An Introduction to Structural Health Monitoring

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Structural health monitoring......

- The process of implementing a damage detection, characterization strategy and remedial measure for an engineering structures is referred to as Structural Health Monitoring (SHM).
- The **damage** is defined as changes to the material and/or geometric properties of the system which adversely affect the system's performance.
- SHM results lead to suggest some optimal remedial measures; if possible. It may be continuous or non-continuous process

Objectives

- To provide a general awareness of the Structural Health Monitoring (SHM) and its potential applications
- To introduce the general apparatus and testing used for monitoring typical engineering structures

Intro and Overview

- The world's population needs an extensive infrastructure system;
  - Buildings, bridges, roads, sewers, highways etc.
- The infrastructure system generally suffers;
  - Carelessness, deterioration, lack of funding in past years

Global Infrastructure Crisis

Introduction and Overview

- Factors leading to the different extensive degradation…

Factor #1 → Neglect, Unsatisfactory inspection and monitoring of existing infrastructure

Consequences → Problems become apparent only when structures are in danger and there is dire need of repair

Result → **Repair costs become comparable to replacement costs**

Introduction and Overview

Factors Leading to Degradation

Factor #2 → **Corrosion** of conventional steel reinforcement within concrete

Consequences → Expansion of steel leads to cracking, spalling, and further deterioration in the structure

Result → **Reductions in strength and serviceability resulting in need for repair and/or replacement**

Introduction and Overview

Factors Leading to Degradation

Factor #3 → Increased loads or design requirements over time (e.g. heavier trucks)

Consequences → Increased deterioration due to overloads or to structural inadequacies resulting from design

Result → **Structures is deemed to be unsafe or unserviceable and strengthening or replacement is required**

Introduction and Overview

Factors Leading to Degradation

Factor #4 → Overall deterioration and/or aging

Consequences → Various detrimental effects on structural performance, both safety and serviceability

Result → **Need for repair, rehabilitation, strengthening, or replacement**

SHM Definition

Structural Health Monitoring

(Non- continuous)

Semi/ Destructive/ Non-destructive in-situ structural evaluation method (after the structure has matured)

(Continuous)

Uses several types of sensors, embedded in or attached to a structure

(Before and after concrete maturity for smart analysis; experimental or study level)

Structural safety, strength, integrity, performance

Testing / In-situ structural evaluation methods

Concrete Testing

Non-destructive

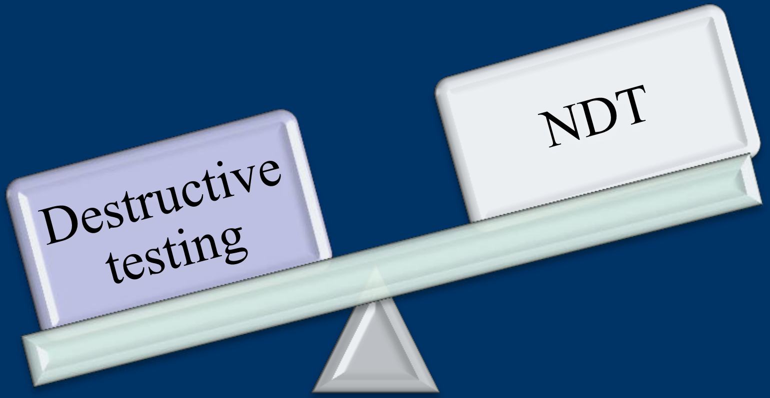
- Does not destroy the test specimen
- After testing, allows the part to be used for its intended purpose

Destructive(/Semi) destructive

- Carried out until specimen's failure
- will render the part unusable for its intended purpose.
- The affected part will have to be repaired or removed.
- Localized destruction of the concrete specimen
- After testing, structural element is usable.

Cost Effectiveness

- Destructive testing
  - Huge Cost initially has to put in for taking sample and then to test it.
- NDT
  - It is an easy and simple process and a lot many tests can be performed on concrete, less amount require for sampling of concrete



Destructive Testing

Core sample test

Load bearing test

Destructive testing: Core sampling

(ASTM C 42 and 39)

- A direct assessment on strength can be made by core sampling and testing. Cores are usually cut by means of a rotary cutting tool with diamond bits.
- A cylindrical specimen is obtained usually with its ends being uneven but parallel and sometimes with embedded pieces of reinforcement.
- The cores are visually described and photographed, giving specific attention to compaction, distribution of aggregates, presence of steel etc.

Ground Penetrating Radar (GPR) or any other scanning instrument may be employed to scan concrete for reinforcement location and service ducts.

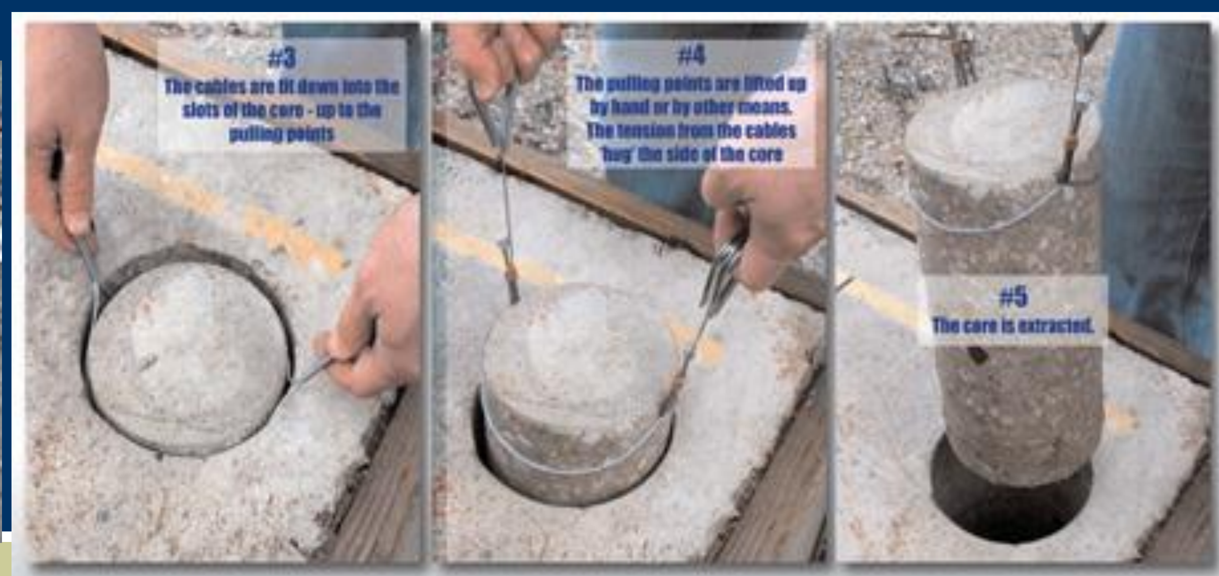
Uses of core sample

- Core sample is used for testing the physical properties of the concrete like compressive strength, density, water absorption, crack depth and chemical test like depth of carbonation and chloride content etc.
- It can also be used to inspect the interior region of the structural members.
- Different codes and standards set different values for the minimum diameter of concrete cores, ranging from 75 mm (in Australia) to ideal 150 mm (Britain). However, 100 mm core is a practical size in most structure inspections. The accuracy of cores for strength reduces when the ratio of diameter to nominal maximum aggregate size is greater than3.

Uses of core sample

- **H/D ratio**:
- Depth of the core that can be cut may be even up to 430mm or more with varying diameters.
- The preferred length of the capped or ground specimen is between 1.9 to 2.1 times the Diameter.
- ASTM C 42 provides correction factors for tests on cores with length-to diameter ratios between 1 and 2 while ASTM C 39 gives procedure for preparing and testing the samples

Concrete Core sampling



Concrete Core sampling

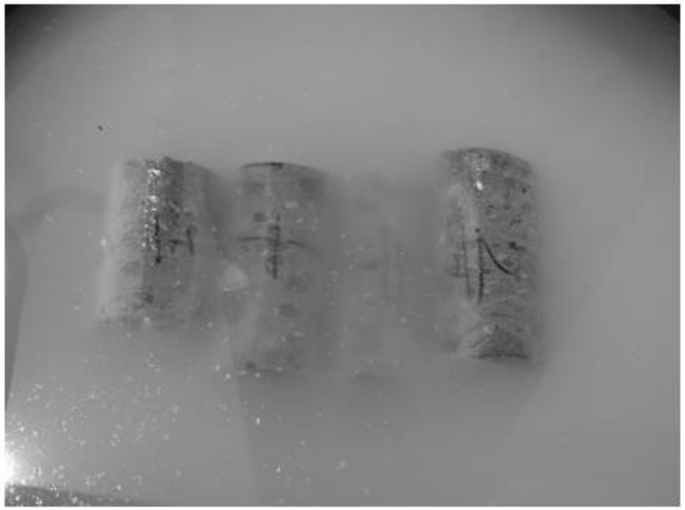
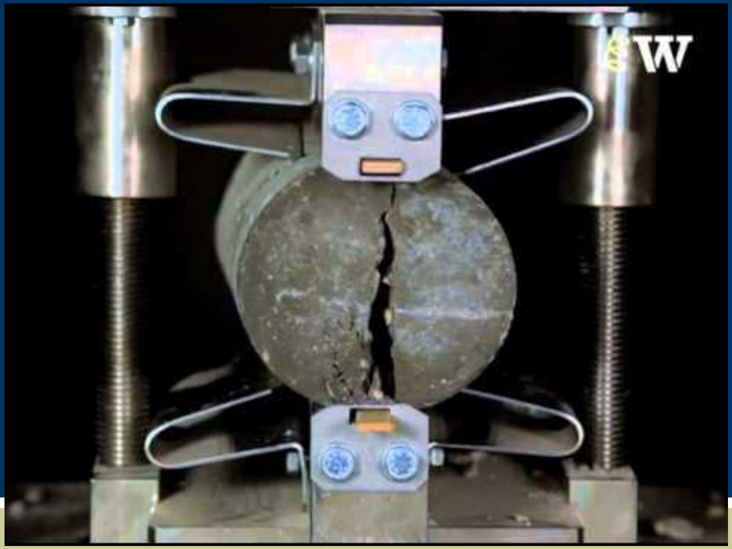


Fig. Core Samples Dipped in Lime Water



Destructive testing: Tips

- Take core sample after the concrete is strong enough to permit sample removal without disturbing the bond between the mortar and coarse aggregate.
- Cut surfaces should not display erosion of the mortar and the exposed coarse aggregate particles should be firmly embedded in the mortar. Don’t use samples that have been damaged during removal.
- Drill cores perpendicular to surface and not near formed joints or obvious edges of a concrete placement.
- Take cores near the middle of a concrete placement when possible. In columns or walls, for instance, samples should be taken near mid-height—not at the top or bottom.

Destructive testing: Tips

- **Presence of transverse reinforcement steel**:
- Compressive strength of core with cut rebar is always less than corresponding strength of core without rebar.
- It appears that strength reduction due to existence of rebar in cores is between 25 to 60 percent. This reduction in cast cylindrical samples is about 16 to 24 percent.
- It seems that rebar cutting leads to weakness in cores compressive strength due to crack formation between concrete and rebars.
- There is not reliable relationship for correcting compressive strength results of cores with rebar.

Factors affecting the compressive strength of extracted concrete cores

Figure . Separation of rebars after compression test of cores

- **Size of stone aggregate**:

If the ratio of diameter of core to maximum size of stone aggregate is less than 3, a reduction in strength is reported.

For concrete with 20mm size aggregate, 50mm dia core has been tested to give 10% lower results than with 100 mm dia cores.

Factors; contd..

- **Age of concrete**:

- No age allowance is recommended by the Concrete Testing practitioner as some evidence is reported to suggest that in-situ concrete gains little strength after 28 days.
- Whereas others suggest that under average conditions, the increase over 28 days' strength is 10% after 3 months, 15% after 6 months. Hence it is not easy to deal the effect of age on core strength.

Factors; contd..

- **Drilling operations**:

The strength of cores is generally less than that of standard cylinders, partly as a consequence of disturbance due to vibrations during drilling operations. Whatever best precautions are taken during drilling, there is always a risk of slight damage.

- **Site conditions vis-a-vis standard specimens**:

Because site curing is invariably inferior to curing prescribed for standard specimens, the in-situ core strength is invariably lower than the standard specimens taken and tested during concreting operations.

Destructive testing: Load Test

- Load test has commonly been used in civil engineering industry to verify the adequacy of floor structures.
- Generally, water, sand or bricks are used to reproduce the uniformly distributed loads , however, some researchers have recommended hydraulic jacks for rapid loading.
- Deflections and crack widths are monitored at various intervals both during loading and unloading phases.
- ACI 318 chapter 20 provides detailed testing procedure and criteria of acceptance and rejection. Several researchers have recommended different methods for applying loads and investigating structural response for the load tests.

Destructive testing: Load Test

- As per ACI 318 the test load should not be less than 0.85(1.4DL + 1.7LL). As per recommendations of ASCE, live load of 60 psf for shops and apartments, and 100 psf for assembly areas and corridors is used to calculate the test load.
- In case a panel is partially used as an assembly area and partly for the ordinary use, an average live load of 80 psf can be used.
- The test load may be applied in equal increments as recommended by the ACI.

Load test in progress

Fig. Load Application with Loose Sand within Wooden Shuttering.

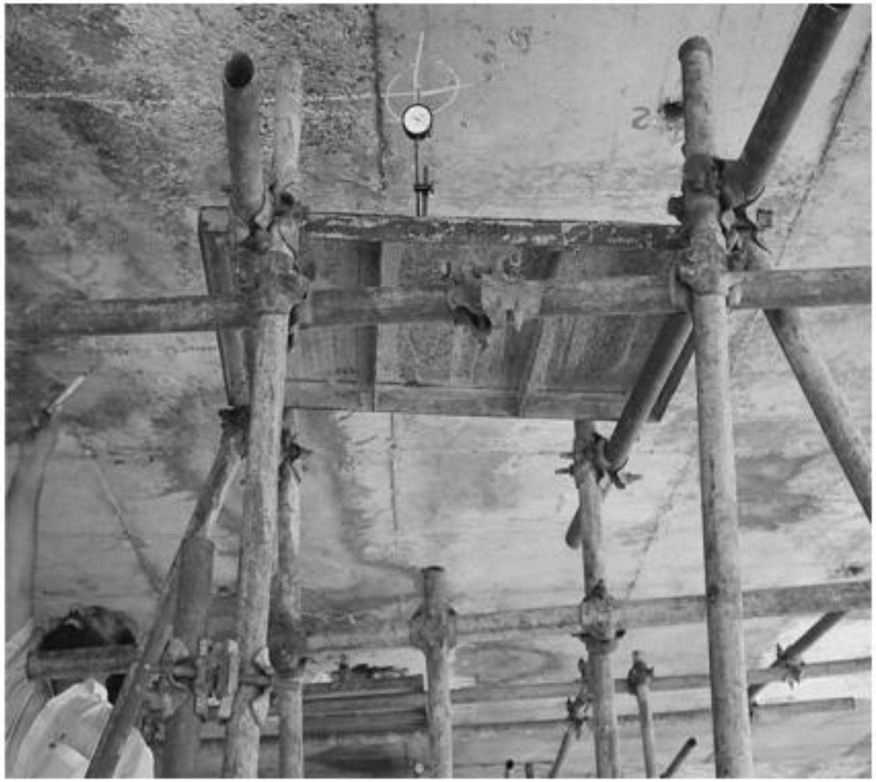


Fig. Deflection Gauge Installed at the Center of Panel

Non Destructive Testing

Why NDT?

- Quality control of new construction
- Troubleshooting of problems with new construction;
- Condition evaluation of older concrete for rehabilitation purposes;
- Quality assurance of concrete repairs.
- Assessment of existing structures in the absence of drawings
- Confirming workmanship
- Rapid & on site accumulation of data
- Whether concrete is hardened properly and gained design strength or not

Outcomes of NDT?

- Gives results without structural damage
- Quick assessment of the structure
- Determining position of reinforcement
- Location of Cracks/Joints/Honeycombing and concrete quality
- In some cases, it is required to assess concrete damaged due to fire or any other natural disaster

Deliverable by NDT

- Elastic Modulus
- Density
- strength
- Cracks and Voids Determination
- Reinforcement Location
- Surface Hardness
- Quality of Workmanship

Scope

- To suggest the methodology to be followed & applicability of any specific non destructive testing suitable for the structure.
- Automatic interpretation of data from NDT, with the goal of detecting flaws accurately and efficiently.
- To propose retrofitting techniques for structures failing in this kind of testing.

NDT Disadvantages

- More than one test method may be required
- Environmental conditions may affect or distort the results
- Some conditions cannot be determined with a reasonable degree of accuracy without destructive testing

Brief of NDT

1)Strength evaluation of Concrete

No.	Measurement	Application	Equipment
1	Surface strength (rebound number)	Surface Zone Strength Assessment	Rebound Hammer
2	Homogeneity of Concrete	Quality of Concrete	Ultrasonic pulse velocity meter
3	Combined ultrasonic and rebound number determination	Uniformity/homogeneity, Location of internal defects	Ultrasonic Pulse velocity tester
4	Pull-off strength (bond strength	Surface Zone Strength Assessment	Pull off Tester

Brief of NDT

No.	Measurement	Application	Equipment
5	Pull out force	Surface zone strength assessment	Pull out “Lock” Test (Construction Stage) Pull Out “Capo” Test (after construction
6	Break off test	The break off test at failure can be related to compressive or flexural strength	Break off tester
7	Penetration resistance	Surface Zone Strength Assessment	Windsor Probe

Brief of NDT

2) Corrosion assessment, location and dia. of rebar and cover

No.	Measurement	Application	Equipment
1	Corrosion potential (half-cell)	Status of Corrosion activity	Half Cell Potential Meter
2	Resistivity	Rate of probable corrosion	Resistivity Meter
3	Carbonation depth	Corrosion risk and cause	Carbonation Test Kit
4	Chloride content	Corrosion risk and cause	Chloride Field Test System

Brief of NDT tests

No.	Measurement	Application	Equipment
5	Voids and Corrosion	Viewing interior of concrete like for concrete pipes, concrete with large voids etc.	Endoscopy
6	Scanning Of dia. of rebar and cover	It is used for locating rebars , diameter of rebars and concrete cover	Profometer
7	Cover and re-bar measurement	Corrosion risk and cause	Micro Cover Meter

Brief of NDT

3) Crack measurement in buildings and structures

No.	Measurement	Application	Equipment
1	Length changes	Strain measurement	digital strain gauges
2	Radiographic Images	Cracks, location of rebars	Radiographic source and detector
3	Acoustic Emission technique	To measure the location and activity of cracks	SPARTAN & MISTRAS System
4	Infra Red Images	Cracks, delamination	Infra Red Thermal Imaging Systems

Some of the NDT Methods

VISUAL INSPECTION

Experience and well trained observer

Visual inspection

- An inspection is performed of existing structures in order to gather data needed to evaluate the various performance values of the structure
- Inspections shall consist of two types: document checks and site inspections.
- When inspecting structures, the study shall be conducted in accordance with the retrofitting method whose employment is being considered.

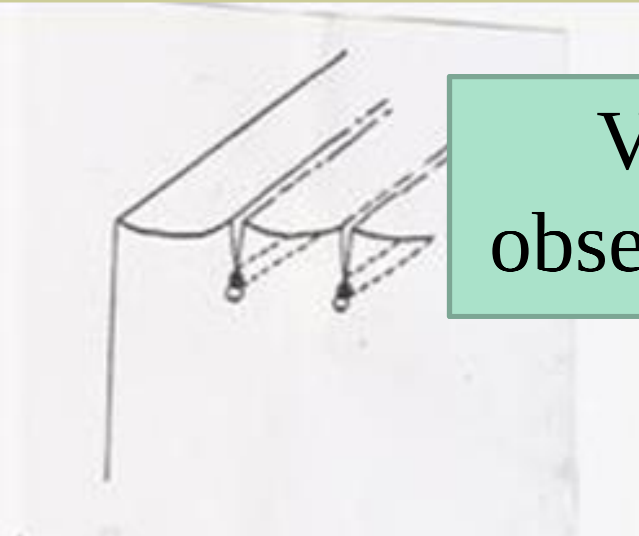
Visual observations

- Surface Staining
- Cracks
- Color change and Weathering
- Surface pitting and Spalling
- Differential movements and Displacements
- Presence of algal and vegetable growth
- Surface voids
- Honeycombing
- Bleed Marks
- Constructional and Lift Joints
- Lack of Uniformity

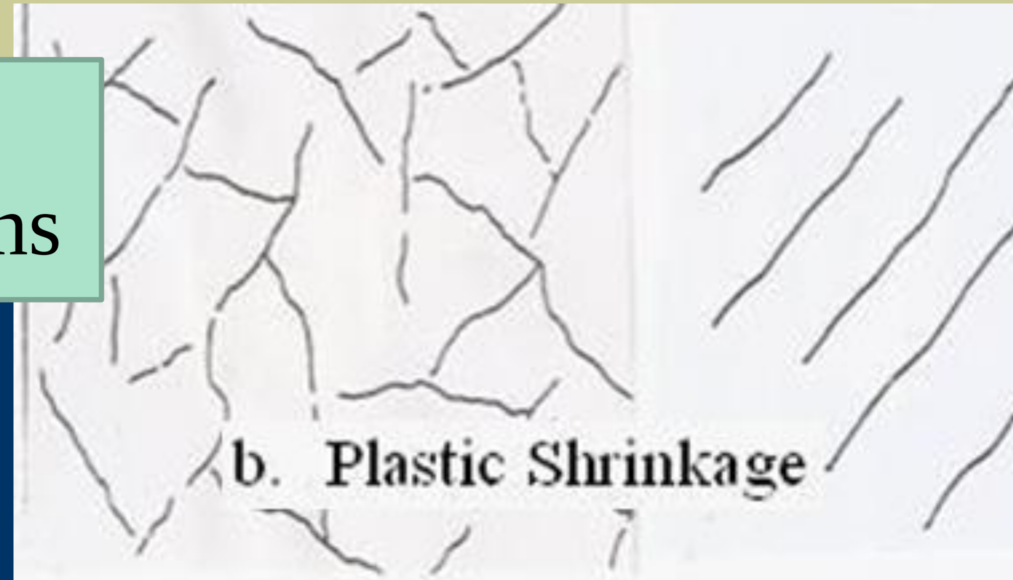
Non-Structural cracks which can occur in concrete

Type of Cracking	Common Location	Cause of Cracking	Remedy	Time of Appearance	Fig. No.
Plastic Settlement	Top of columns, slabs	Excess bleeding	Reduce bleeding	10 min to 3 h	a
Plastic shrinkage	RCC slabs	Rapid early drying	Prevent evaporation just after casting	30 min to 6 h	b
Early thermal contraction	Thick walls and slabs	Rapid cooling	Reduce heat and insulate	1 day to 2 or 3 weeks	
Long term drying shrinkage	thin wall and slabs	Inefficient joints	Reduce water content, Improve curing	Several weeks or month	C/1, C/2
Crazing	Slabs	Rick mixes over travelling, poor curing	Improve curing and finishing	1 to 7 day	
Corrosion of reinforcement	Column and beams	Inadequate cover, poor quality concrete	Eliminate the listed cause	more than 2 years	d
Alkali aggregate reaction	Deep location	Reactive aggregate and high alkali cement	Eliminate the listed cause	More than 5 years	e
Sulphate Attack	Members expose to sulphate attach	Soluble sulphates as SO_3 in soil and ground water	Ref. table 4 IS: 456-2000	—	f

Visual observations

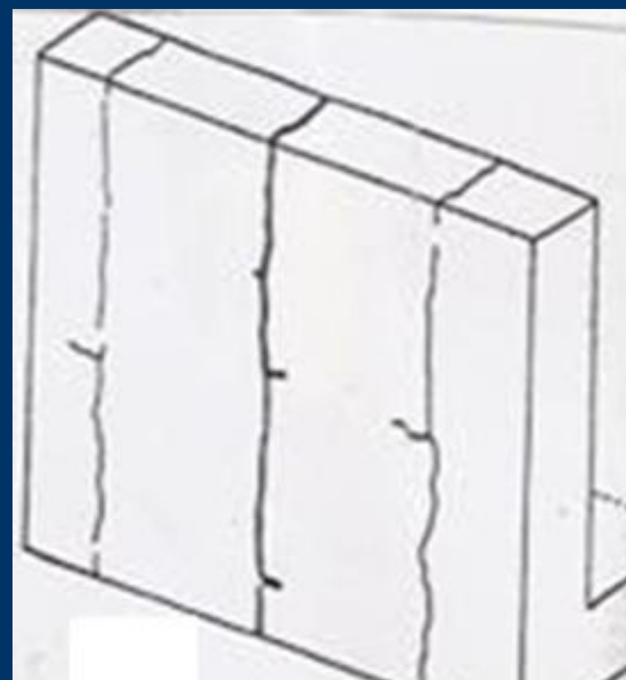


a. Plastic Settlement



b. Plastic Shrinkage

C1. Restrained Drying Shrinkage

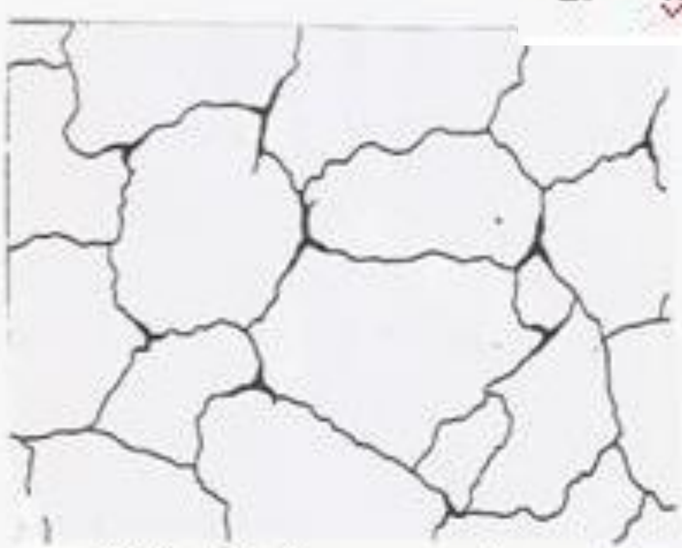


C2. Unrestrained Drying Shrinkage

Visual observations

d. Reinforcement Corrosion

f. Sulphate Attack



e. Alkali Aggregate Reaction

Visual inspection of Fire Damaged Concrete:(like blast etc.)

Changes in fire-damaged concrete:	
<300^0C Boundary cracking alone	
250-300^0C	Aggregate colour changes to pink to red
300^0C	Paste develops a brown or pinkish colour
300-500^0C	Serious cracking in paste
400-450^0C	Portlandite converts to lime
500^0C	Change to anisotropic paste
500-600^0C	Paste changes from red or purple to grey
573^0C	Quartz gives a rapid expansion resulting from a phase change from alpha to beta quartz
600-750^0C	Limestone particles become chalky white
900^0C	Carbonates start to shrink
950-1000^0C	Paste changes from grey to buff

Visual inspection of fire damage concrete

Change in aggregate	
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Testing concrete by tapping method

- As part of visual inspection the strength of concrete may be roughly obtained by **tapping** method.
- However, this may not be treated as substitute of cube testing.
- Tapping concrete with a *hammer* is one of the oldest form of non-destructive testing. Strength of concrete may be determined either from its hardness when scratched with a metal "pencil" or a ***chisel***, or from the character of the sound when struck with a hammer, or from the character of the mark left after a hammer blow.
- Ten blows of average force are made at different points on the specimen.
- The tapping method is used for an approximate determination of strength of concrete, because the force of the blow and the accompanying sound vary greatly depending on subjective factors.

Strength of concrete by tapping method:

Strength of concrete (N/mm^2)`	**Test Results**		
	Blow of hammer (0.4 kg) upon concrete surface	**Blow of hammer (0.4kg) upon chisel placed at right angles to concrete surface**	**Scratching by chisel**
Blow 6.0	Sound- Toneless deep dent with crumbling edges	Chisel is easily driven into concrete	Concrete cuts easily and crumbles
6-10	Sound-slightly toneless. Dent has smooth edges, concrete crumbles	Chisel can be driven into concrete deeper than 5 mm	Visible scratches 1-1.5 mm deep
10-20	Sound -clear with whitish mark remains	Thin scales split off round the mark	Visible scratches no deeper than 1 mm
Over 20	Sound-ringing metallic mark-visible	Mark is not very deep	Barely visible scratches

Conclusions

- Visual inspection is a very powerful NDT method. Its efficiency, however, is to a large extent governed by the experience and knowledge of the investigator. A broad knowledge of structural behaviour, materials, and construction methods is desirable. Visual inspection is typically one aspect of the total evaluation plan, which will often be supplemented by a series of other NDT methods or invasive procedures.
- Visual features may be related to workmanship, structure serviceability and material deterioration, and it is particularly important that the engineer be able to differentiate between the various types of cracking which may be encountered.
- Visual inspection will also provide the basis of judgment relating to access and safety requirements.
- There are already frightening examples where public safety has been put at risk due to lack of simple regular visual inspection.

NDT: Rebound Hammer Test (ASTM C 805)

- *Objective*

► To find the compressive strength of concrete with the help of suitable correlation between rebound index and compressive strength

► Many readings are needed (generally 10)

► Assessing the uniformity of concrete

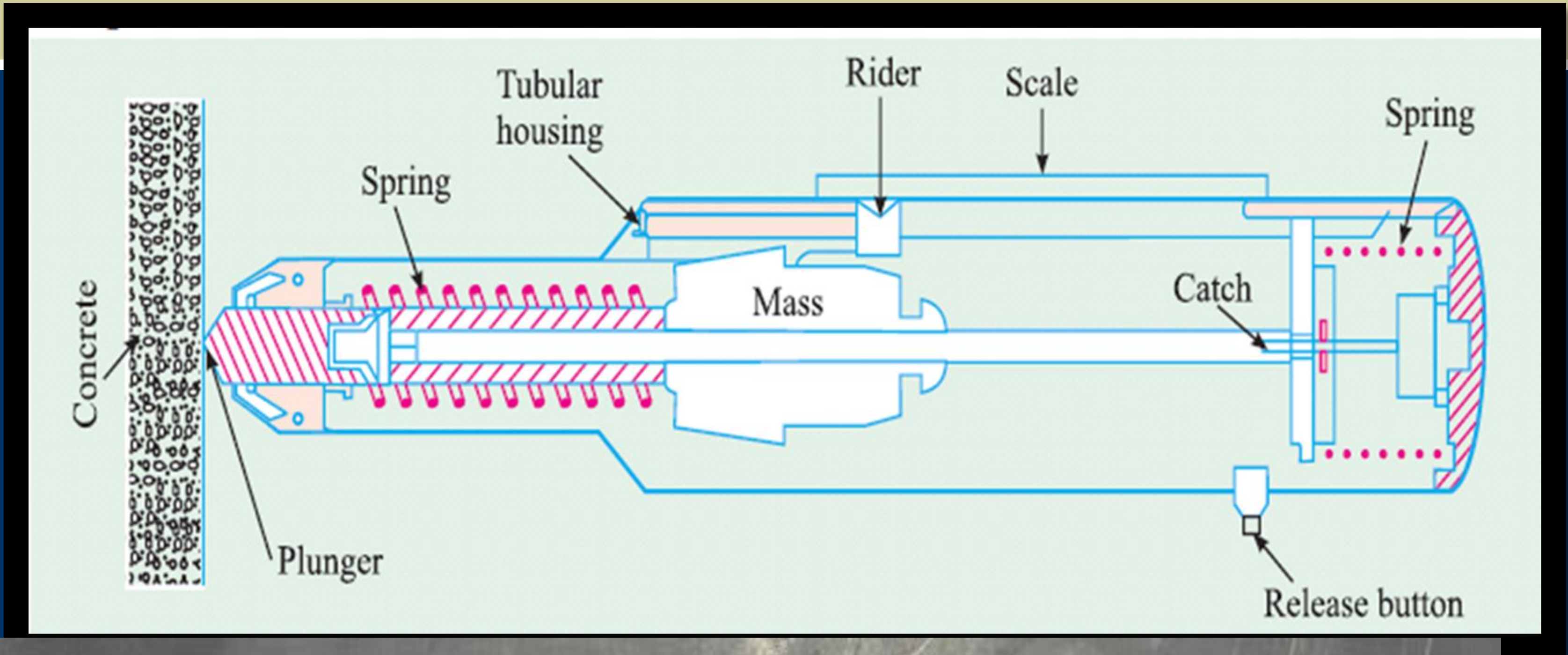
► Assessing the quality of concrete in relation to standard requirement It works on the principle that the rebound of an elastic mass depends on the hardness of the surface against which the mass impinges

Working Principle

- When plunger is pressed against concrete, spring controlled mass rebounds & extent of such rebound depends upon the surface hardness which is co-related to compressive strength. Compressive strength can be read directly from the graph provided on the body of the hammer.

- ► The rebound values usually are considered reliable when at least six readings deviate not more than +2.5 to 3.5 on the impact scale. The compressive strength is then determined by taking average of rebound reading.

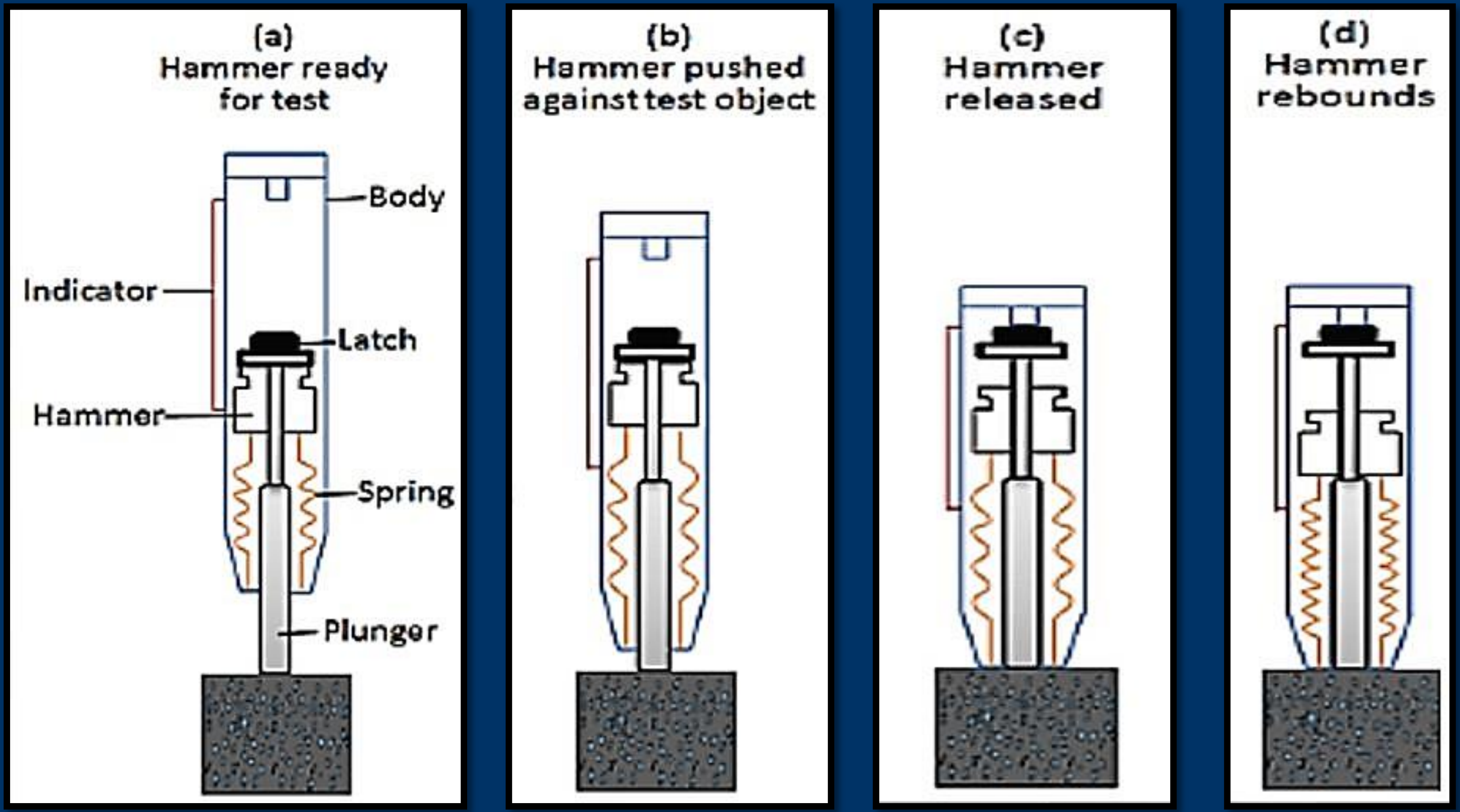
Apparatus


Tubular housing
Rider
Scale
Spring
Spring
Concrete
Mass
Catch
Plunger
Release button

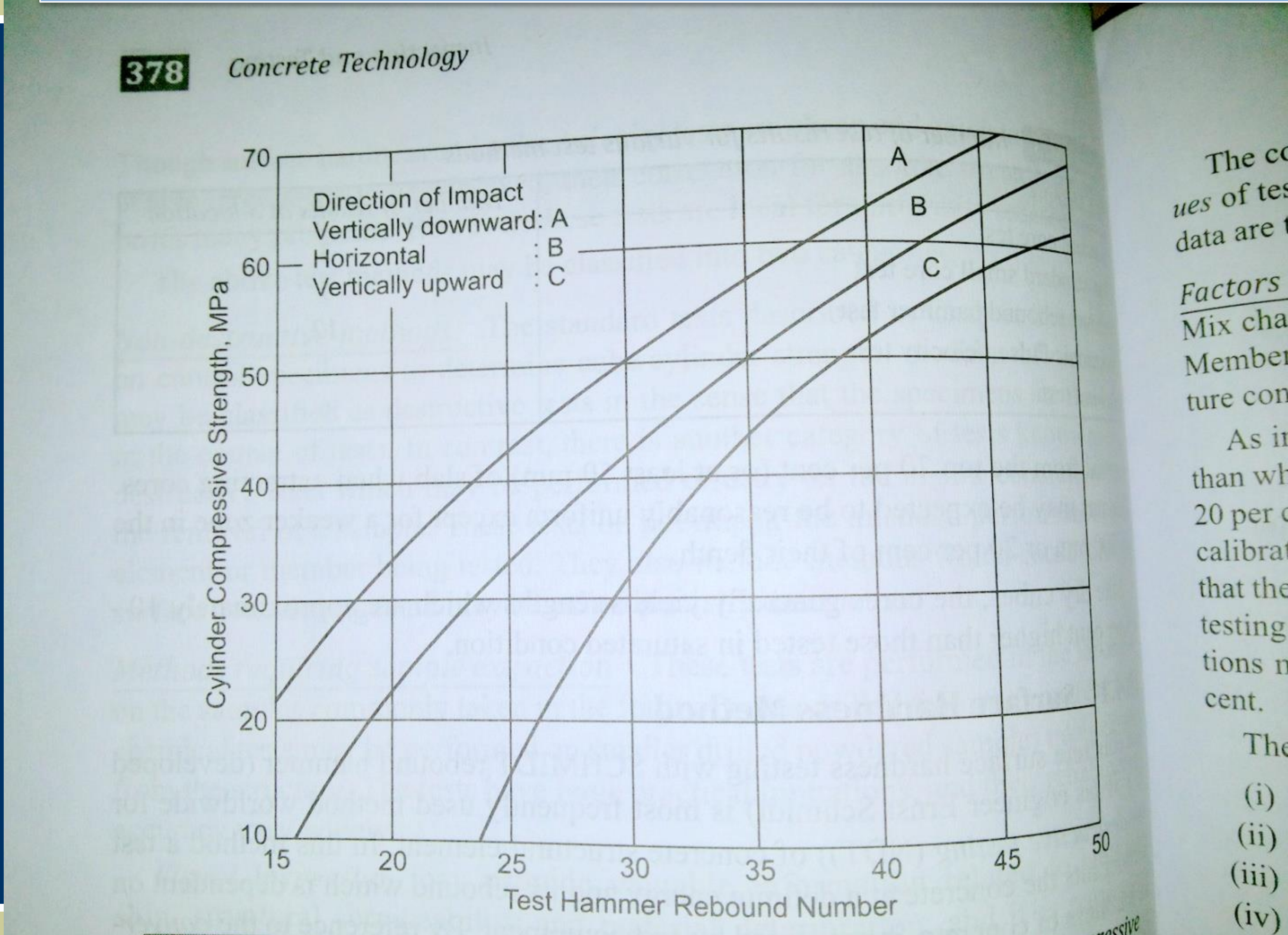
- Hammers available :

Device	Measuring Direction	Applications	Weight
Original Schmidt Hammer	Impact direction perpendicular to the surface	Used for the non-destructive measurement of the concrete/mortar compressive strength characteristics	900 g
Silver Schmidt Hammer	independent of impact direction	Suitable for testing a wide variety of concrete, mortar and rock	600 g

Procedure of application



Rebound Hammer & strength of Concrete



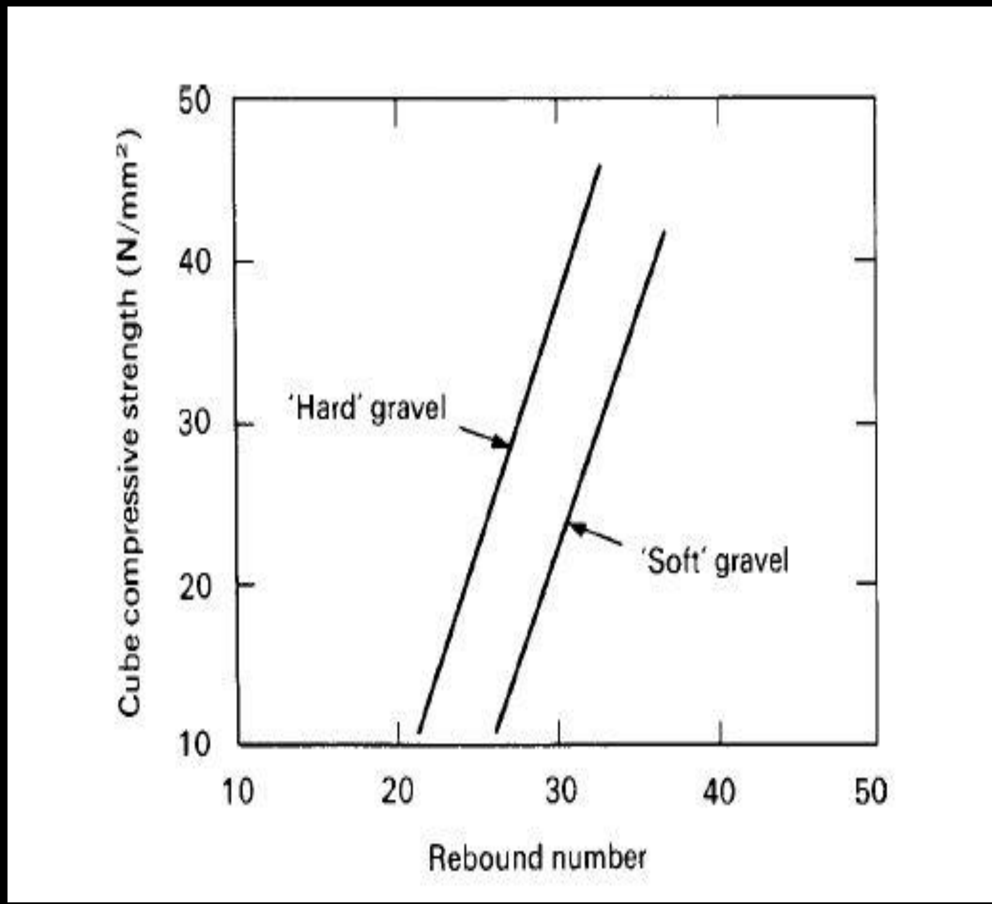
Factors affecting Test result

► Type of cement

Concrete made with high alumina cement can give strength 100% higher than that with OPC cement. Concrete made with super sulphate cement can give 50% lower strength

- Type of aggregate

Gravels and crushed rock aggregates give similar correlation ,but concrete made with light weight aggregates require special calibration



Comparison of hard and soft gravels

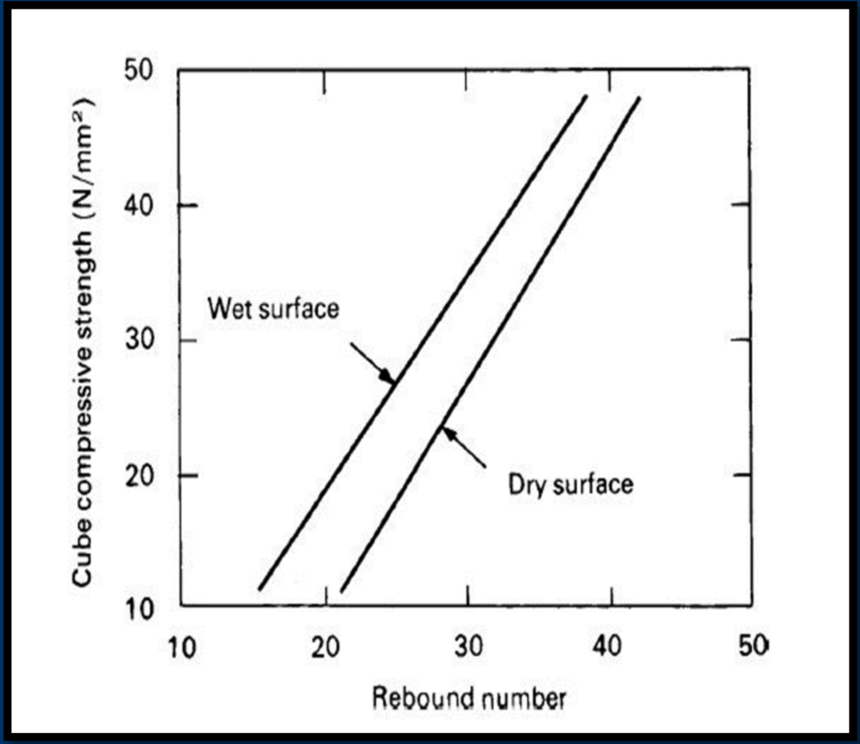
Tcs , John h. Bungey

Factors affecting Test result

- **Surface condition and Moisture content of Concrete**

  Test is suitable only for close texture concrete. Open texture concrete, honeycombed concrete are unsuitable

  A wet surface will give 20% lower strength in an equivalent dry concrete



Influence of surface moisture condition

Tcs, John h. Bungey

Factors affecting Test result

► Carbonation of concrete surface

The influence of carbonation of concrete surface on rebound number is very significant. Carbonated concrete gives about 50% higher strength than normal concrete

Important Points

- For testing smooth clean and dry surface is to be selected
- Rough surface resulting from incomplete compaction, loss of grout, spalled surface do not give reliable result and should be avoided
- The point of impact should be at least 20 mm away from any edge or shape discontinuity
- For taking measurement the rebound hammer should be held at right angle to the surface of concrete member
- Around each point of observation, six average of these reading of rebound indices are taken and average of these reading after deleting outliers becomes the rebound index for the point of observation

Interpretations of Results

Average Rebound Number	Quality of Concrete
more than 40	Very good hard layer
30 to 40	Good layer
20 to 30	Fair
less than 20	Poor concrete

Ultrasonic Pulse Velocity test

❑OBJECT

- ► The homogeneity of the concrete
- ► The presence of cracks, voids and other imperfections
- ► Changes in the structure of the concrete which may occur with time
- ► The quality of the concrete in relation to standard requirements

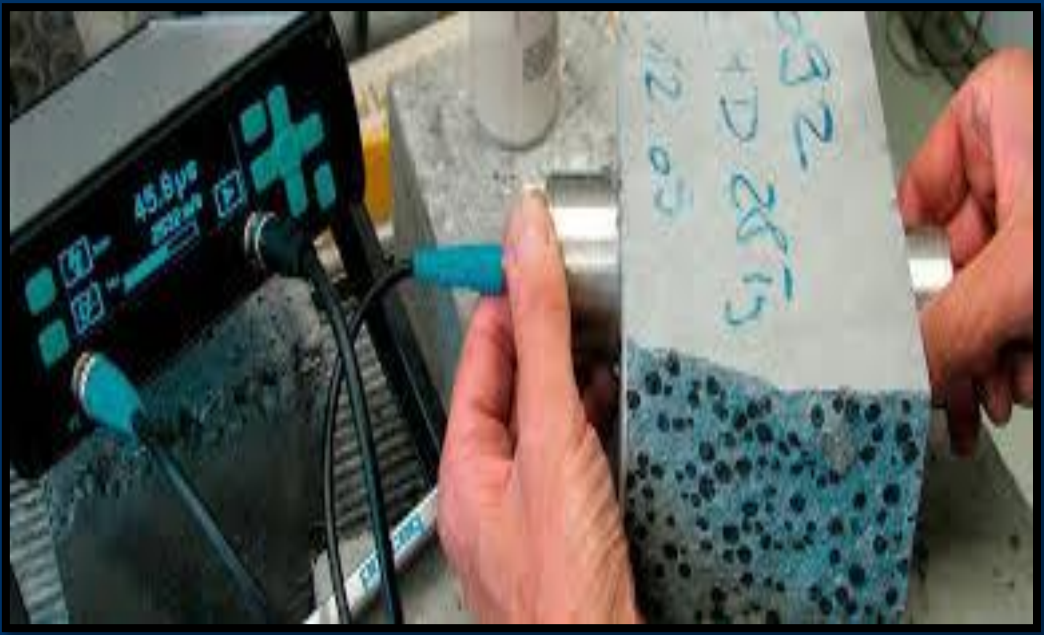
UPV Test (ASTM C597)

❑Principle

- The method is based on the principle that the velocity of an ultrasonic pulse through any material depends upon the density, modulus of elasticity of material

Apparatus

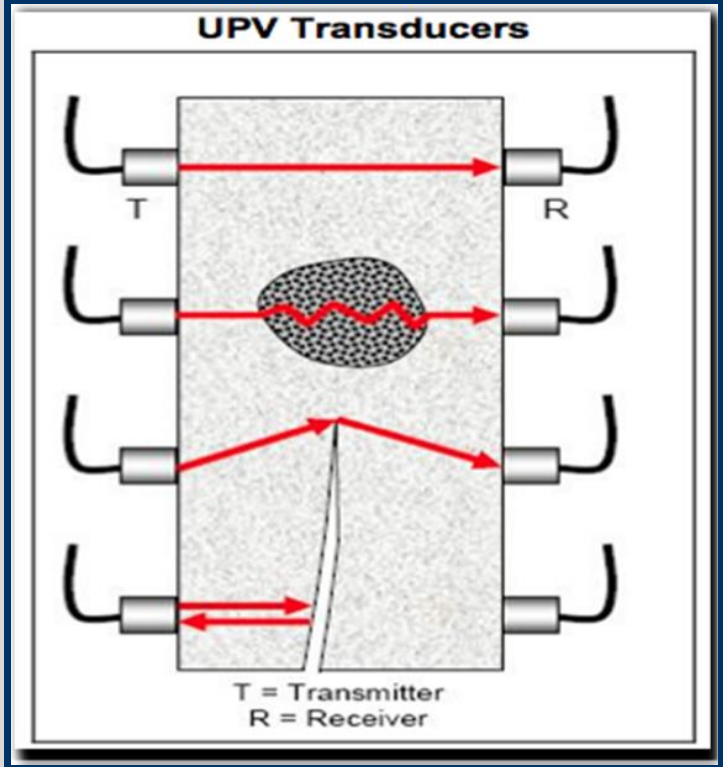
PUNDIT (Portable Ultrasonic Nondestructive Digital Indicating Tester)



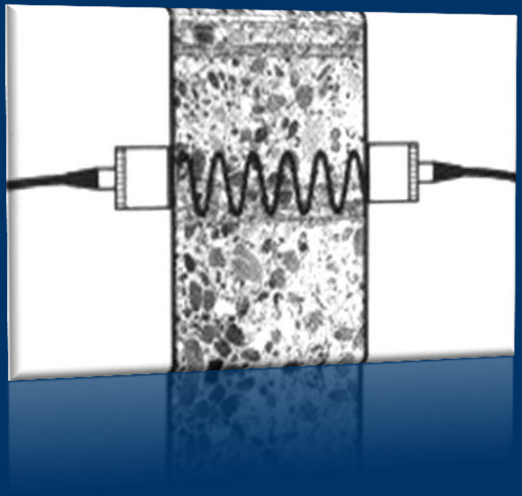
The UPV equipment includes a transducer, a receiver and an indicator for showing the time of travel from the transducer to the receiver

How it works?

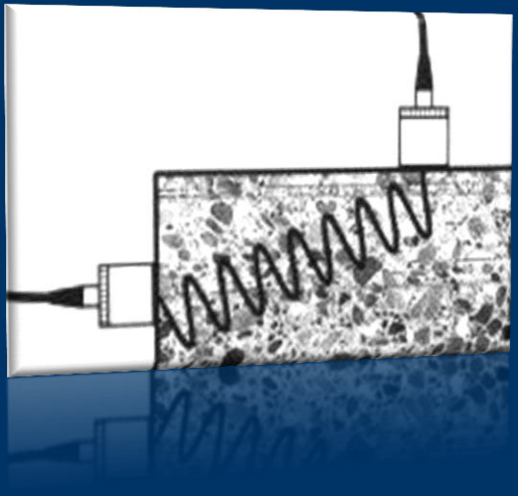
- Ultrasonic waves are very similar to light waves in that they can be reflected, refracted, and focused.
- Reflection and refraction occurs when sound waves interact with interfaces of differing acoustic properties.
- Ultrasonic reflections from the presence of discontinuities or geometric features enables detection and location of cracks



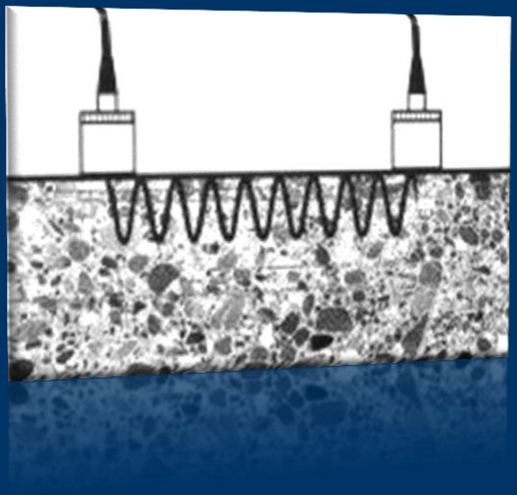
Transducer Arrangement



Direct Transmission



Semi-direct Transmission



Indirect or surface
Transmission

- A pulse of longitudinal vibration is produced by an electro-acoustical transducer, which is held in contact with one surface of the concrete member under test. After traversing a known path length (L) in the concrete, the pulse of vibration is converted into an electrical signal by a second electro-acoustical transducer, and electronic timing circuit enable the transit time (T) of the pulse to be measured. The pulse velocity (V) is given by

$$V = L/T$$

where
V = pulse velocity (km/s),
L = path length(cm) ,
T = transit time(μs).

- The velocity of pulse in a concrete is related to the concrete modulus of elasticity.

- $V = \sqrt{\frac{E}{\rho}}$

where,

E = modulus of elasticity,

p =density of the concrete

Interpretations of Results

No	Pulse velocity (km/s)	Concrete Quality
1	Above 4.5	Excellent
2	3.5 to 4.5	Good
3	3.0 to 3.5	Medium
4	Below 3.0	Doubtful

Factors affecting

- Smoothness of contact surface under test

  The pulse velocity of saturated concrete may be up to 2% higher than that of similar dry concrete
- Path length, Shape and Size of the Concrete Member
- Temperature of concrete

  5º-30º Ideal

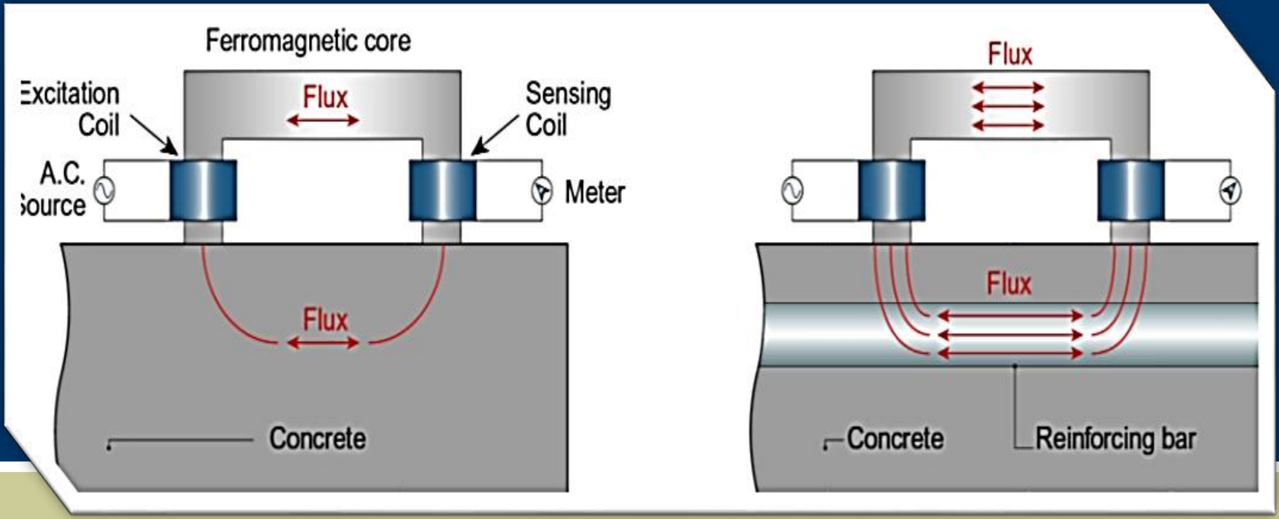
  30º -60º Reduction in UPV up to 5%

  Below 5º increase up to 7.5%
- Stress of concrete
- Moisture condition of concrete
- Presence of reinforcing steel

  Pulse velocity in steel 1.2 to 1.9 times the velocity in plain concrete

Electromagnetic cover measurement / Profometer

- The basic principle is that "the presence of steel affects the field of an electromagnet"
- It is used to measure the concrete cover and bar diameter in existing RCC structures. It can also identify the bar locations and their spacing. The scanning area permissible by the instrument is 0.5 x 0.5m / 1.0 x 1.0m / 2.0 x 2.0m.



PRINCIPLE : The principle is based upon the measurement of change of an electromagnetic field caused by steel embedded in the concrete.

Applications

- Quality control to ensure correct location and cover to reinforcing bars after concrete placement
- Investigation of concrete members for which records are not available or need to be checked
- Location of buried ferromagnetic objects other than reinforcement, e.g. water pipes, steel joists, lighting conduits.

Electromagnetic cover measurement

Covermeter image of reinforcement in a structure

The scanning direction should be perpendicular to rebars

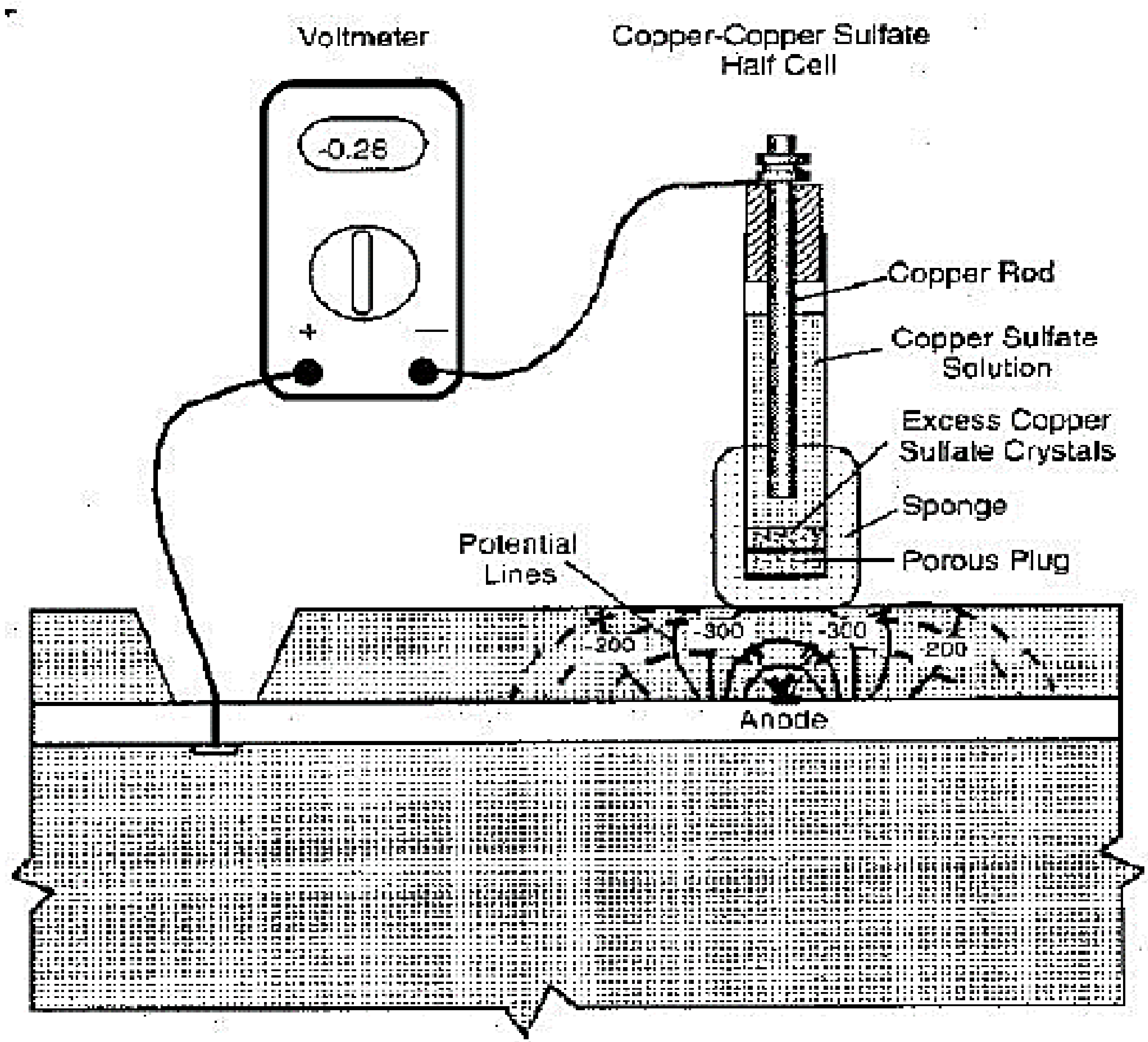
HALF-CELL ELECTRICAL POTENTIAL METHOD

- Corrosion analyzer is based on electro chemical process to detect corrosion in the reinforcement bar of the structure. The instrument measures the potential and the electrical resistance between the reinforcement and the surface to evaluate the corrosion activity

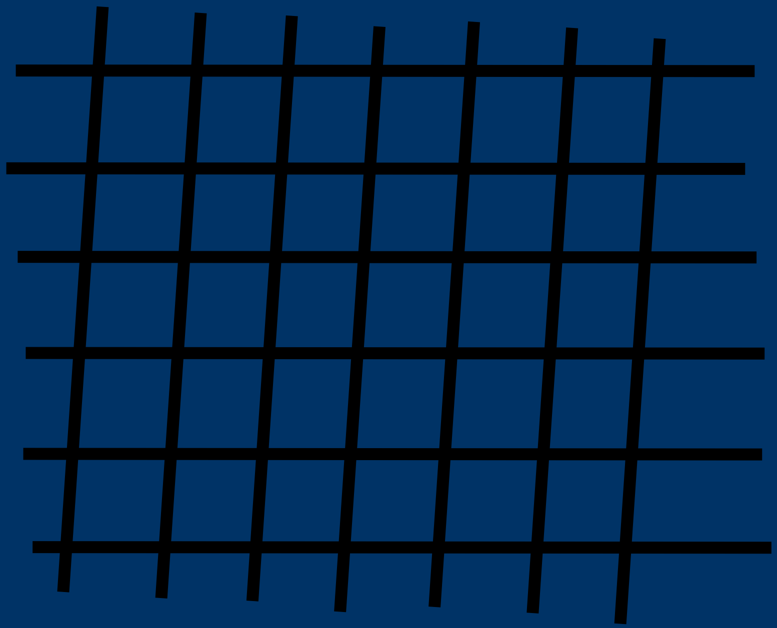
Guidebook of NDT of Bridge , Railway

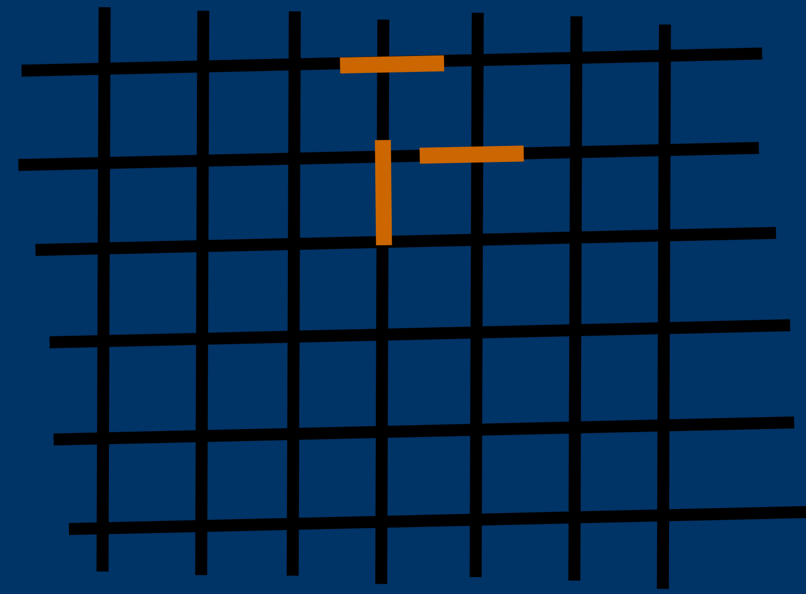
In field it is achieved by connecting a wire from one terminal of a voltmeter to the reinforcement and another wire to the copper sulphate reference electrode.

Apparatus for Half-Cell Potential Measurement



How it works?





If there is no corrosion on rebars, potential difference does not occurs

If there is corrosion on rebars, potential difference occurs.

Evaluation

Half-cell potential (mV) relative to copper-copper sulphate electrode	% chance of corrosion activity
< -200 mV	greater than 90% probability that corrosion activity not taking place
200mV to – 350mV	corrosion activity uncertain
> - 350mV	greater than 90% probability that Corrosion occurring

Resistivity Meter

This instrument is used to measure the electrical resistance of concrete cover for corrosion status of reinforced bars. Lower the electrical resistance, the more is the probability of corrosion of metal.

PRINCIPLE- It is based on the principle that the corrosion of steel in concrete is an electro-chemical process, which generates a flow of current and can dissolve metals. The lower the electrical resistance, the more readily the corrosion current flows through the concrete and the greater is the probability of corrosion.

The limits of possible corrosion are related with Resistivity as under:-

With p>12 kΩcm .... corrosion is improbable
With p=8 kΩcm .... corrosion is possible
With p<8 kΩcm ....corrosion is fairly certain

where p is resistivity

Permeability Tester

This instrument is used for determination of the air permeability of cover concrete. This operates under vacuum & used on concrete structure. It permits a rapid & non destructive measurement of quality of the cover concrete with respect to its durability.

PRINCIPLE- Permeability tests measure the ease with which liquids, ions and gases can penetrate into the concrete. In situ tests are available for assessing the ease with which water, gas and deleterious matter such as chloride ions can penetrate into the concrete

Main Uses

Used to locate cracks, porosity, and other defects that break the surface of a material and have enough volume to trap and hold the penetrant material. Liquid penetrant testing is used to inspect large areas very efficiently and will work on most nonporous materials.

Video Boroscope

This instrument is used to monitor the internal condition of the concrete structure.

PRINCIPLE- It's simple principle is to illuminate the test specimen with light examine the specimen with the eye and magnifying the defects which can not be detected by the unaided eye


Built-in
High Resolution
Digital Camera

Crack Detection Microscopes

It is a portable type of instrument which detects the width of the crack on the surface of structure. Used extensively to record the extent of crack widths on existing piers and abutments which are distressed.

Infrared Thermography (ASTM D 4788)

Infrared Thermal Imager

It is used to get infrared and visual images of defects at different locations on concrete and steel structure. It gives the condition of images captured.

Infrared Thermography (ASTM D 4788)

PRINCIPLE : it is based on the principle that the materials with subsurface anomalies, such as voids caused by corrosion of reinforcing steel in a material, affect heat flow through that material. These changes in heat flow cause localized differences in surface temperatures. Thus, by measuring surface temperatures under conditions of heat flow into or out of the material, one can determine the presence and location of any subsurface anomalies.

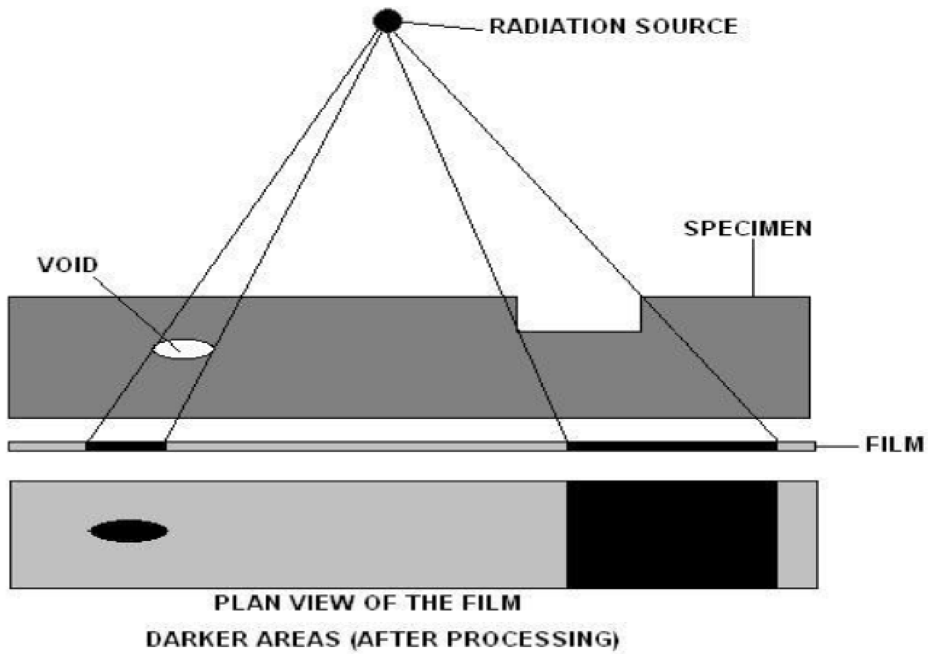
- Presence of internal "flaw" alters heat flow through material and results in hot or cold spots on the surface.

Radiographic Evaluation of Concrete:

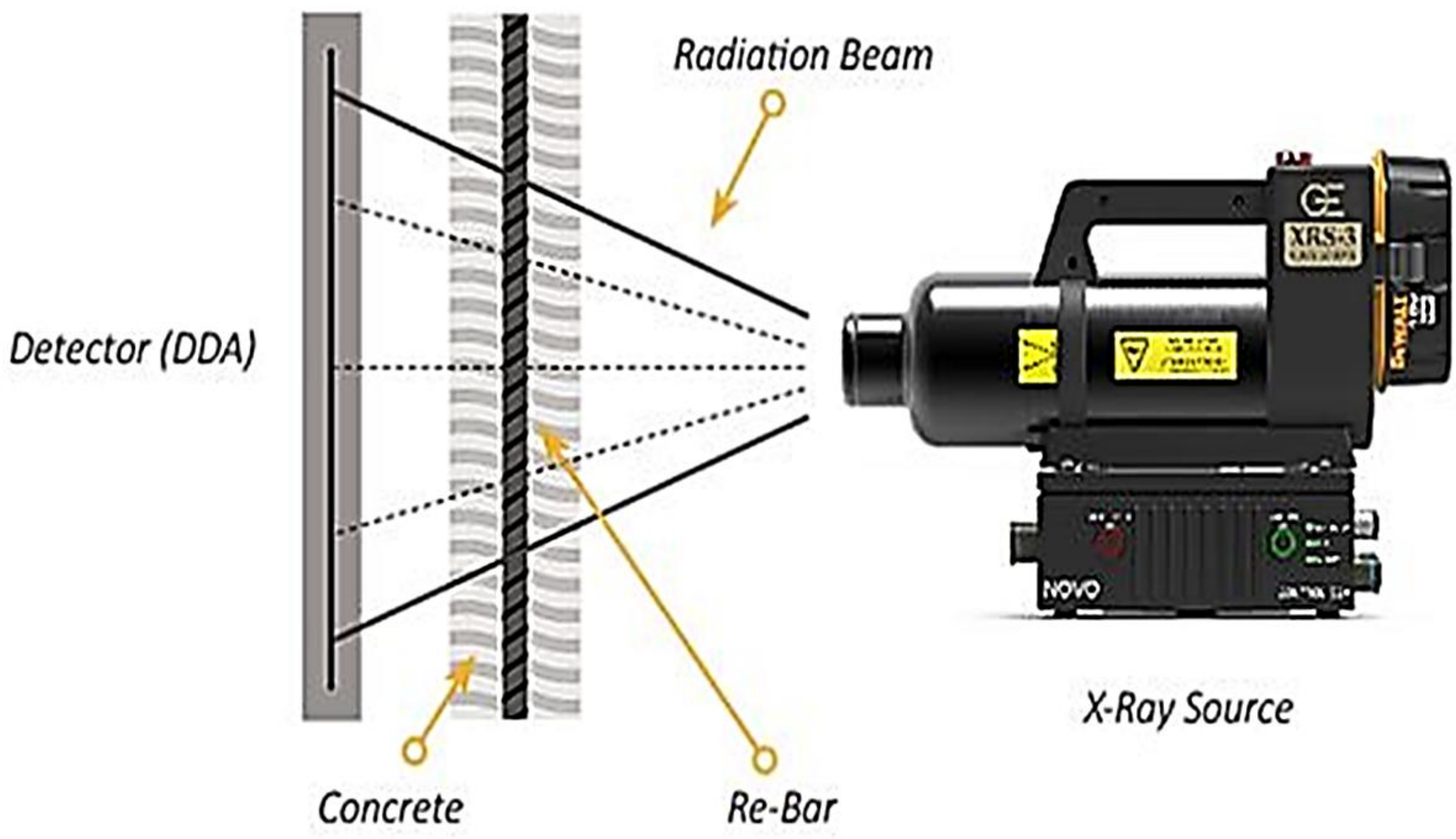
- Radiography is similar to taking X-ray or gamma radiation pictures in the medical field. Radiography can determine the internal condition of a structural member and can locate embedded steel. As the radiation passes through the member its intensity is reduced according to the thickness, density and absorption characteristics of the materials within the member.
- The quantity of radiation passing through the member is recorded on X-ray film. Reinforcing bars absorb more energy than the surrounding concrete and show up as light areas on the exposed film.
- Cracks and voids, on the other hand, absorb less radiation and show up as dark zones on the film. Crack planes parallel to the radiation direction are detected more readily than cracks perpendicular to the radiation direction.

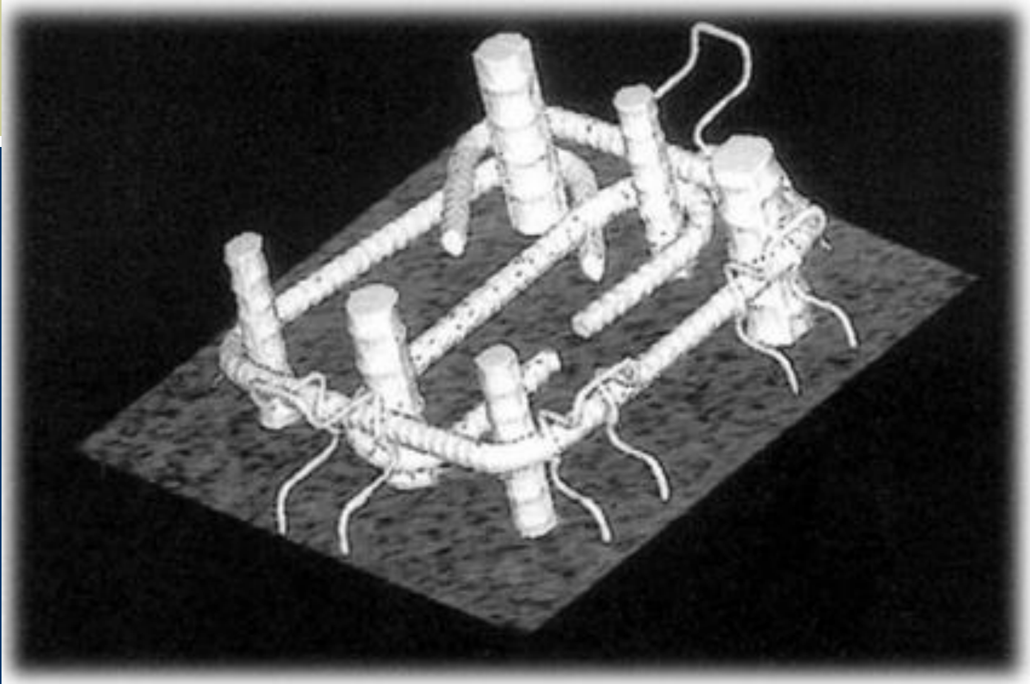
- Short wavelength electromagnetic radiation (high energy photons) to penetrate various materials.
- The amount of radiation emerging from the opposite side of the material can be detected and measured

- ❑ X-Ray Equipment
- ❑ Gamma Rays Equipment



Setup for concrete test



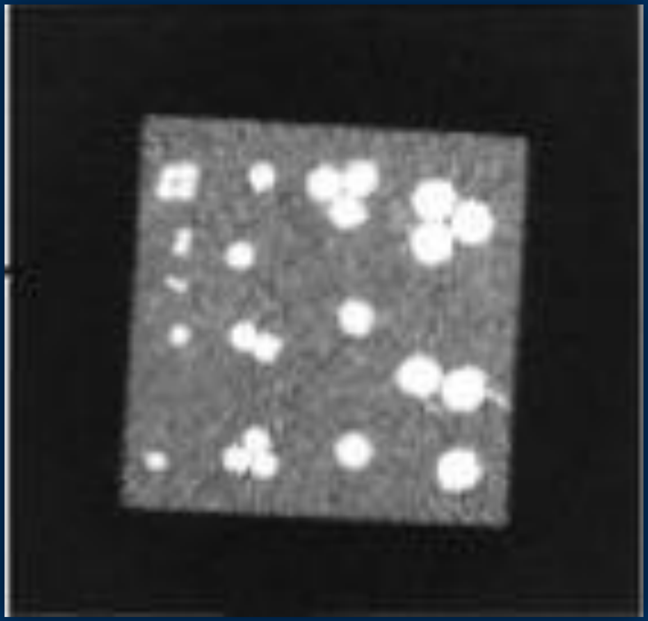


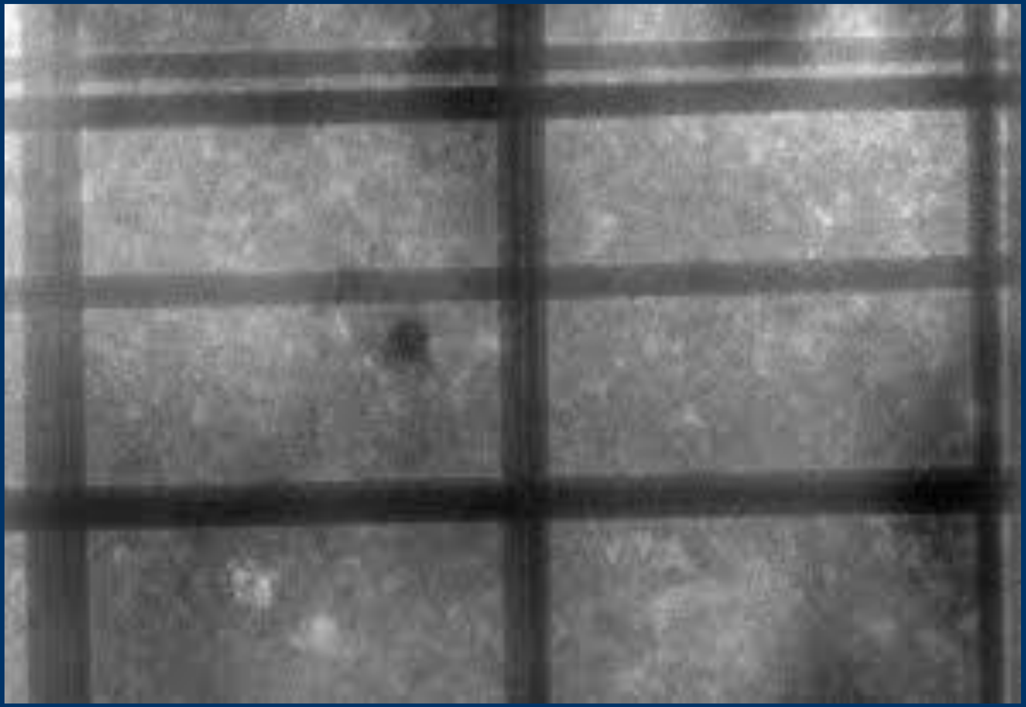
X-Ray Image of reinforced concrete column

X-Ray Equipment

Detection of Reinforcement

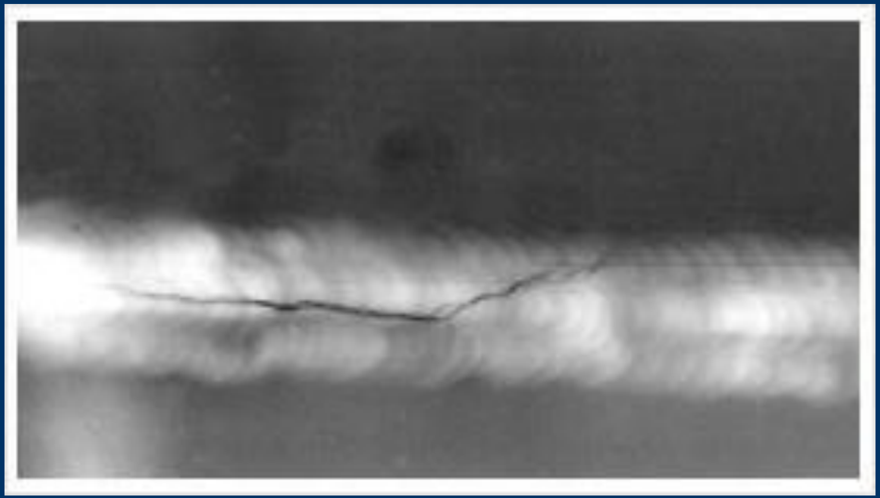
- Reinforcing bars absorb more energy than the surrounding concrete and show up as **light areas** on the exposed film.





Determination of Cracks

- Cracks and voids, on the other hand, absorb less radiation and show up as dark zones on the film.
- Crack planes parallel to the radiation direction are detected more readily than cracks perpendicular to the radiation direction.



Application in Structural Engineering

- Moisture Content
- Detection of reinforcement location
- Detection of Voids and Cracks
- Detection of quality of grouted post-tensioned tendons
- Measurement of bar depth and flaw depth
- The failure of cables
- Discontinuities of the ducts
- Broken wires or cables in some cases

General cautions in radiography

- Specifically trained and accredited persons for implementing the technique
- Define a protection area around structure
- Move away all the persons during the entire test

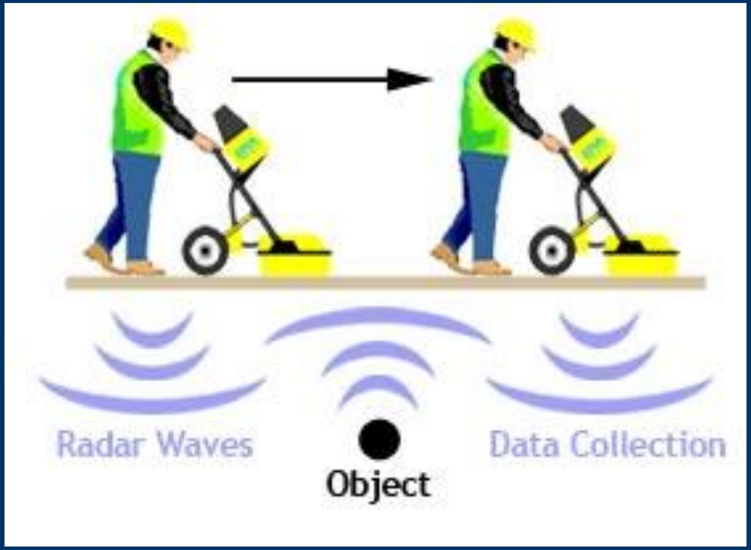
- Specifically trained and accredited persons for implementing the technique
- Define a protection area around structure
- Move away all the persons during the entire test

Disadvantages

- For application in Bridges with long span, the power required will be very high
- Several hundred meters of area will need to be cleared so that no possibility of accidental exposure.
- Not feasible in densely populated area

Ground Penetrating Radar (GPR)

GPR is another safe and effective way to locate buried obstructions in concrete structures. The system locates rebar, post-tension cables, conduits and voids, inspects walls, floors, bridge decks, tunnels, balconies, parking garages, etc., measures slab thickness and locates targets to a depth of 18" and more.



Self navigating Robot for horizontal surfaces

Radar concrete scanner (3-D imager)

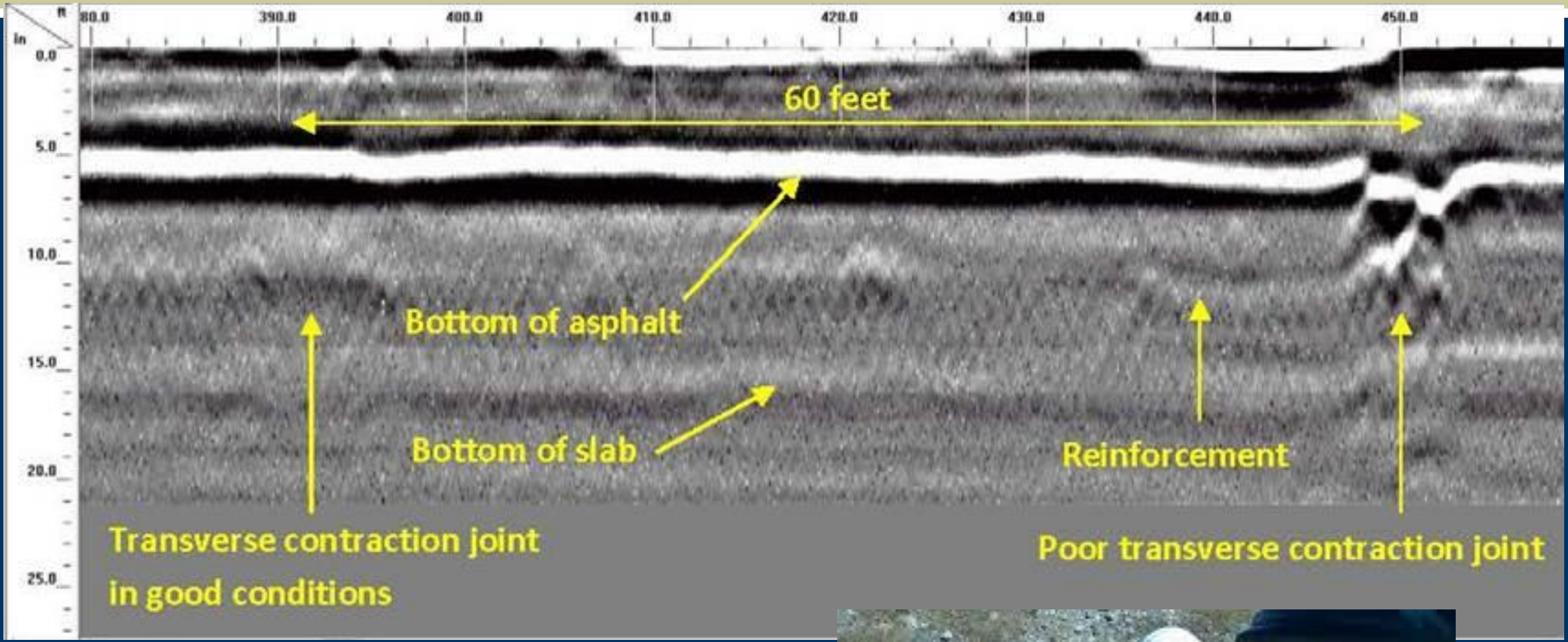
- **Automation and Scanning**

Small lightweight scanner with vacuum attachment

- Scanning Area Speed:
- Ultrasonic Echo/Impact Echo
  $1 m^2/h$, 0.02 m point grid
- Radar :
  $15 m^2/h$, 0.05 m line grid

BAM, Germany

Ground Penetrating Radar (GPR)



Advantages of radar concrete scanner (3-D imager)

- To locate safe areas to core drill new stacks for electrical and plumbing
- To locate safe areas to anchor HVAC, Mechanical and seismic anchors
- To determining safe areas to cut doorways, stairways and door openings
- To asses slab thickness /survey: Slab on Grade (S.O.G) and elevated
- To locate structural beams: S.O.G. and elevated
- To locate utility pipes under concrete and pavement
- To locate rebar and post tension cable (vertical and horizontal) in concrete
- To determine size and precise location of reinforcement within concrete
- To identify and map reinforcing steel and hydronic lines within concrete
- To map and identify conduits and utility cables within concrete
- To identify air/water filled voids in or behind concrete

Automated long term / Continuous SHM

Long term SHM

- SHM is about assessing the in-service performance of structures using a variety of measurement techniques

Leading to “smart” structures (sometimes using smart material)

- A **smart structure** integrates the properties of embedded sensors, actuators and control mechanisms in order to respond to a given stimulus in a functionally useful manner. Usually it involves implementing hardware and/or software control mechanisms.

Long term SHM

- **Smart materials** are designed materials that have one or more properties that can be significantly changed in a controlled fashion by external stimuli, such as those from mechanical, thermal, chemical or other sources (resulting in formation and change in stress, temperature, moisture, pH, electric or magnetic fields). It exhibits smart behavior.

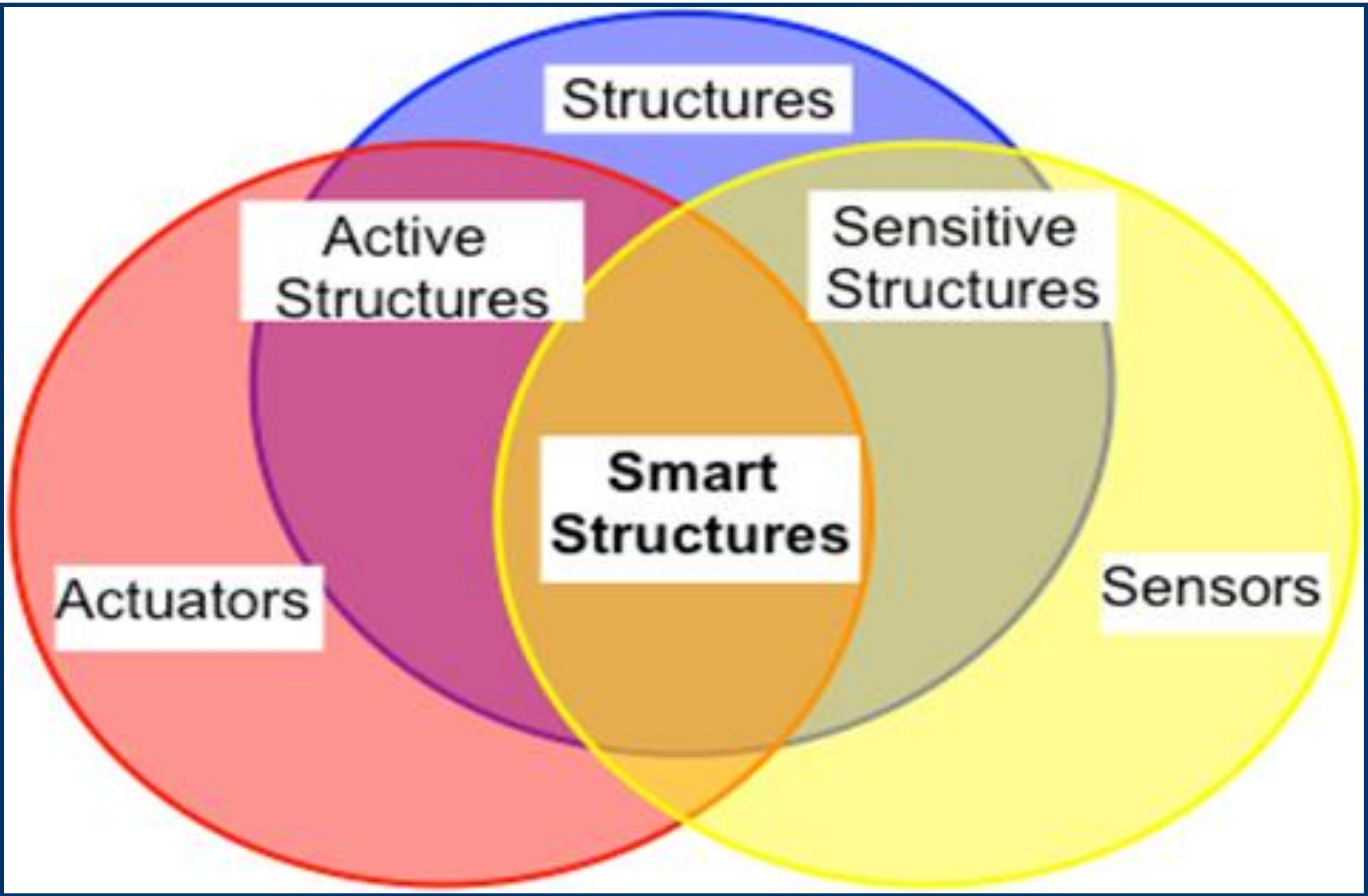
- Smart behaviour occurs when a material can sense some stimulus from its environment and react to it in a useful and reliable manner.

Long term SHM

Actuator: Machine component for moving something

Sensor:

A digital device to detect change



Long term SHM

Taylor Bridge, in Headingly, Manitoba, Canada incorporates numerous sensors into its design, and is one of the world’s first Smart Structures

Why is Long term SHM becoming popular?

Emerging use of SHM is a result of:

1. The increasing need for…
   - Monitoring of innovative designs and materials
   - Better management of existing structures
2. The ongoing development of…
   - New sensors (e.g. FOS; fiber optics sensor, "smart" materials etc.)
   - Data acquisition systems (DAS)
   - Wireless and internet technologies
   - Data transmission, collection, archiving and retrieval systems
   - Data processing and event identification

The SHM / Body Analogy

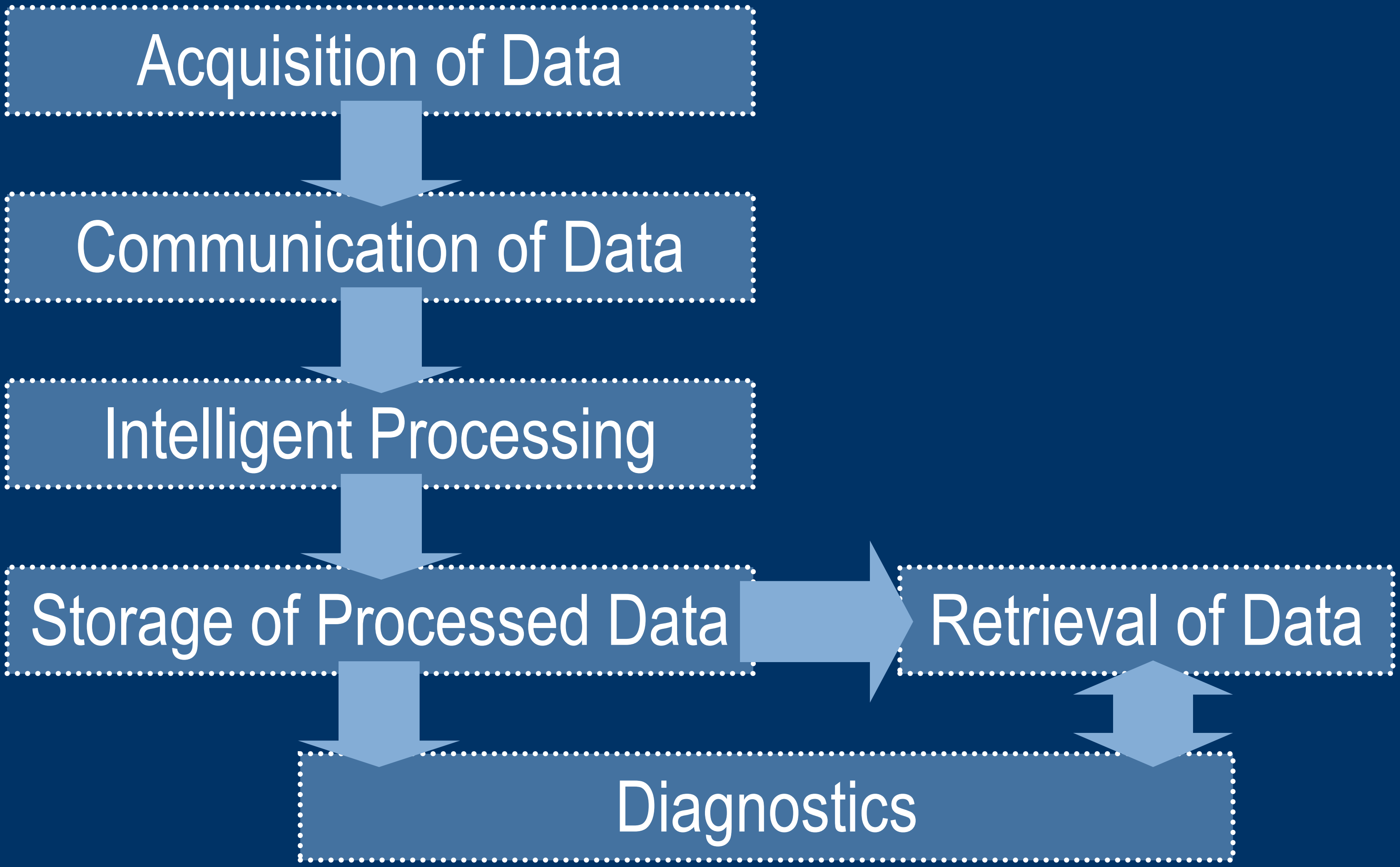
Medical Doctor

- Monitor patient's health
- Uses medical equipment to check overall health
- Prescribes corrective medicine if required

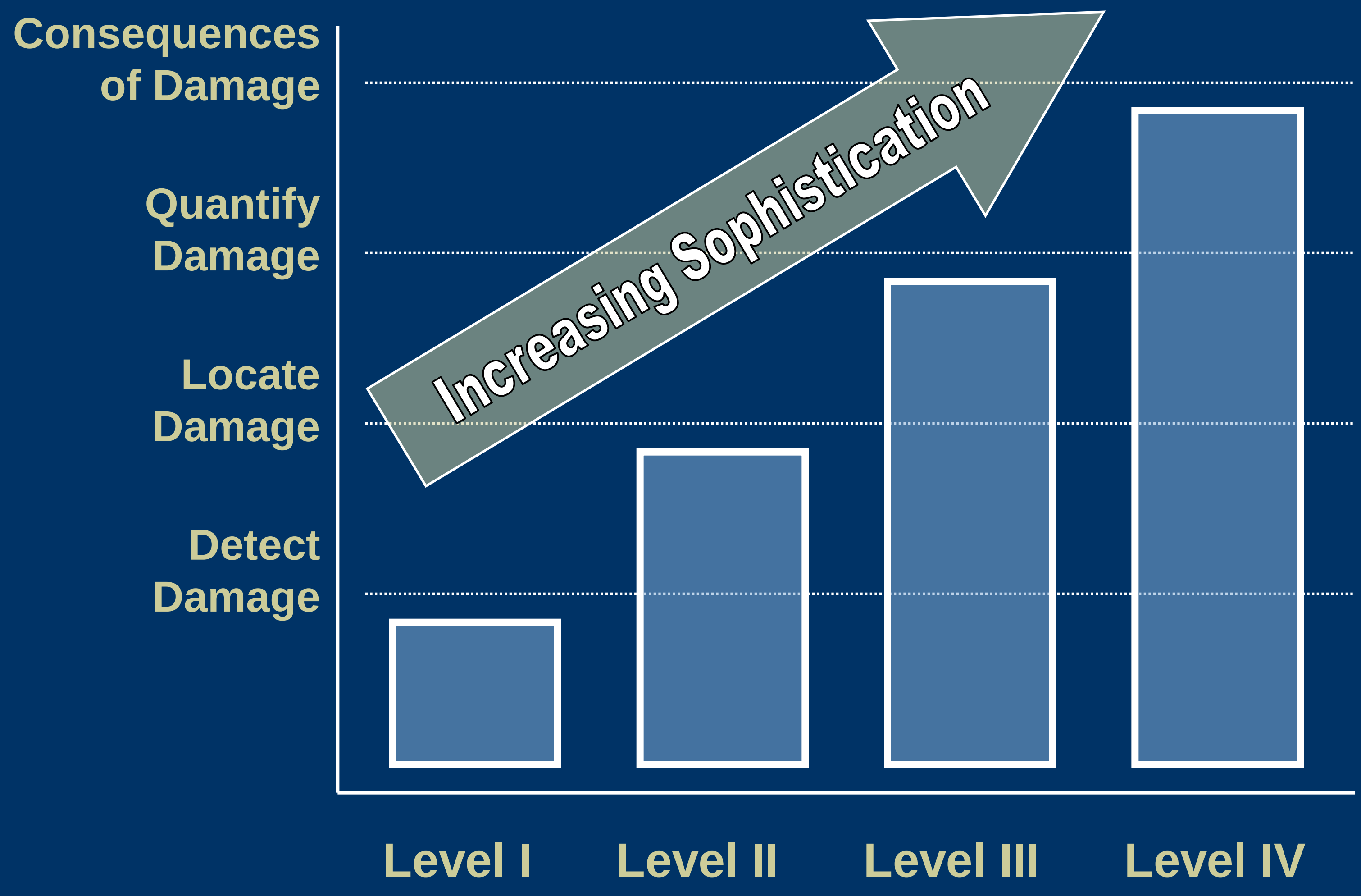
SHM Engineer

- Monitor condition of structures
- Uses sensors to check overall structural health
- If excessive stress or deformation, corrects situation

Automated SHM System Components



Classification of SHM Systems



Classification of SHM Systems

Level IV

Detect presence, location, severity and consequences of damage

Level III

Detect presence, location and severity of damage

Level II

Detect presence and location of damage

Level I

Detect presence of damage

Advantages of SHM

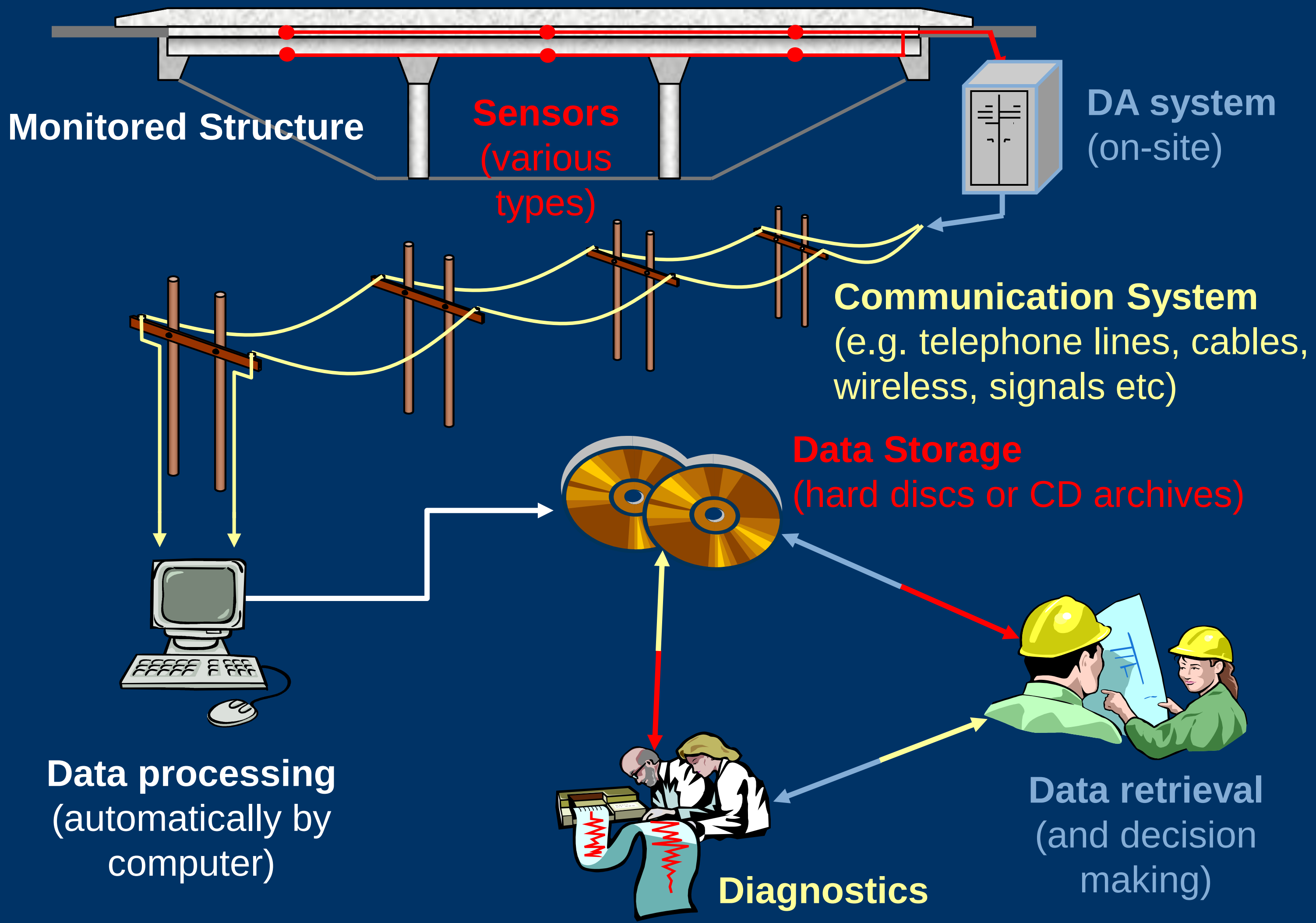
Advantages of SHM include…

- Increased understanding of in-situ structural behaviour
- Early damage detection
- Assurances of structural strength and serviceability
- Decreased down time for inspection and repair (time during which a machine is out of action or unavailable for use)
- Development of rational maintenance / management strategies
- Increased effectiveness in allocation of scarce resources
- Enables and encourages use of new and innovative materials

Section 3: Methodology

- **Ideal SHM system**:
  - ❶ Information on demand about a structure’s health
  - ❷ Warnings regarding any damage detected
- Development of a SHM system involves utilizing information from many different engineering disciplines including…

System Components Schematic



1 – Acquisition of Data

The collection of raw data such as strains, deformations, accelerations, temperatures, moisture levels, acoustic emissions, and loads

(a) Selection of Sensors

- Appropriate and robust (strong) sensors
- Long-term versus short-term monitoring
- What aspects of the structure will be monitored?
- Sensors must serve **intended function** for **required duration**

1 – Acquisition of Data

(b) Sensor Installation and Placement

- Must be able to install sensors without altering the behaviour of the structure
- Features such as sensor wiring, conduit, junction boxes and other accessories should be well known for proper operation and function (must be accounted for in the initial structural design)

1 – Acquisition of Data

(c) Transfer to Data Acquisition System (DAS)

Method ❶ - Lead wire

- Direct physical link between sensor and DAS
  - least expensive and most common
  - Not practical for some large structures
  - Long lead wires increase signal "noise"

Method ❷ - Wireless transmission

- More expensive
- Signals are transferred more slowly and are less secure
- Use is increasing day by day

1 – Acquisition of Data

(d) Data Sampling and Collection

General Rule: The amount of data should not be so scanty (short) as to jeopardize (endanger) its usefulness, nor should it be so voluminous as to overwhelm interpretation

Issues:

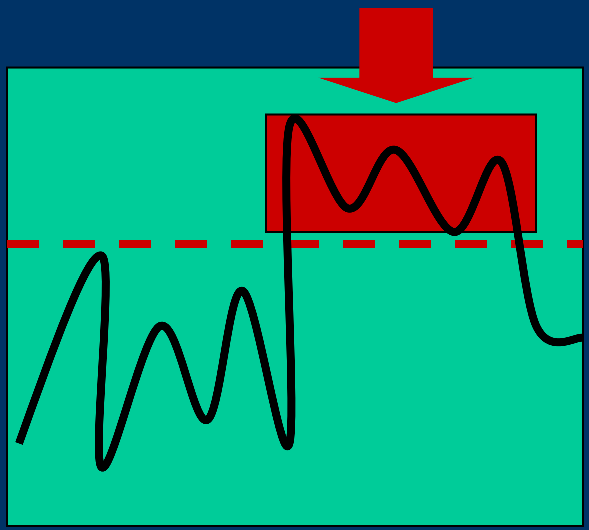
- Number of sensors and data sampling rates
- Data sorting for onsite storage
- In some cases, **large volumes of data**

Result:

- Efficient strategies needed for data sampling and storing

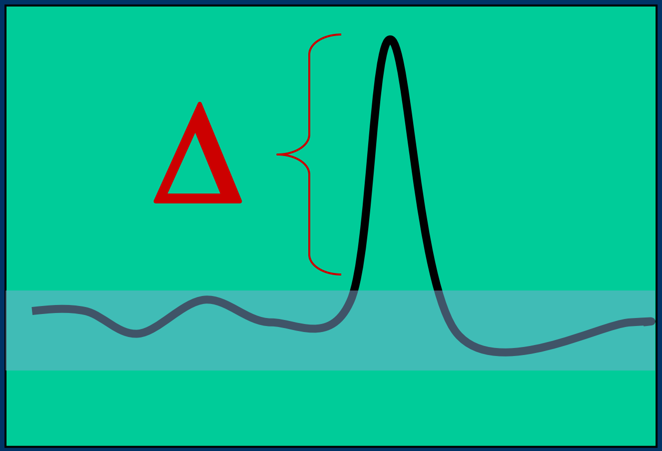
1 – Acquisition of Data

Example Data Acquisition Algorithms (Generally any of two approaches)



Record only values greater than a threshold value

(and times that readings occur)



Record only significant changes in readings

(and times that changes occur)

1 – Acquisition of Data

What is monitored, how and why?

Load

Magnitude and configuration of forces applied to a structure

- Are they as expected?
- How are they distributed?

Measured using load cells or inferred using strain data

Deformation

Excessive or unexpected deformation, may result in a need for rehabilitation or upgrade

- Are they as expected?

Measured using various transducers (LVDTs etc.)

1 – Acquisition of Data

What is monitored, how, and why?

Strain

- Strain: Intensity of deformation
- Magnitude and variation of strains can be examined to evaluate safety and integrity
- Measured using strain gauges
  - FOS, electrical, vibrating wire, etc.

Temperature

- Changes in temp. cause deformation
  - Thermal Expansion
  - Repeated cycles can cause damage
- Temperature affects strain readings
  - Temp must be “removed” from strain data
- Measured using TCs, ITCs, thermistors

* TCs: thermocouples, ITCs: integrated temperature circuits

1 – Acquisition of Data

What is monitored, how, and why?

Acceleration

- Loads cause accelerations of structural components and vice versa
  - How is the structure resisting accelerations and the resulting loads?
- Widespread use in highly seismic regions
- Measured using accelerometers

Wind Speed and Pressure

- Wind loads can govern the design of long-span bridges and tall buildings
  - Record speed and pressure at various locations
- Measured using anemometers

Accelerometer: An instrument for measuring the acceleration of a moving or vibrating body

Anemometers: A device used for measuring wind speed

1 – Acquisition of Data

What is monitored, how, and why?

Acoustic Emissions

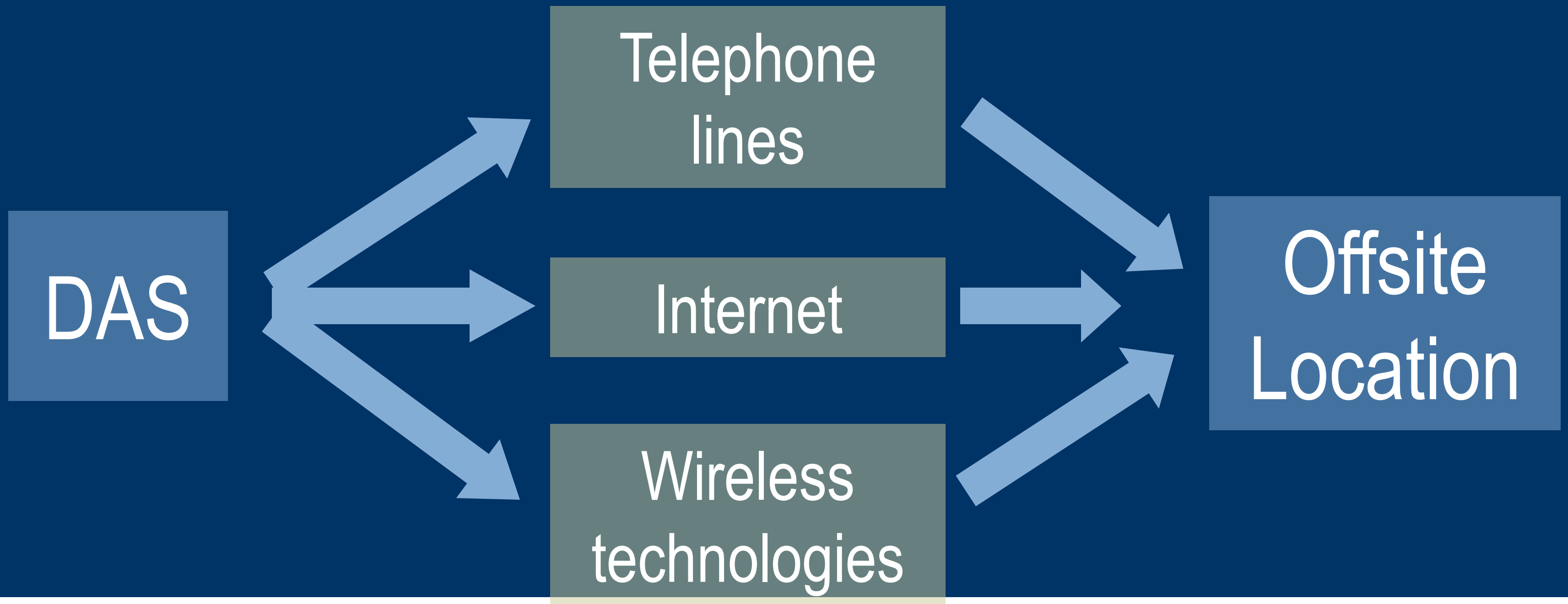
- When certain structural elements break, they emit noise
  - AE listens for the noises, and pinpoints locations using triangulation
- Used in post-tensioned concrete and cable-stayed structures
- Measured using microphones

Video Monitoring

- Time-stamped videos and pictures can be used to witness extreme loads or events
  - Data can be correlated with images
  - Permits fining of overloaded trucks
- Emerging internet camera technology is used

2 – Communication of Data

- Refers to data transfer from the DAS (Data acquisition system) to an offsite location
- Allows for remote monitoring, elimination of site visits



3 – Intelligent Processing of Data

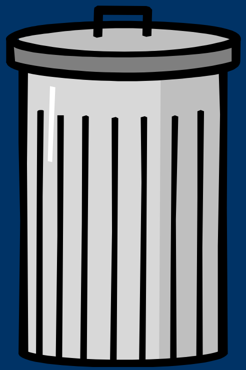
- Required before data can be stored for later interpretation and analysis
- The goal is to remove un-useful data, noise, thermal, or other unwanted affects and to make data interpretation:
  - **Easier**
  - **Faster**
  - **More accurate**

4 – Storage of Processed Data

- Data may be stored for very long periods of time
  - Retrieved data must be understandable
  - Data must not be corrupted
  - Sufficient memory must be available

- Data files must be well documented for future interpretation

- It is common to disregard raw data and store only processed or analyzed data
  - This does not allow for re-interpretation



5 – Diagnostics

- **Extremely important** component
  - Converts abstract data signals into useful information about structural response and condition
- No "standard" rules exist for diagnostics
- Methodology used depends on…
  - Type of structure
  - Type and location of sensors used
  - Motivation for monitoring
  - Structural responses under consideration

6 – Data Retrieval

When storing data for retrieval, consider…

- ❶ Significance of data
- ❷ Confidence in analysis

Remember:

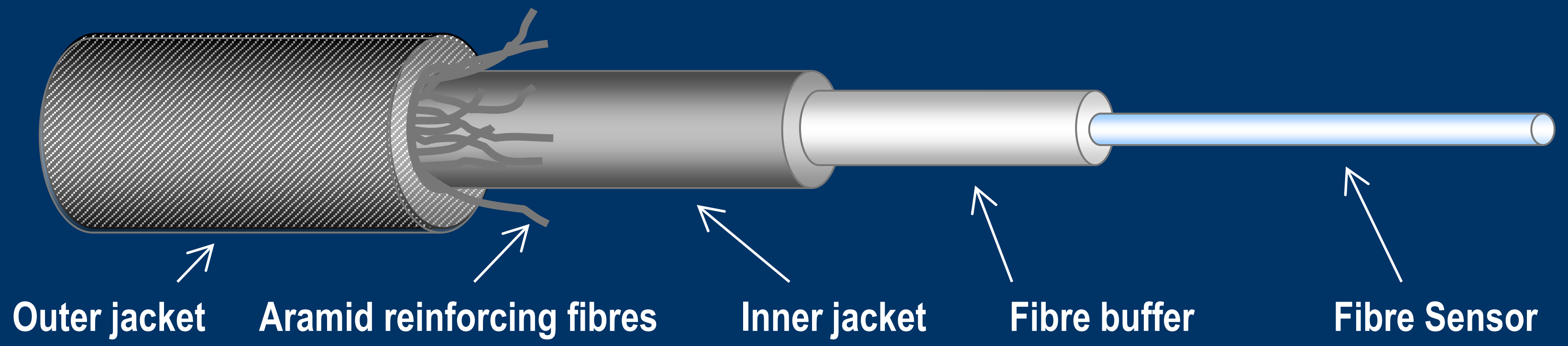
The goal of SHM is to provide detailed physical data which can be used to enable rational, **knowledge-based engineering decisions**.

Section 4: Sensor Technology

- Many sensor types are currently available
  - Choice for SHM depends on various factors
- **Fibre optic sensors** (FOSs)
  - Newer class of sensors
  - Emerging for infrastructure applications
  - Recent and ongoing developments

Sensor Technology

Typical Optical Fibre



Assorted fibre coatings are required to protect the fibre from…

Abrasion

Protection during handling and installation

Concrete

Alkaline environment is harmful to glass fibres

Moisture

Weakens the fibres and controls growth of microcracks

Fibre Optic Sensors

Sensor development is driving advances in SHM

Beddington Trail Bridge, Calgary, Alberta
- FOS sensors installed during construction in 1993
- Sensors were still performing well in 1999

FOS Advantages

Stability

Increased long-term stability and decreased noise

Non-conductive

Immune to electromagnetic and radio frequency interference

Innovative Sensing Capabilities

Flexibility

Multiplexing (more than one info. combined) and Distributed sensing

Convenience

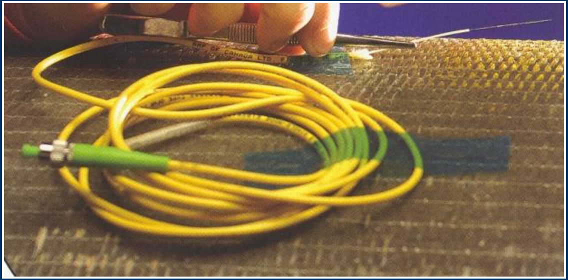
Light, small diameters, non-corrosive, embeddable, easily bondable

Different Types of Sensors

LOAD	Load cells
DISPLACEMENT	Linear Variable Differential Transformer
	Linear Potentiometer
ACCELERATION	Accelerometers, an electromechanical device used to measure acceleration forces; forces may be static, like the continuous force of gravity or, useful for **sensing** vibrations in systems or for orientation **applications** as is the case with many mobile devices,
TEMPERATURE	Thermocouples
	Integrated Temperature Circuits
STRAIN	Vibrating wire strain gauges
	Electrical resistance gauges

Types of FOS

Bondable

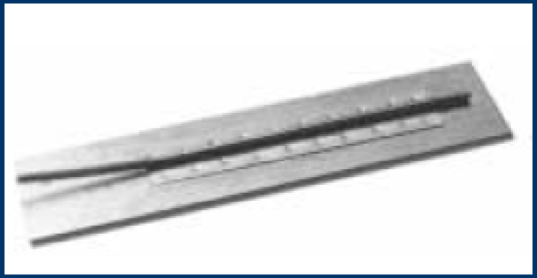


Hand Installation

Care required during installation

Protection against humidity and environment required

Weldable



Embeddable

Premanufactured, easy to install

Sensor encapsulated in stainless steel container

Do not require protection against humidity or the chemical environment of concrete (embeddable sensors)

Section 5: SHM Testing Categories

Overall SHM categories can be distinguished based on:

1. **Timescale of the monitoring**

Continuous ⟷ Periodic

2. **Manners in which responses are assessed in the structure**

Static load ⟷ Dynamic load ⟷ Ambient vibrations

Field Testing

- This is the most common type of Field testing
- Loads are **slowly placed and sustained** on the structure

  → **No dynamic effects** (loads move on real structures)
- There are essentially **three types of static field tests**:

1. Behaviour Tests
2. Diagnostic Tests
3. Proof Tests

Static Field Testing

1. Behaviour Tests

Goal → Study mechanics of structure and/or verify methods of analysis

∴ Testing loads ≤ Maximum service loads

Results → How loads are distributed in structure; for this we can make use of Shake table .

Static Field Testing

2. Diagnostic Tests

Goal → Determine interaction between various components in structure (how they help or hinder each other)

Essentially same method as Behaviour Tests

Results → Beneficial Interaction → Use to advantage
Detrimental Interaction → Repair

Static Field Testing

3. Proof Tests

Goal ➡ Induce "**proof loads**" to test the load carrying **capacity** of the structure

Increase load until linear elastic limit reached

Results ➡ Proof load is maximum load the structure has withstood without suffering damage

CAUTION: Extreme care should be taken during proof testing
Monitoring should be continuous during testing
Supporting analysis is required

Dynamic Field Testing

- For testing behaviour of structures subject to **moving loads**
- In a typical dynamic field test (for a bridge):
  - → A test vehicle travels across a “bump” on the bridge
  - → Dynamic response of the bridge is excited, measured and analyzed
- Essentially four types of dynamic test:

1. Stress History Tests
2. Dynamic Amplification Tests
3. Ambient Tests
4. Pull-back Tests

Dynamic Field Testing

1. Stress History Tests

- Used for bridges that are **susceptible to fatigue** loading
- Determines the **range of stresses** that the bridge undergoes
- Requires a modern DAS with a **rapid sampling rate**
- Strain profiles are recorded and analyzed to **determine the fatigue life** of the structure (the time until failure by fatigue)

NOTE: Fatigue failure is a potentially disastrous type of failure which is caused by repeated cycles of loading and unloading

Dynamic Field Testing

2. DLA Tests (Dynamic Load Allowance like field load test)

- Structural design generally assumes loads are static – this is not always the case, particularly for bridges
- For dynamic loads, static loads are multiplied by a *dynamic amplification factor (DAF)*
- Various different dynamic test methods are used to calculate the DAF for bridges (no standard method exists)

Dynamic Field Testing

3. Ambient Vibration Tests

- Vibration characteristics of structure are examined **based on vibrations** due to wind, human activity, and traffic
- **Changes in vibration characteristics** of bridge may indicate damage (vibration based damage identification)
- Strategically-placed **accelerometers** measure vibration response of bridge, and resulting data is analyzed using complex algorithms

Problems:
Global properties (vibration frequencies) have low sensitivity to local damage
Vibration characteristics affected by environment, temp. and boundaries

Dynamic Field Testing

4. Pull-back Tests

- Usually conducted on bridges to determine response to lateral dynamic excitation
- Use cables to pull structure laterally and suddenly release
- Accelerometers used to monitor structure's response
- Data analysis is similar to that required for an ambient vibration test

Periodic Monitoring

- Periodic SHM conducted to **investigate detrimental changes** that might occur in a structure
- Behaviour of structure is **monitored at specified time intervals** (days, weeks, months, years…)
- Examples include periodic monitoring:
  - through ambient vibration;
  - through testing under moving traffic;
  - through static field testing;
  - of crack growth; and
  - of repairs

Continuous Monitoring

- Monitoring **undergoes** for an extended period of time
- Used in field applications to avoid high repair **costs** and relative **complexity in future**
- **Real-time** monitoring and data collection
  1. Stored on site for analysis later
  2. Communicated to remote location for real-time analysis
- Usually only applied to **important structures** or when there is **doubt about the structural integrity**

Section 6: SHM System Design

1. Design Issues…

Sensors installed on FRP reinforcing grid prior to installation in a concrete bridge deck

- Definition of SHM objectives
- Types of monitoring
- Sensor placement
- Durability and lifespan of SHM

SHM System Design

2. Installation Issues…

Contractor education and careful sensor identification are critical in SHM projects

- Contractor education
- Sensor identification
- Sensor damage during construction
- Structural changes induced by presence of SHM system
- Protection against deterioration and vandalism (destroy)

SHM System Design

3. Use Issues…

Dissemination of performance results

Continuity of knowledge

Data collection and management

Public awareness

SHM System Design: Methodology

1. Identify the damage or deterioration mechanisms
2. Categorize influence of deterioration on the mechanical response
   - Theoretical and numerical models of structure
3. Establish characteristic response of key parameters
   - Establish sensitivity of each to an appropriate level of deterioration
4. Select the parameters and define performance index
   - Relates changes in response to level of deterioration
5. Design system
   - Selection of sensors, data acquisition and management
   - Data interpretation
6. Install and calibrate SHM system (baseline readings)
7. Assess field data and adapt system as necessary

What is Civionics?

CIVIL ENGINEERING + ELECTRONICS

= CIVIONICS

Cooperation between engineers from various specific disciplines to form a new discipline within the field of civil engineering that refers to the applications of electronic systems in civil engineering applications

Civionics Specifications

ISIS (Intelligent Sensing for Innovative Structures) Canada has recently published “Civionics Specifications” - a manual providing best-practice guidelines for applying SHM

Topics include:

Fibre optic sensors

- Fibre sensors and readout units
- Long gauge FOSs and readout units

Wiring procedures and connections

- Sensor cables
- Conduits
- Junction boxes
- Cable termination
- On-site control rooms

FOS installation procedures

SHM system and FOS suppliers

Section 9: The Future of SHM

SHM is increasingly seen as an important tool in the maintenance of **sustainable infrastructure systems through innovative research**

Ongoing advancements are expected, emerging technologies include:

→ **Smart Composites**

→ **Live Structures**

Section 10: Summary and Conclusion

Structural Health Monitoring

- Provides the civil engineering community with a **suite of options for monitoring, analysing, and understanding** the **health of our infrastructure systems**
- Provide **essential tools** to engineers who must take steps to **improve the sustainability** of infrastructure systems