surfaces of the plate. Each time the P-wave arrives at the top surface it produces a characteristic displacement. Thus the waveform is periodic, and the period, t, is equal to the travel path, $2T$, divided by the P-wave speed. Since frequency is the inverse of the period, the frequency, fp, of the characteristic displacement pattern is:

$$fp = Cp/2T \qquad \textbf{Eq. (1)}$$

Thus, if the frequency of an experimental waveform can be determined, the thickness of the plate (or distance to a reflecting interface) can be calculated:

$$T = Cp/2fp \qquad \textbf{Eq. (2)}$$

Note that Eq. (2) is an approximation that is suitable for most applications in plate-like structures. When using the method to measure plate thickness, a correction factor is needed. For prismatic members, the value of the correction factor depends on the geometry of the member. In practice, the frequency content of the recorded waveforms is obtained using the fast Fourier transform (FFT) technique to obtain the amplitude spectrum.

2.5 Frequency analysis

An impact on the top surface of an infinite plate results in multiple reflections of stress waves between the top and bottom surfaces. The multiple reflections give a periodic character to the displacement response at points close to the impact point. In finite solids containing flaws, multiple reflections occur between a variety of interfaces and free boundaries. As a result, time domain waveforms become complex and difficult to interpret. However, if the waveforms are transformed into the frequency domain, multiple reflections from each interface become dominant peaks in the amplitude spectrum -- at frequency values corresponding to the frequency of arrival of reflections from each interface. These frequencies can be used to calculate the location of the interface at each test point. It has been found that, for impact-echo testing, data interpretation is much simpler and quicker in the frequency domain than in the time domain[1].

The transformation from the time to the frequency domain is based on the idea that any waveform can be represented as a sum of sine curves, each with a particular amplitude, frequency, and phase shift. This transformation is carried out using the principles of the Fourier transform. As an example, Fig. 2.5 shows the digital time domain waveform, $g(t)$, given by the function:

$$g(t) = \sin(2 (\Pi) 20 t) + \sin(2 (\Pi) 40 t) + \sin(2 (\Pi) 60 t)$$

where t = time, s.

This function is composed of three sine curves of different amplitudes having frequencies of 20, 40, and 60 Hz.

The digital sample in Fig. 2.5(left) is made up of discrete points. The time interval between points is 0.001 seconds; this is equivalent to a sampling frequency of 1000 Hz.

The objective of frequency analysis is to determine the dominant frequency components in the digital waveform. This is most easily accomplished by using the fast Fourier transform (FFT) technique. The FFT results can be used to construct the amplitude spectrum, which gives the amplitudes of the various frequency components in the waveform. The amplitude spectrum obtained by the FFT contains half as many points as the time domain waveform, and the maximum frequency in the spectrum is one-half the sampling rate, which for this example is 500 Hz. Fig2 2.5 (right) shows the initial portion of the computed amplitude spectrum; the peaks occur at 20, 40, and 60 Hz. Each of the peaks corresponds to one of the component sine curves.

In the FFT technique, the frequency interval, in the spectrum is equal to the sampling frequency divided by the number of points in the waveform. For this example, there are 256 points in the complete time domain waveform, and the frequency interval is equal to 1000 Hz divided by 256, or 3.9 Hz. Since the frequency interval is proportional to the sampling frequency, a slower sampling rate enhances resolution in the frequency domain. However, slower sampling rates leads to longer record lengths which can result in complex spectra due to reflections from side boundaries of the test object. Experience has shown that a sampling frequency of 500 kHz with 1024 points per record is desirable in most applications.

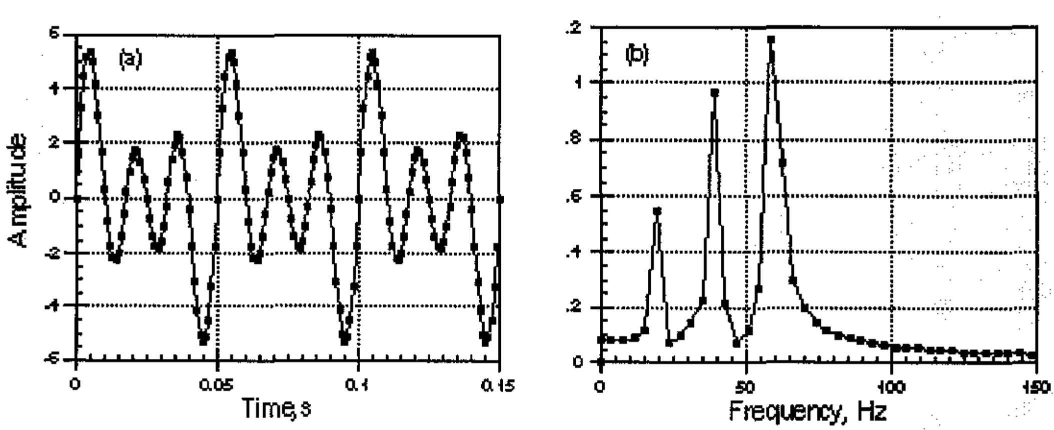


FIGURE 2.7

Example of frequency analysis using Fast Fourier Transform Technique.

2.6 Parameters that affect Impact-echo data quality for testing concrete structures

Test Location

A survey grid can be drawn out covering the area of interest on the structure, detailed enough to supply sufficient data so it is possible to interpret between the points. In actual practice, the test location should be at regular intervals of say 0.5m to 1.0m or preferably where there is any suspicion of a defect[8].

Impact source

The type and size of impactor is important to produce an acoustic wave with optimal frequency range[9]. This will assure more accurate data interpretation by giving the best compromise between penetration and level of detail. An approximate relationship has been reported between the diameter of the used sphere and the impact echo result. In general the larger the steel sphere the greater the depth of penetration, whilst smaller size ball bearing gives better near surface resolution. Table 2.2 shows the various steel sphere diameters with their correspondences contact time, frequency and resolution

The impact force also has a direct influence on the output energy. Greater force corresponds to increased amplitudes in the time waveform and in the spectrum. However, by normalising the input spectra at the maximum amplitude, it has been observed that the amplitudes in the maximum frequency region are slightly greater for smaller impact sources than for greater source.

Particular care should also be exercised in order that the impactor dose not cause the concrete surface to crumble on impact, otherwise a longer contact time will result in a lower frequency input signal. Experience shows that multiple strikes on the same spot may help to overcome this problem.

TABLE 2.2

Guidance on the steel sphere diameter in relation to the shallowest detectable target

Steel sphere diameter (mm)	Contact Time (μs)	Frequency ,*f* (kHz)	Resolution = λ/2 (mm)
4.7	85	11.8	148
6.0	117	8.6	203
9.55	125	8	219
4.7	62	16.2	108
6.0	70	14.3	122
9.55	109	9.2	190

2.7 Limitations of Impact-echo Method

The availability of commercial *impact echo* systems with data acquisition analysis enclosed in a tool box, enable almost everybody to carry out such a test. But not always the claimed capabilities of the systems could be verified or the results reproduced; especially in the presence of complex element geometry (for example box girder bridge, crossing reinforcement), the experimental results are not always unequivocal and can easily lead to misinterpretation. The requirement for skilled personnel that can provide a reliable and thorough interpretation of the impact echo data has been perhaps so far a limitation to a wider employ of this method.

Potential reasons that may lead to ambiguity of the impact echo data are as follows[9]:-

- Three-dimension dispersion of the impact-echo wave through the concrete due to the presence of aggregate and other inhomogeneities.
- Possible reduction in frequency of the impact echo signal due to crumbling of the concrete surface resulting in longer contact time and thus lower frequency.
- Possible lack of sensitivity of the transducer/accelerometer.

2.8 Cracking in concrete

Cracking in concrete is an important topic because failure of concrete is the consequence of cracking. Cracking may impair the durability of concrete by allowing ingress of aggressive agents; adversely affect the watertightness or sound transmission of structures or their appearance[10].

Microcracking

Microcracks have not been universally defined in terms of size, but an upper limit of 0.1mm has been suggested. Investigations have shown that very fine cracks at the interface between coarse aggregate and cement paste exist, in fact, prior to application of the loads on concrete. They are probably due to the inevitable differences in mechanical properties between coarse aggregate and the hydrated cement paste, coupled with shrinkage or thermal movement. Microcracking is a general feature of concrete. As long as the cracks are stable, their presence is not harmful.

As an increasing load is being applied, these microcracks remain stable up to about 30%, or more, of the ultimate load and then begin to increase in length, width, and number. The overall stress under which they develop is sensitive to the water/cement ratio of the paste. This is the stage of slow crack propagation. Upon further increase in load, up to between 70 and 90% of ultimate strength, cracks open through the mortar (cement paste and fine aggregate); they bridge the bond cracks so that a continuous crack pattern is formed. This is the fast propagation stage. However, high strength concrete exhibits a lower cumulative length of microcracks than normal strength concrete.

Interesting results of measurement of crack length is showed in fig 2.6. It can be seen that there was very little increase in total length between the beginning of loading and stress equal to 0.85 of the prism strength. A further increase in stress resulted in a large increase in total length of cracks. At a stress/strength ratio of about 0.95, not only interface (bond) cracks but also mortar cracks were present, and many cracks tended to become oriented parallel to the direction of the applied load.

Figure also shows the crack development under cyclic stress. Immediately prior to failure, the cracks became longer. Like wise, sustained loading at a stress/strength ratio of 0.85 led to an increase in cracking prior to failure.

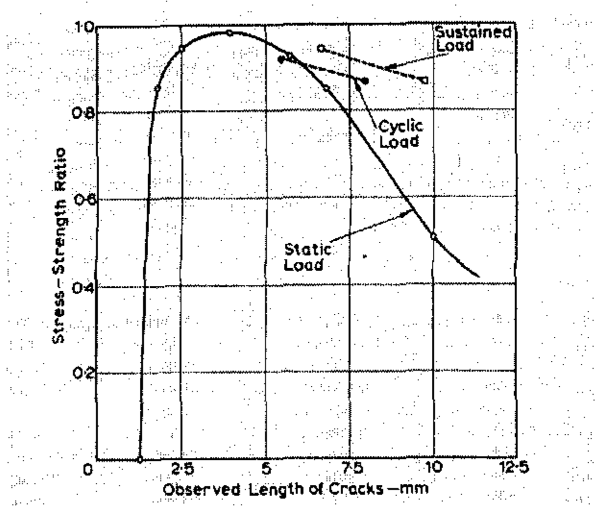


FIGURE 2.8

Relation between observed crack length and stress/strength ration in compression (based on prism)

2.9 Fatigue strength of concrete

Cyclic load is the basic loads on the structural concrete of bridge designs. Under repeated loads, concrete suffers damages resulting from progressive growth of internal microcracks. After a sufficient number of load repetitions, concrete fails at a load less than its static strength. The fatigue strength of concrete is therefore a fraction of its static strength that the concrete can support repeatedly for a given number of load cycles. At fatigue failure, concrete exhibits increased strains and reduced modulus (i.e. slope of its stress-strain curve) due to the progressive internal damages from microcracking.

Let us consider a concrete specimen subjected to alternations of compressive stress between values $\sigma_l(\geq 0)$ and $\sigma_h(>\sigma_l)$. σ_l is normally greater then zero due to dead load while σ_h is due to dead plus live load. The stress strain curve varies with the number of load repetitions, changing from concave towards the strain axis (with a hysterics loop on unloading) to a straight line, which shifts at a decreasing rate (i.e. there is some irrecoverable deformation) and eventually becomes concave towards the stress axis. The degree of this latter concavity is an indication of how near the concrete is to failure. Failure will take place only above a certain limiting value of σ_h, known as fatigue limit or endurance limit. If σ_h is below fatigue limit, then stress strain curve will indefinitely remain straight. The changes in the stress-strain curve with the number of applied cycles are illustrated in Fig 2.7 for compressive loading and Fig 2.8 for direct tension.

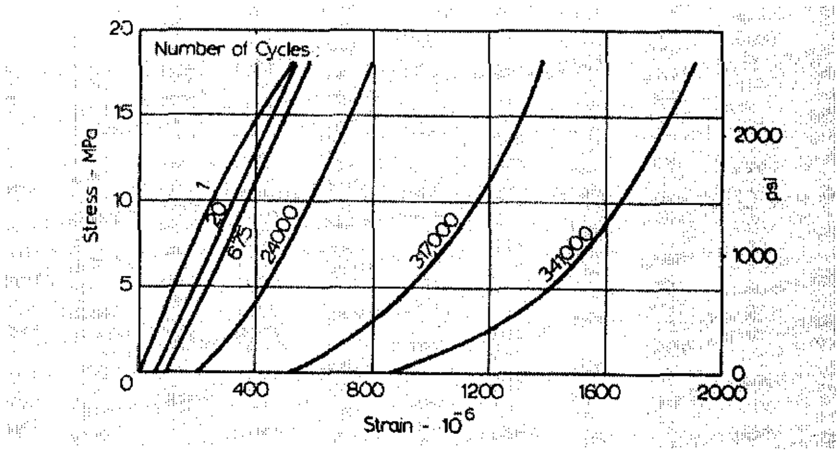


FIGURE 2.9

Stress-strain relation of concrete under cyclic compressive loading[10]

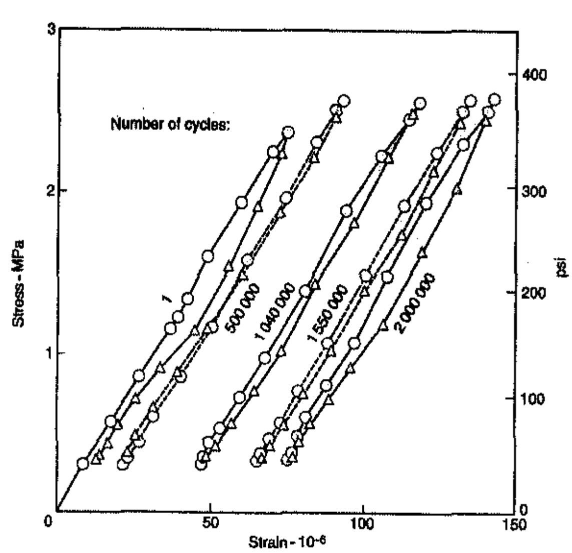


FIGURE 2.10

Stress-strain relation of concrete under cyclic loading in direct tension[10]

The change in strain with the number of cycles of loading can be described as consisting of three phases. In phase 1, which is the initiation phase; strain increases rapidly, but at a progressively decreasing rate, with the number of cycles of loading. In phase 2, which represents the stable state, strain increases approximately linearly with the number of cycles. In phase 3, which represents instability, strain increases at a progressively increasing rate until failure in fatigue takes place. An example of this behaviour is shown in Fig 2.9.

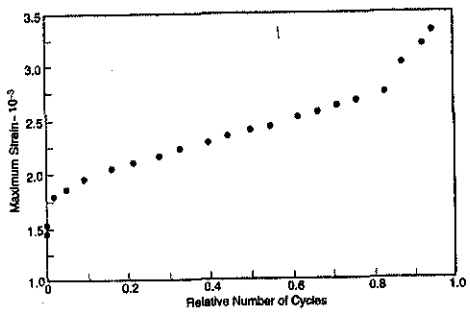


FIGURE 2.11

Relation between strain and relative number of cycles of loading in compression (σ_h =0.75 of the static strength; σ_i=0.05 of static strength.)[10]

The fatigue strength of concrete can be represented by means of a modified Goodman diagram (see Fig 2.10). The ordinate from a line at 45° through the origin shows that the range of stress (σ_h- σ_l) for a given number of cycles; thus the range of stress that a given concrete can withstand a specified number of cycles can be read off the diagram. For a given σ_l, the number of cycles is very sensitive to the range of stress. For instance, an increase in range from 57.5 to 65 % of ultimate strength has been found to decrease the number of cycles by a factor of 40.

The modified Goodman diagram shows that, for a constant range of stress, the higher the value of the minimum stress the lower the number of cycles that a given concrete can withstand. From the fact that the lines of Fig 2.10 rise to the right, it can also be seen that the higher the ratio σ_h/σ_l the lower the fatigue strength of concrete. The frequency of the alternating load, at least within limits of 1.2 to 33 Hz, does not affect the resulting fatigue strength. Because of a high scatter in the fatigue test results, the application of the concept of probability of survivor in fatigue has to be used in design. This applies both in compression and in flexure.

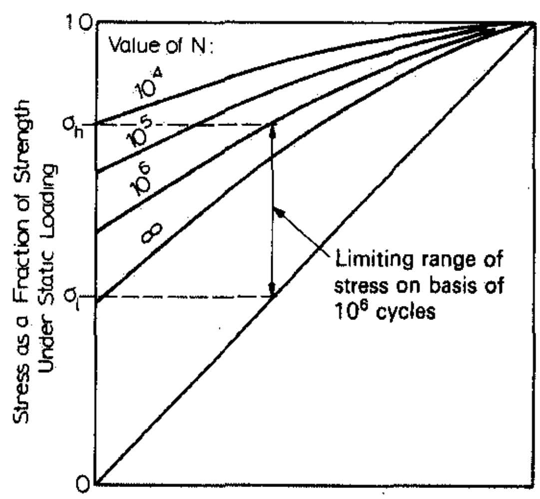


FIGURE 2.12

Modified Goodman diagram for concrete in compression fatigue[10]

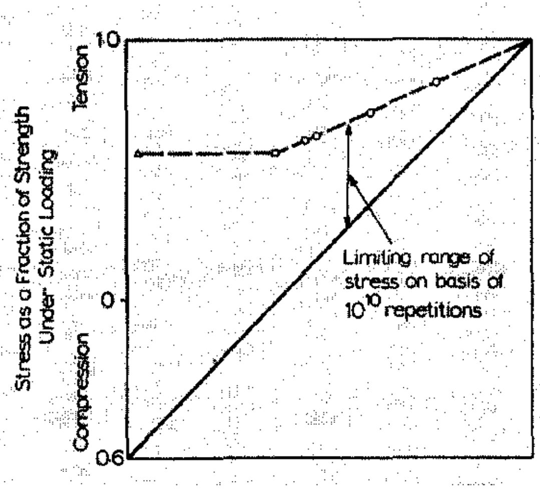


FIGURE 2.13

Modified Goodman diagram for concrete in flexural fatigue[10]

CHAPTER 3
METHODOLOGY

3.1 General

This chapter presents methods of the laboratory works including samples preparation, details of testing for static compressive and flexural test; and also impact echo test on beams subjected to cyclic load. The concrete samples are prepared in the form of concrete cubes and concrete plain beam; mixed and cured in accordance with British Standard. After 60 days, the concrete samples are tested to obtain its static compressive and static flexural strength. Impact echo test for samples subjected to cyclic load are then carried out. For fatigue, concrete samples are tested at 60 days after mixed because the concrete strength development is practically the same after 60 days. The following flowchart shows the sequence of laboratory works:-

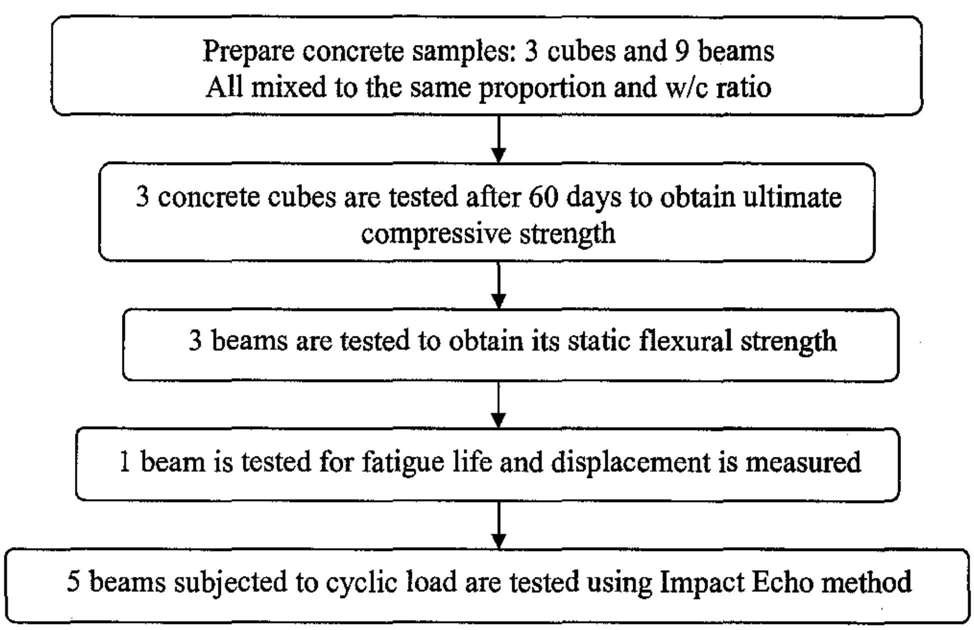


FIGURE 3.1

Flow Chart of Methodology

3.2 Tools/Equipment and Materials

Six (6) major tools/ equipment and materials required in this study are as follows:-

- Dynamic Universal Testing Machine (Dynamic UTM)
- 7mm diameter steel ball with thin steel stem
- Accelerometers
- Amplifier
- Oscilloscope
- Concrete samples

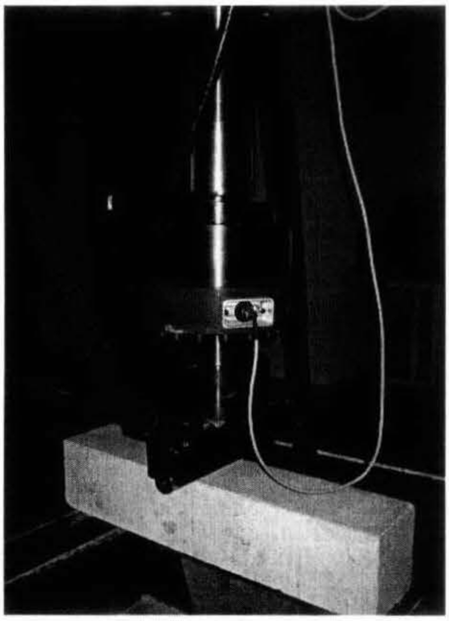


FIGURE 3.2

Dynamic UTM

FIGURE 3.3

Zwick Roell pump controller

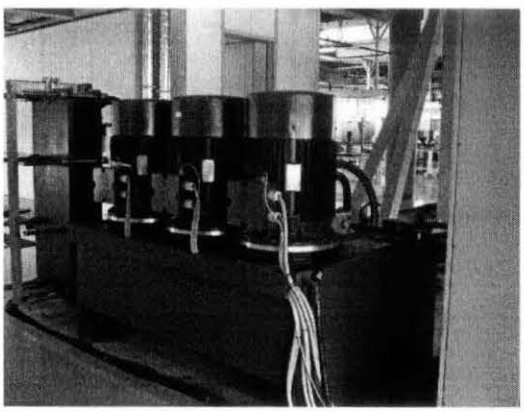
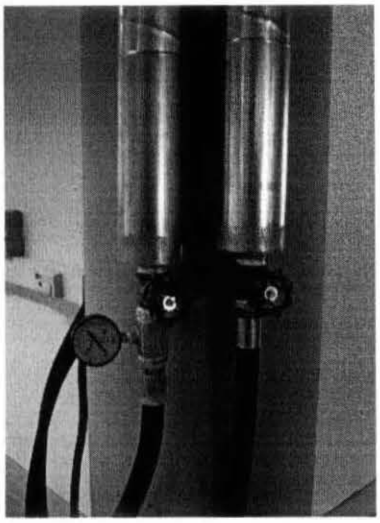


FIGURE 3.4

Pump for dynamic UTM



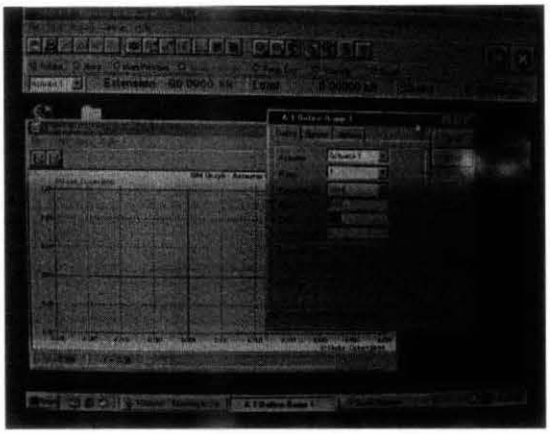


FIGURE 3.5

Cooling system for Dynamic UTM

FIGURE 3.6

Computer for test monitoring

FIGURE 3.7

Accelerometer

FIGURE 3.8

Striking concrete surface with steel ball

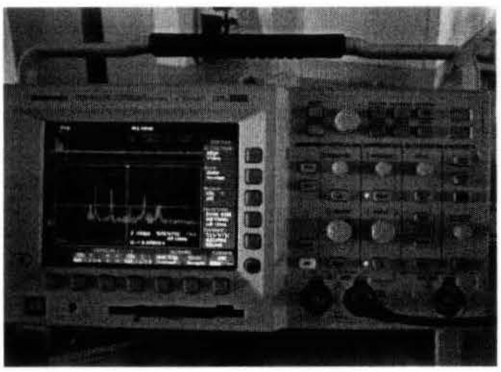


FIGURE 3.9

Oscilloscope

FIGURE 3.10

Impact echo tools

3.3 Preparation of concrete specimens

Concrete samples in the form of cubes (150mmx150mmx150mm) and plain beam (150mmx150mmx750mm) are prepared and stored in a curing tank. The mix proportion for both the concrete specimens is 1:2.03:2.74, w/c=0.55 and the maximum course aggregate size is 20mm. The procedures of samples preparation are as follows:-

1. The concrete mixer is cleaned and moistened.
2. Coarse aggregates followed by fine aggregates were put in the mixer and mixed for 20 seconds.
3. 50% of total water required is added and mixed for 1 minute and then left for 8 minutes.
4. Cement is added and mixed for 1 minute. The remaining water is added and mixed for another 1 minute.
5. The mixture is poured out on a tray and mixed by hand until visually homogenous.
6. The moulds were filled in 3 layers and vibrated for 15 seconds.
7. The moulds were placed under wet Hessian and polythene sheeting for 24 hours.
8. The concrete samples were demoulded after 24 hours and were placed in curing tank.

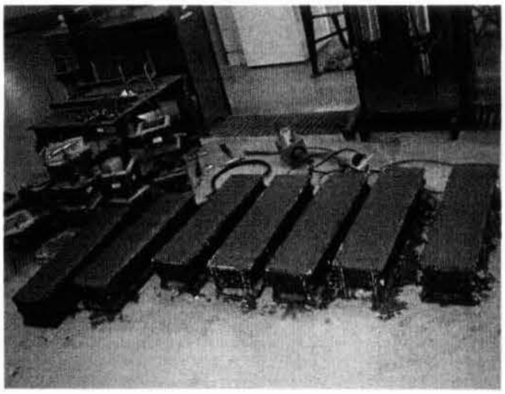


FIGURE 3.11
Preparing concrete samples

FIGURE 3.12
Concrete samples in curing tank

3.4 Static Test

Three concrete cubes are tested to obtain its compressive strength at 60 days and the result is recorded as P_c. Three concrete beams are tested using centre point loading method. Static load is applied at the rate of 1KN/s until the beam collapsed. The concrete beam is placed on two supports at a distance of 650mm, as illustrated in Fig 3.13. The load that caused the beam to fail is recorded as P_t.

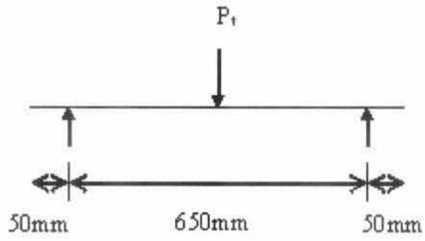


FIGURE 3.13

Tensile test using centre point loading method

3.5 Fatigue Test

For fatigue, the frequency of the load applied is 2Hz (2 cycles per second). Initially, the upper load chosen is 15KN while the lower load is 5KN. But it was soon find out that 15KN of upper load made the beam collapse too fast, so subsequently the load setting is changed to 14KN for upper load while lower load is maintained. One beam is tested for fatigue until failure, the displacement of the beam and the total number of cycles which caused the beam to collapse is jotted down.

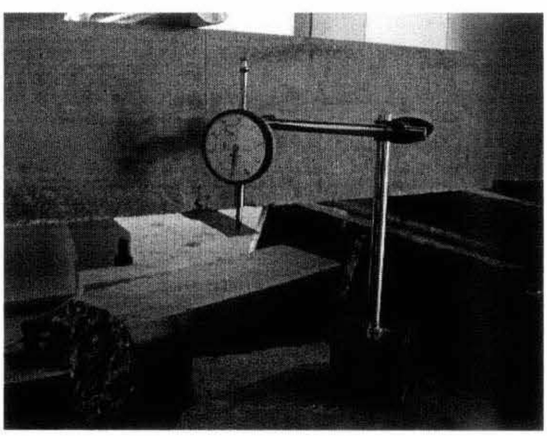


FIGURE 3.14

Dial gauge for beam displacement measurement

3.6 Impact Echo Test

Impact echo test is carried out on 6 beams subjected to cyclic load at certain interval of number of cycles until the beams collapsed. For the first testing, the impact echo test is carried out on beam 100mm x 100mm x 500mm with minimum load 1KN and maximum load 5KN. But it is found out that the capacity of the testing machine is too big for the beam, so subsequent beams are changed to 150mm x 150mm x 750mm. Impact echo results are recorded in form of frequency domain waveform and the readings for peak frequency are recorded manually. The result are recorded corresponds to the number of cyclic load that has been imposed. The details of load setting for each specimen are illustrated in table 3.1.

TABLE 3.1

Load setting for concrete specimens

Specimen	Size (mm x mm x mm)	Minimum Load (KN)	Maximum Load (KN)
1	100 x 100 x 500	1	5
2	150 x 150 x 750	5	15
3	150 x 150 x 750	5	15
4	150 x 150 x 750	5	14
5	150 x 150 x 750	5	14
6	150 x 150 x 750	5	14

The accelerometer is placed at the centre of the beam while the impactor is stroke at four (4) different locations as illustrated in figure 3.15; approximately 2cm from the accelerometer.

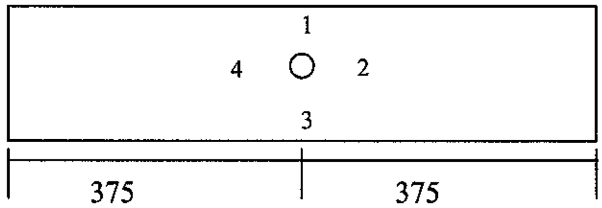


FIGURE 3.15

Location for striking of impactor

CHAPTER 4
RESULTS AND DISCUSSION

4.1 General

This chapter presents the results and discussion of the research. Firstly, the result of static test on concrete specimen; which consists of two kind of test: static compressive and static flexural test, to obtain the ultimate strength of the concrete specimens. Secondly, result for fatigue test, including the displacement of beam corresponds to number the cycles imposed and also the total of number of cycles for the beams to collapse. Finally is the impact echo test. All results are tabulated and graphed.

4.2 Static Test

Table 4.1 shows the result of compressive test on concrete cube; where Pc is the minimum load which cause the cube to fail and σ_c is the concrete compressive strength, calculated by dividing Pc with the cross sectional area of the cube. Table 4.2 shows the result of flexural strength test on plain beam; where Pt is the minimum load which cause the beam to collapse while σ_t calculated by using the following formula:

$$\sigma_t = 1.5P_tL_e / bh^2$$

L_e = effective length of the beam (distance between two supports)

b = width of the beam

h = depth of the beam

From the average reading, it is found that the tensile strength for the concrete specimen is approximately 12% of its compressive strength, while theoretically the tensile strength of concrete is 10-20% of its compressive strength.

It is from this static test the load setting for fatigue test is determined. The upper load or maximum load for fatigue test is lower than the concrete ultimate strength so that the concrete will fail only after numerous cycles of load is imposed on it.

TABLE 4.1

Result of compressive test

Cube	Pc (KN)	σ_c (N/mm^2)
1	742.50	33.00
2	885.15	39.34
3	891.45	39.62
Average	839.70	37.32

TABLE 4.2

Result of flexural test

Beam	P_t (KN)	$\sigma_{t,}$ (N/mm^2)
1	16.00	4.62
2	15.50	4.47
3	15.00	4.33
Average	15.50	4.47

4.3 Fatigue Test

Table 4.3 shows the result of fatigue test. It is found out that for specimen 1, the beam did not collapse even after numerous number of cyclic load has been imposed on it. It is then realised that capacity of the dynamic UTM is too big (500KN), so for a small beam with low capacity, the machine cannot apply the load correctly. So for subsequent fatigue test the beam size is changed to increase its capacity and also to accommodate with the capacity of dynamic UTM.

For specimen 2 and 3, the upper load is 0.95 which cause the beam to collapse at only 50 and 98 cycles respectively. It is hard to correlate their impact echo result with fatigue load; therefore for subsequent test upper load is reduced to 0.9. However, the displacement corresponds to the number of cycles imposed for beam 3 is presented in table 4.4 and fig 4.1. n/N is the relative number of cycles; whereby n is the number of cycles when the reading is recorded while N is total number of cycles which cause the beam to collapse.

It is found out that the trend of the graph can be divided into 3 phases. Phase 1 is where the beam displacement increased drastically when n/N increased from 0 to 0.2. Phase 2 is where the increment is lower when n/N increased from 0.2 to 0.6. Phase 3 is where the increment is much lower when n/N increased from 0.6 until the beam collapsed.

For specimen 4, 5 and 6, the frequency domain waveforms are recorded at certain interval of cyclic load, but only the result for specimen 4 is presented in this report because it offers the best correlation. The impact echo result will be discussed in next section.

TABLE 4.3

Result of fatigue test

Specimen	Size (mm x mm x mm)	Load Ratio		Load Range	Number of cycles N
		Minimum	Maximum		
1	100 x 100 x 500	0.16	0.8	0.64	-
2	150 x 150 x 750	0.3	0.95	0.65	50
3	150 x 150 x 750	0.3	0.95	0.65	98
4	150 x 150 x 750	0.3	0.9	0.6	1258
5	150 x 150 x 750	0.3	0.9	0.6	2000
6	150 x 150 x 750	0.3	0.9	0.6	1461

TABLE 4.4

Displacement of beam subjected to cyclic load

No. of cycles	Relative number of cycle n/N	Displacement mm
0	0	0
10	0.10	0.04
20	0.20	0.04
30	0.31	0.05
40	0.41	0.06
50	0.51	0.07
60	0.61	0.07
70	0.71	0.08
80	0.82	0.085
90	0.92	0.09
98		collapsed

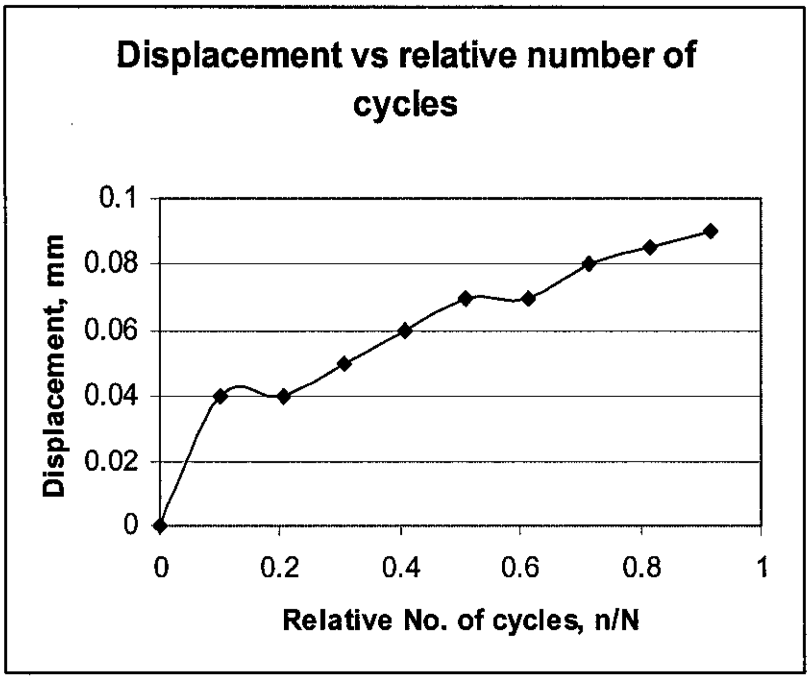


FIGURE 4.1

Graph of beam displacement VS relative number of cycles for specimen No. 3

4.4 Impact Echo Test for specimen No.4

The impact echo result for specimen no.4 is recorded at 0, 20, 150, 300, 400, 500, 800 and 1000 number of cycles, the beam failed at 1258 number of cycles. Four readings are taken for each interval, but only the selected waveforms are presented here. However, the peak frequency recorded at all four locations are shown in table 4.5.

Fig 4.2 shows the waveform of impact echo result at 0 cycles in frequency domain. The peak frequency recorded is 7000 Hz. Fig 4.3 shows the waveform at 20 cycles, the peak frequency maintained 7000Hz. The number of peaks has reduced because the specimen has rearranged itself on the support and is more stable now.

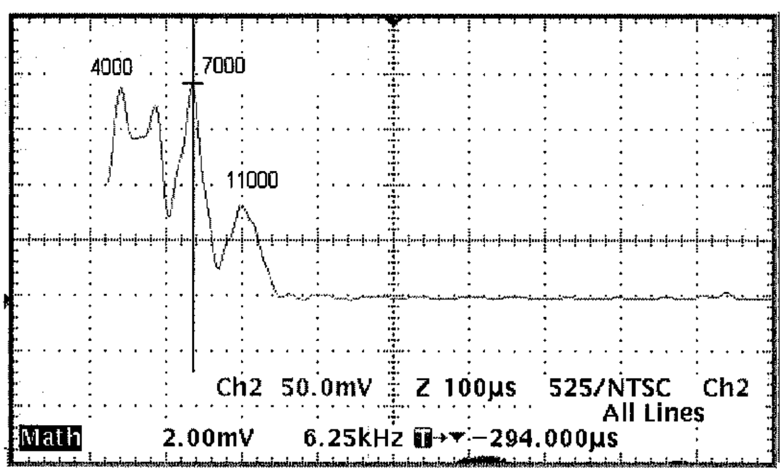


FIGURE 4.2

Frequency domain waveform before any load is applied. (0 cycle)

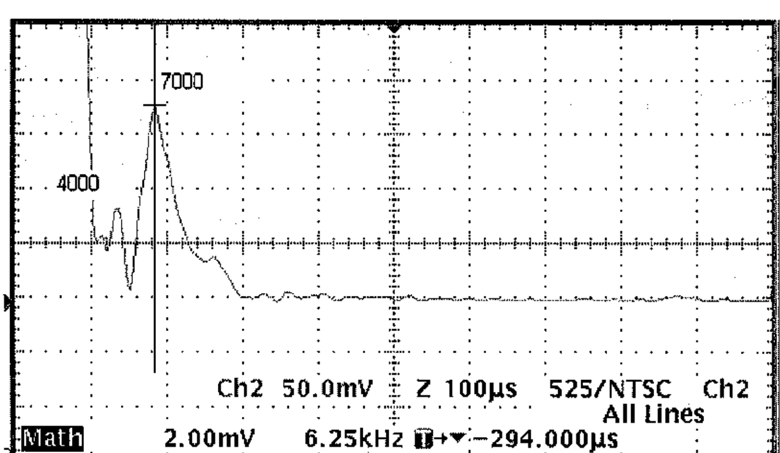


FIGURE 4.3

Frequency domain waveform after 20 cycles of load is applied.

Fig 4.4 shows the frequency domain at 150 cycles. It is observed that the peak frequency has increased to 7100Hz.

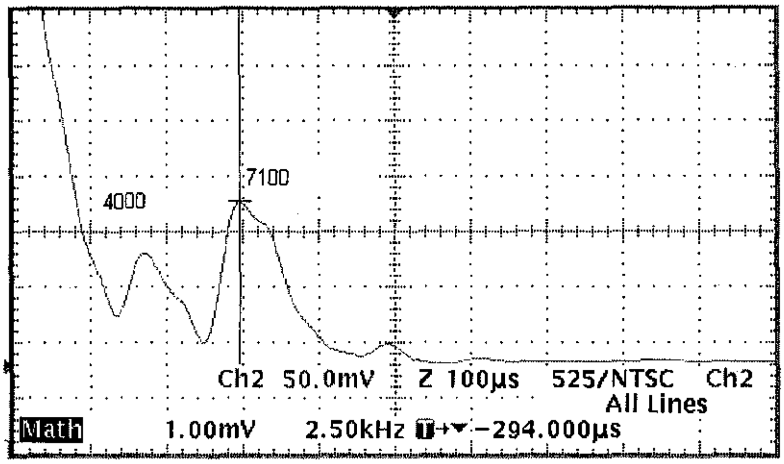


FIGURE 4.4

Frequency domain waveform after 150 cycles of load is applied.

Fig 4.5 shows the frequency domain at 300 cycles, the peak frequency has increased to 7230Hz.

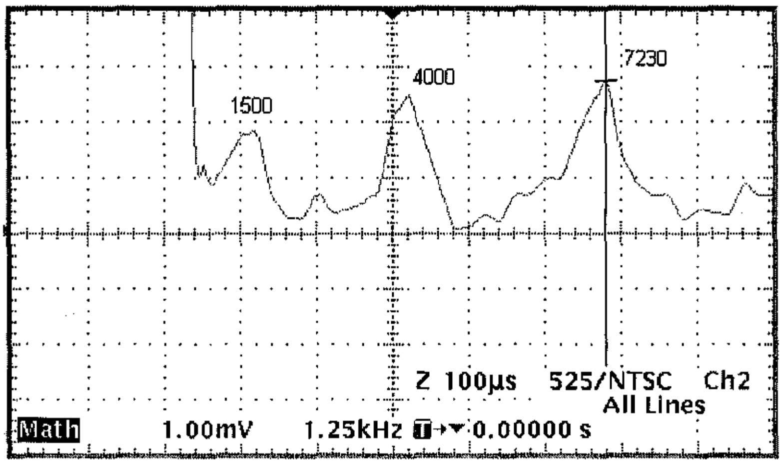


FIGURE 4.5

Frequency domain waveform after 300 cycles of load is applied.

Fig 4.6 shows the frequency domain at 400 cycles. The peak frequency is 7230Hz; which remain unchanged since 300 cycles.

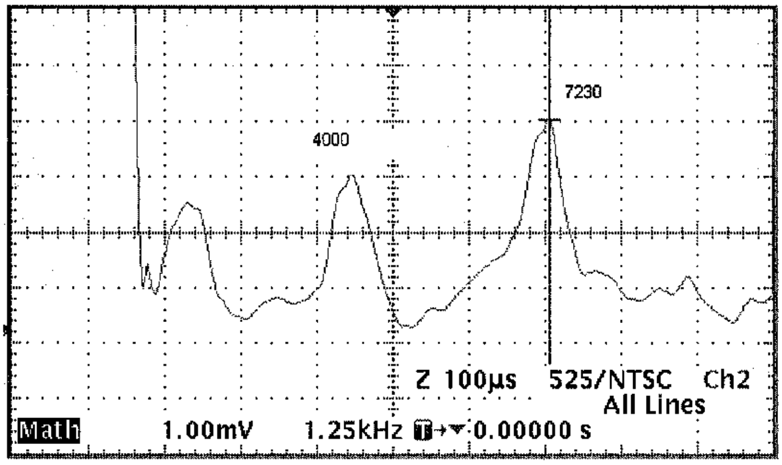


FIGURE 4.6

Frequency domain waveform after 400 cycles of load is applied.

Fig 4.7 shows the frequency domain at 500 cycles, the peak frequency has increased to 7250Hz.

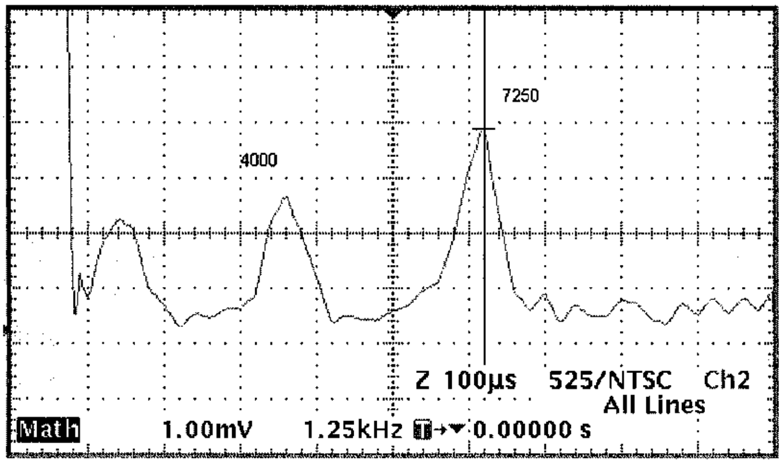


FIGURE 4.7

Frequency domain waveform after 500 cycles of load is applied.

Fig 4.8 shows the frequency domain after 800 cycles. The peak frequency is still 7250Hz, same as the frequency at 500 cycles.

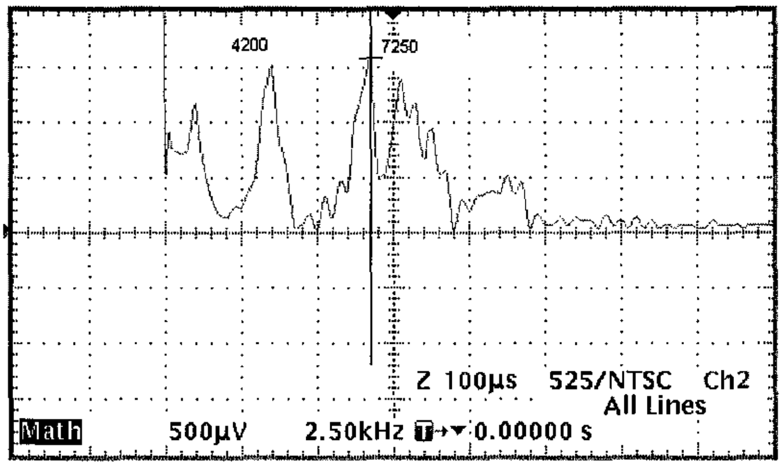


FIGURE 4.8

Frequency domain waveform after 800 cycles of load is applied.

Fig 4.9 shows the frequency domain after 100 cycles, the peak frequency remain unchanged; which is still 7250Hz.

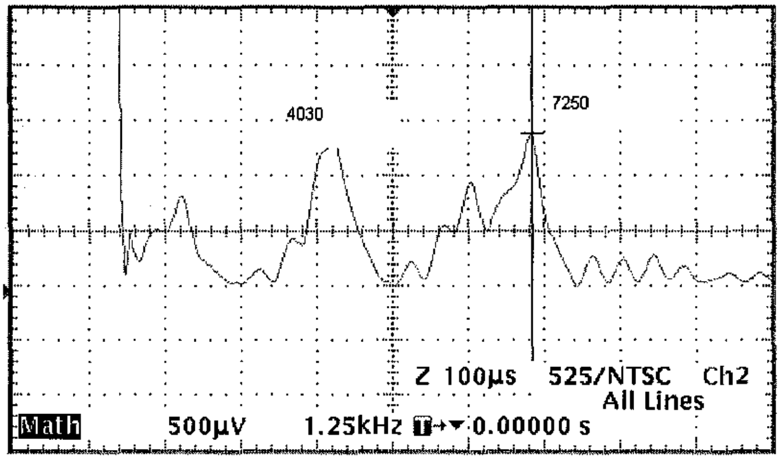


FIGURE 4.9

Frequency domain waveform after 1000 cycles of load is applied.

Table 4.5 shows the peak frequency recorded and analysis of the result. The frequency is chosen by comparing the readings at all four locations; the reading which is repeating is selected. The wave speed of the beam is calculated by assuming that at 0 cycle, there is no flaw in the beam, therefore its effective depth is 150mm. Using equation 2,

Wave speed, Cp	=	2Tf
	=	$2*0.15m*7000s^{-1}$
	=	2100 m/s

Using the same equation, the effective depth, h' for 20, 150, 300, 400, 500, 800 and 1000 cycles are calculated. The crack length is therefore the revised effective depth deducted by the original depth:

Crack depth = h - h'

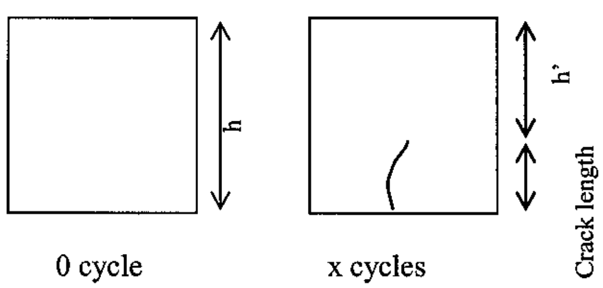


FIGURE 4.10

Illustration of crack propagation

The theoretical tensile stress which cause the crack propagation is calculated using formula $\sigma_t = 1.5P_tL_e/ bh'^2$.

Fig 4.10 shows the graph of chosen frequency versus relative number of cycles while Fig 4.11 shows the graph of calculated crack length versus relative number of cycles. The graph shows that the crack development has the trend similar to that of the displacement of beam subjected to cyclic load, which also consists of 3 phases.

TABLE 4.5

Impact-echo result

No. of cycles	Relative no. of cycles	peak frequency (Hz)				(Col 1) Chosen Frequency Hz	(Col 2) Effective depth mm	(Col 3) Crack depth mm	(Col 4) σ_t N/mm2
		loc 1	loc 2	loc 3	loc 4				
0	0	7000	7000	7000	4000	7000	150.00	0.00	4.04
20	0.02	6880	3880	7000	7000	7000	150.00	0.00	4.04
150	0.12	7100	9000	7100	7100	7100	147.89	2.11	4.16
300	0.24	4000	7230	7230	7230	7230	145.23	4.77	4.31
400	0.32	7230	7230	7250	7230	7230	145.23	4.77	4.31
500	0.40	7230	7250	7250	7250	7250	144.83	5.17	4.34
800	0.64	7250	7230	7250	7230	7250	144.83	5.17	4.34
1000	0.79	7240	7250	7250	7250	7250	144.83	5.17	4.34
1258	1	collapsed							

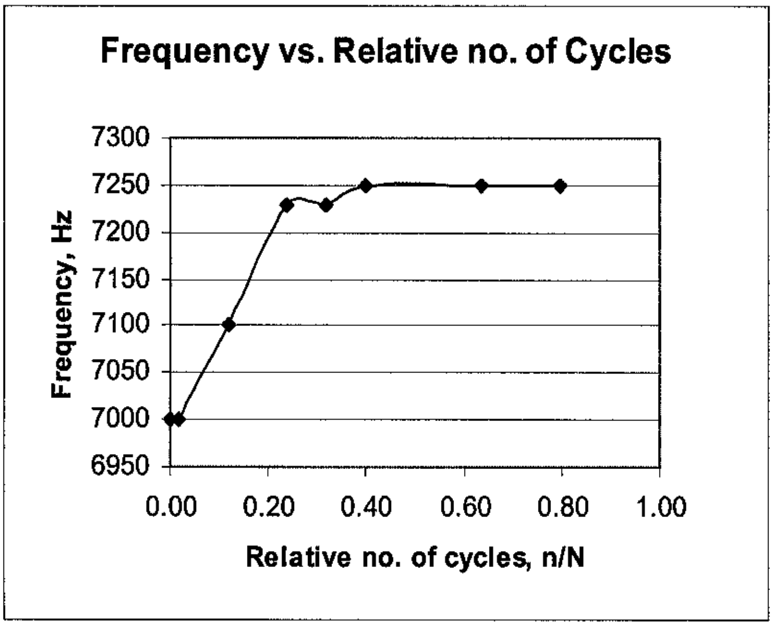


FIGURE 4.11

Frequency versus relative number of cycle

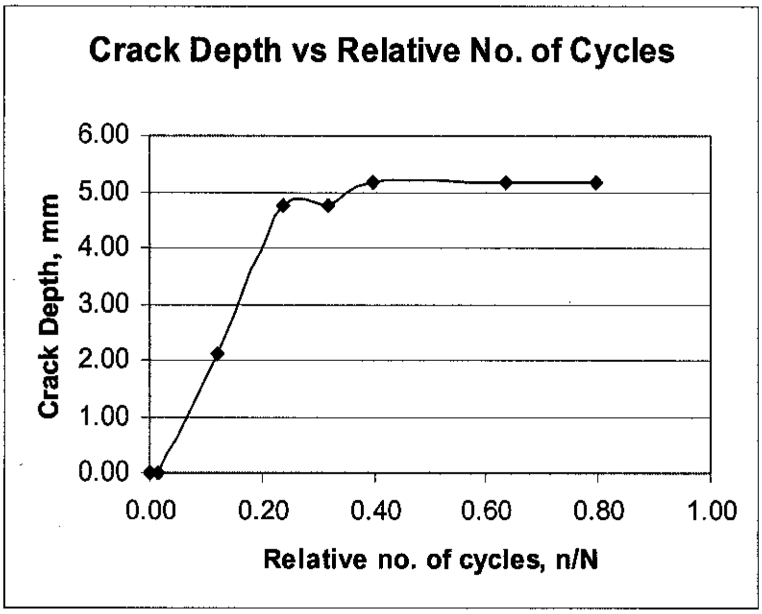


FIGURE 4.12

Crack depth versus relative number of cycle

The result shows that the frequency measured from impact echo test and also the displacement of beam increases as the number of cycle increases. This is because when cyclic load is applied at the centre of the beam, the beam gradually displace while cracks start to develop. Frequency is the inverse of time required to travel to bottom of beam reflected by boundary of beam or internal inhomogeneity. Therefore time required to be reflected back to surface and detected by the transducer is shorter when the crack is longer.

Numerous parameters can affect the accuracy the result, such as quality of concrete surface, input force, noise from surrounding, geometry of the concrete samples, multiple reflection of wave due to multiple internal cracks, moisture content and etc.

According to Martin and Forde[5], the weaker the surface, the longer the contact time and the lower the frequency. During the laboratory works, it is observed that when the impactor is stroke harder on the concrete samples, the amplitude recorded will be higher while vice versa when stroke lighter but the frequency recorded is the same most of the time. However, if the input energy is too low, the wave might not be able to penetrate to the bottom of the sample; if strike too hard may damage the surface. In this experiment, the impactor is stroke manually. Therefore the input energy varies each time impact echo test is carried out.

Another important factor that influences the result is the noises from surrounding and mounting method. During the laboratory works, the accelerometer is held by hand, a slight movement of our hand will cause the highly sensitive accelerometer to vibrate. Besides, the dynamic UTM itself is a very noisy machine, combination of noises and the movement of impactor will result in complex waveform, make us difficult to differentiate the peaks in the frequency domain.

The geometry of the concrete sample has very much influence towards impact-echo reading. An online journal by C.Colla [6] mentioned that for a flaw or inhomogeneity in the concrete to reflect the propagating wave, and thus be detected via impact-echo technique, it is necessary that its lateral dimension be greater then the wavelength and the wavelength be smaller than twice the depth of the flaw. A correction factor is needed for this case, but in this experiment it is assumed that the sample has infinite lateral dimension.

In plate like structures, wave reflections from the side boundaries do not have a significant effect on the measured response. However, for a concrete beam, the transient wave propagation is significantly affected by the close proximity of the side boundaries[7].

Another reason that contributed to the complexity of the waveform recorded is when the crack propagated at an inclined plane(refer figure 4.13). The multiple reflection of wave is illustrated in figure 4.14.

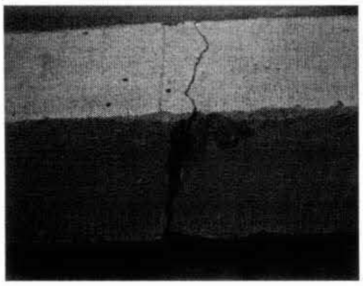


FIGURE 4.13
Crack propagate in inclined direction

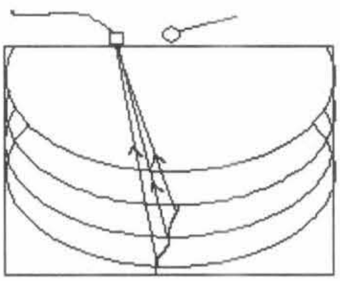


FIGURE 4.14
Multiple reflection due to inclined crack propagation

To predict the remaining service life of a concrete structure subjected to cyclic load, impact echo test can be carried out. By referring to figure 4.11, the relative number of cycle for the particular frequency recorded can be estimated. By relating the relative number of cycles with the design life and axle load imposed on the structures, the reaming life can be estimated.

CHAPTER 5
CONCLUSION & RECOMMENDATION

5.1 Conclusion

From the experiment carried out, it is concluded that there is a strong correlation between impact echo results with the fatigue life of concrete structures. The frequency recorded from impact echo test increases when number of cycle increases. Impact echo test can be used to determine the crack development with progressive cyclic load. There is also a great potential of using impact echo method to predict the remaining service life of concrete structures subjected to cyclic load.

Anyway, the usage of impact-echo method in detecting flaws in concrete structures is found to be interesting and has great potential for wider application. Unavailability of commercial pack of impact echo equipments at our laboratory also made the studies more challenging.

5.2 Recommendation

- When carry out impact echo test, strike the impactor at a location with better external surface to avoid prolonged contact period.

- Take into consideration the moisture content of the concrete structure.

- Shut down unused equipment like dynamic UTM when carry out impact echo test to reduce noise level.

- Select suitable ball size depends on the thickness of the concrete sample and also strikes the impactor with optimum force so that it has adequate force to penetrate through the samples.

- Take into consideration of the geometry of the concrete samples. A correction factor is needed if the lateral dimension of the sample is less than 2 times the thickness of the sample.

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APPENDIX

Operation of Dynamic Universal Testing Machine

1. Release the pressure valve for Dynamic Universal Testing Machine.
2. Release the valve for cooling of the pump to ensure the temperature is always below 60°C. (Caution: the system will shut down automatically when the temperature reached 60°C)
3. Switch on the computer and Zwick Roell controller.
4. Switch on the main pump, after all failure indicators are ok, push “Reset” and then start pump 1 and press “on”.
5. Once the computer has started up, double click on “Workshop Release 23” icon. A general menu will appear, click on “Toolkits”.
6. Isolator on the computer screen will indicate whether pressure is detected at the Universal Testing Machine main valve.
7. Once isolator is on, click on “Main Pressure”, followed by “Pump Pressure”, “Group Pressure” and lastly “High Low Pressure”. Respectively pressure indicators will indicate whether each component is working.
8. As the machine needs to “warm-up” in order to prevent “knocking”, the actuator needs to be raised and lowered using remote controller.
9. Then click on “Tools” and select “Ramp” for static testing while “Dynamic” for dynamic testing.
10. Go to “Tools” and select “Status” for load monitoring. For creating another window for stroke monitoring, go to the existing status window and click on “Tools” and followed by “Clone”. In the new window, click on “Tools” again and select “Feedback Channel” followed by “Stroke”.
11. For real time graph, click on “Tools” and select “Realtime Graph”.
12. Click “start” to proceed with testing.

Operation of Impact-echo Equipments

1. Connect the accelerometer to the amplifier as an input source.
2. Connect the amplifier to oscilloscope from the output channel.
3. Before start using the oscilloscope, calibrate it using a calibration probe. Calibrate the channel that will be connected with amplifier until the lines of the rectangular graph are parallel, say channel 1.
4. Select the component of x-axis and y-axis. In this study, the output of channel 1 is set to amplitude of the wave in time domain. Press FFT and another waveform for frequency domain will appear.
5. Adjust the vertical and horizontal scale of graph to obtain a clearer display for both channel 1 and FFT.
6. Attach the accelerometer on the concrete sample.
7. Press “trigger”, the oscilloscope will be able to capture the waveform when it detects any changes. Press “start” and “stop” if want to freeze a particular waveform.
8. Strike the sample with steel ball.
9. Press cursor and choose either “horizontal cursor” or “vertical cursor” or “bring both cursors to screen”. Utilise the horizontal and vertical cursor to obtain the peak reading.
10. The oscilloscope has a function of saving waveform and also the co-ordinates of the waveform in spreadsheet format in floppy disk. The files are quite big, so maximum only two files can be saved in one floppy disk. It may take around 1 minute to save a file.