University of Sheffield

Department of Civil and Structural Engineering

Msc Course: Structural Dynamics

CIV 615: Blast and Impact

3. Measurement and Interpretation of Loading and Structural Response

3.2 Blast Loading on reinforced concrete slabs

LECTURE NOTES

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1. Introduction

The place for testing in Structural Engineering

Testing is one of the five basic phases of structural engineering. Each phase gives information to and receives guidance and constraints from the others. These interactive relationships are shown below.

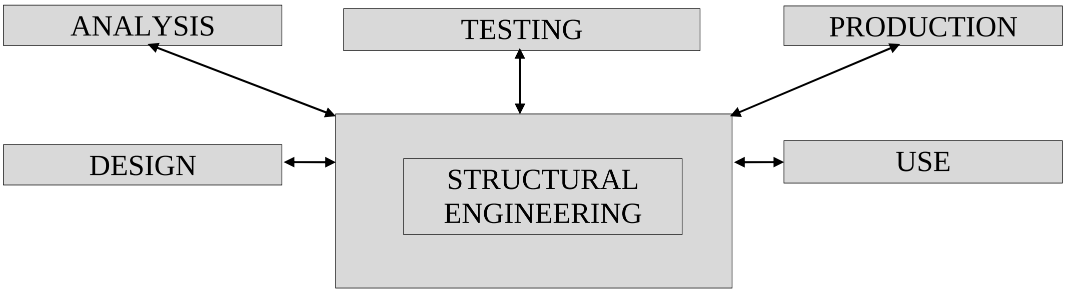


Figure 1.1 Phases of Structural Engineering

Notes:

The purpose of structural testing

The structural testing purposes can be considered from many perspectives; the usual reference is in terms of the structure being tested. Structural testing to be performed on a prototype or actual structures can be described in six basic parts as summarised in Table 1.1. This table gives the relationships among test purposes, evaluation criteria, test activities and the desired insights needed from structural testing.

Basis/Source of Test Activity	**Six Basic Parts of Test Planning, Organising and Activities**
Test Purposes	Determining Loading Conditions, Determining Boundary Conditions, and Laboratory or Field Simulations
Test Purposes	Determining Test Methods and Procedures, Safety Procedures and Basic Test Sequences
Test Purposes/Evaluation Criteria	Selecting and Installing Diagnostic Devices - Sensors, Transducers and Gauges
Test Purposes/Evaluation Criteria	Obtaining Data, Results, Observations and Other Descriptions of Structural Responses
Evaluation Criteria	Analysis, Organisation and Presentation of Data, Correlation/Interpretation of data and Test results
Insights into Structural Behaviour	Evaluated and Interpreted Data and Test Results, Analysis of Failures and Other Responses

Table 1.1 - Test design and planning

Notes:

Potential problems with short term loading tests

Among the potential problems in shock testing are:

(1) Containment of the test item and any debris that may result from the test.

(2) Rugged and reliable data systems which may be required to withstand shock loads as well.

(3) Tailoring the shock pulse to meet the test requirements.

(4) Maintaining alignment of the test rig or test item and the source.

(5) Test system safety for operators and equipment (e.g. interlocks, alarming systems, firing systems).

(6) Adequate transducers and data acquisition systems which accurately read the high frequency shock pulses and measure the responses of the structural system or component.

Notes:

Calibration of the instruments

Measurement processes depend on the calibrations of the instruments used. Calibration of the instruments relates the inputs they receive to the outputs they indicate. For example, a strain gauge based load cell is subjected to an applied force. The force produces a strain in the sensing portion of the load cell. The output of the load cell's measurement system indicates a voltage change. The voltage change is proportional to the applied force.

Calibration is quantifying and defining the relationships between known inputs and observed outputs and the uncertainties associated with the two measurement processes. In each case it is necessary to have a known reference which is traceable to some accepted standard (for example BS), a calibration procedure which is repeatable and supplies the known condition, and a measurement device calibrated using the reference and accepted procedure

There are two basic approaches to calibration:

(1) relating the operation of a transducer or device and its output to that of a known standard so the history of the instrument can be developed and documented, and

(2) modifying the equations or factors governing the constants used to convert the measured output (e.g. voltage) to the needed indication of behaviour (e.g. strain, acceleration).

Notes:

2. Blast testing on R.C. slabs

Slab specimen, test arena and the charge description

The reinforced concrete slab specimens were based on typical structural elements which can exist in various types of structure (for example bridges and industrial buildings). The models have been designed to represent approximately 1:4 scale and 1:10 scale models of typical prototypes. In the remainder of this lecture the 1:10 scale will be called small or model specimens and the 1:4 scale the large or full scale specimens. Thus the small specimens model the large specimens at 1:2.5 scale i.e. all outside dimensions for the model slab are 2.5 times smaller than for the prototype. The slabs were all square shaped, had rectangular cross-sections and the overall dimensions of a small slab are given in Table 2.1.

		SMALL SLABS
CROSS SECTION		44 x 800 mm
LENGTH		800 mm
SPAN	FIXED SUPPORTS	640 mm
	FREE SUPPORTS	720 mm

Table 2.1 Small specimen dimensions

The dimensions and reinforcement of a typical large scale slab are given bellow.

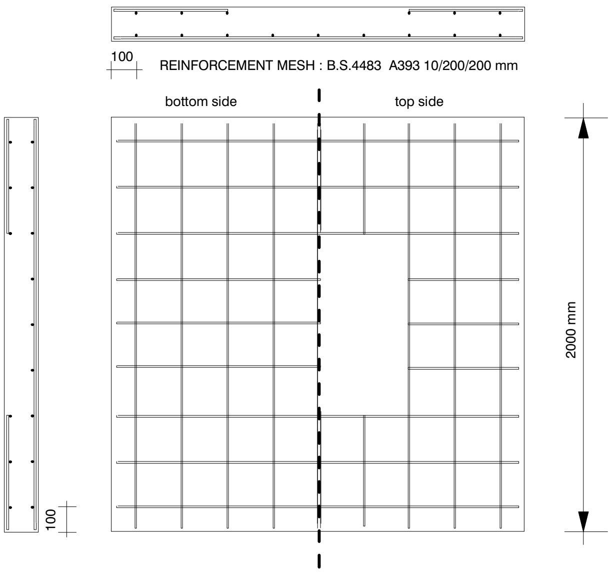


Figure 2.1 - Reinforcement for a large scale slab

Notes:

The explosive used in the impulse tests had a mass density of 1590 kg/m^3, detonation velocity of 8189m/sec, detonation pressure of 2.68 x 10^7 kN/m^2 and mass specific energy of 5111 kJ/kg^2 which gives it a TNT equivalent of 1.13.

Apart from a few initial tests on the small scale slabs where the charge was cylindrical in shape, all charges were of hemispherical shape with the spherical side of the charge facing the specimen.

They were all hand made from 454g explosive sticks that were compacted in to the specially made steel moulds, so producing a charge of uniform shape and consistent density. The L2A1 detonators were placed into a pre-formed 10 mm deep hole in the centre of the flat side of the charge in all tests and then held in place by insulation tape. In all tests the charges were initiated from the side furthest from the specimen.

The large scale charge was chosen to be 1300g since the large blast cell has been proved for that amount of explosive. The diameter of the hemispherical charge was 142.5 mm.

The scaling law for explosions is based on geometrical similarity. The explosive charges and distances from the specimen were scaled according to the cube root scaling laws.

Cube root scaling indicates that a charge of mass M_1 = 1300g will produce the same peak overpressure and shock wave velocity at a distance R_1 from the charge, as a scaled charge of mass M_2 of the same explosive type and shape at range R_2 when:

$$\frac{R_1}{\sqrt[3]{M_1}} = \frac{R_2}{\sqrt[3]{M_2}}$$

So the scale factor is: $$\frac{R_1}{R_2} = \sqrt[3]{\frac{M_1}{M_2}}$$

and for: $\frac{R_1}{R_2} = 2.5$ and $M_1 = 1300\text{g}$ then:

$$M_2 = \frac{1300}{2.5^3} = 83\text{g}$$

Notes:

For practical reasons (the same size detonator was used for both scales), the model charge was actually M_2 = 78g and it had a diameter of 57 mm. You should notice that although the scaled charges gave the same peak pressure and shock wave velocity at scaled distances, the positive duration and impulse produced by the larger charge are 2.5 times greater than corresponding values produced by the smaller charge at scaled distances.

Plate 2.1 - 1:2.5 Scale blast tests site

All explosive tests were performed in blast cells at the laboratories for Civil Engineering Dynamics, University of Sheffield, CEDUS. Since the main objective of the research was to determine the behaviour of the slabs to blast from close range explosive charges it was decided that its stand-off distance to the specimen should be in the region of 250 mm to 50 mm. In all cases stand-offs were measured as a clear spacing between the charge and the specimen. All the tests were, because of the amount of explosive involved, performed in open blast cells and very strict safety procedures were adhered to. The specimens were tested outdoors in the open roof test chambers built of concrete blocks that was 2m wide, 5m long and 2.5m high with a concrete floor and no roof. The testing site is shown in Plate on the left.

Notes:

3. Instrumentation and Results Interpretation

Dealing with uncertainties and doubts

Whenever a test is performed, there is usually a question regarding the quality of the data obtained. This quality is directly related to the uncertainties involved in each part of a test.

There are four important prerequisites that must be fulfilled before the detailed uncertainties associated with a test can be determined:

(1) all instruments and transducers involved in structural tests must be calibrated;

(2) the instrument calibrations must be valid during the period of time covering the tests;

(3) the calibrations must have traceability to national standards;

(4) the details of the structural testing techniques must be well understood (e.g. temperature effects, modelling assumptions and limitations, material properties, etc.).

Notes:

3.1 Digital storage oscilloscopes

These are used in dynamic tests to record and temporarily store the outputs from the transducer measuring devices, e.g. electrical resistance strain gauges, displacement transducers, pressure gauges etc. before being transfered to the personal computer. Although there are many different kind of oscilloscopes they all function on more or less the same basic principles - see figure below.

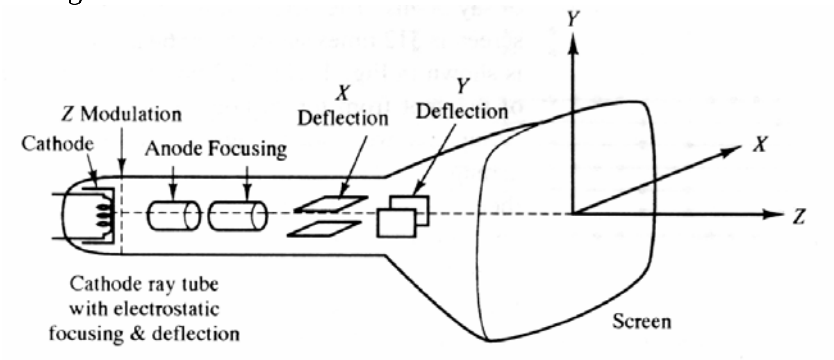


Figure 3.1 - Cathode Ray Oscilloscope - principle of operation

If a filament of wire is heated sufficiently some of its electrons become free and move towards the positive electrode - anode. This is called a termionic emission. By using an anode plate with a hole through it, some of the electrons pass through the hole to produce a beam of electrons. This beam of electrons causes the atoms in the screen to emit light, so a trace that we see on the screen corresponds to the path of the electrons. Since these electrons are directed to pass between a series of oppositely charged metal plates they will be deflected regarding on how much is the voltage difference between the plates. This voltage difference is the product of our input signals. This signals are in its analogue form. Once they are converted by Analogue to Digital Converters they can be stored in the same way as any other computer data.

Notes:

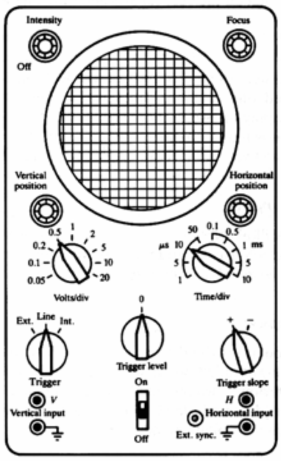


Figure 3.2 - Front panel of a typical oscilloscope

The digital storage oscilloscopes came on the scene in the early 70’s. They offered significant improvements in accuracy resolution and storage capacity when compared to analogue ones which, in essence, had no storage capacity..... Also the horizontal scale of the Cathode-ray tube screen is not in terms of frequency but is calibrated in terms of time per point of data...... An analogue to digital converter digitises the input signal voltage and stores the bits in a solid-state memory much like a computer. With a 12 bit system the data is measured 2^{12} i.e. 4096 times over a designated time period - vertical resolution. At any time the observer can “freeze” the display by storing the currently displayed “block” of data in a second memory buffer which keeps that “block” of data displayed on the screen. Modern digital oscilloscopes have a resolutions of 16 bits i.e. $1/2^{16}$ or 1.5×10^{-3} %. This is about 5 orders of magnitude better than the analogue oscilloscope.

Here, the "GOULD" digital storage oscilloscope OS 4020 will be taken as a typical example. The OS 4020 is a 8-bit high speed dual channel storage system in which each channel stores 2048 data points. It can be set for sensitivities from 5 mv/cm to 20v/cm vertical resolution and capture rate of 200µs/cm to 0.50s/cm of screen so covering any event lasting from 2 ms to 5 sec at a frequency of up to 1 MHz. Both channels are synchronised on the same time base. Triggering to start recording can be done externally or by the pulse from the event itself with pre-trigger varying from 25% to 100% of the record in 25% steps. The system offers post storage expansion of up to 50 times.

After capturing the event on the oscilloscope it was later transferred to the computer by using software developed at The Sheffield University.

Notes:

3.2 Pressure transducers

Dynamic pressures are normally measured with a flush diaphragm type of transducer. The diaphragm may be mounted parallel or perpendicular to the flowing stream. If the stream velocities are large, the mounting direction is important since the parallel diaphragm will sense true steady state pressure and the perpendicular diaphragm will measure total or stagnation pressure (steady state plus velocity head)....... The device used to measure the deflection of the pressure-sensing diaphragm for dynamic conditions may be strain gauges (either semiconductor or foil), an LVDT, a capacitance probe, or piezo electric crystal.

Most pressure transducers require some signal conditioning and a power supply. On the other hand, some can drive a recording device directly without further amplification. The piezoelectric transducers can be used without external power supplies - because they themselves generate the electricity when exposed to the sudden pressure change.

The recommendation for selecting a pressure transducer consists of two part:

(1) knowing or conservatively estimating the pressure conditions (magnitude, rates, temperatures etc.), and

(2) using the information and performance capabilities given by the manufacturer.

The main purpose for employing these gauges in our case was the establishment of the pressure distribution across the surface of the slab.

Notes:

Kulite miniature pressure transducers of two different types were used for all explosion overpressure measurements. They are both made as fully active four arm Wheatstone bridges that utilise either a metal (Kulite HKM-375-1,000) or a silicon (Kulite HKS-375-15,000) diaphragm that deforms under the blast pressure and has a piezo resistive sensor as its sensing element. Both were of a sealed type operational mode with rated pressures of 68.95 bar and 1034.25 bar respectively. The natural frequency of the metal diaphragm was 275 kHz and of the silicon diaphragm was 700 kHz. These were both very satisfactory. The sampling rates used were up to 1 MHz. They were both usually powered with 5V DC and infinite resolution output signals were later amplified from 100 to 2500 times. As can be seen from Plate 3.1, 9.5 mm thread allows very easy installation of the gauge and on all occasions they were mounted in steel holders facing the blast wave.

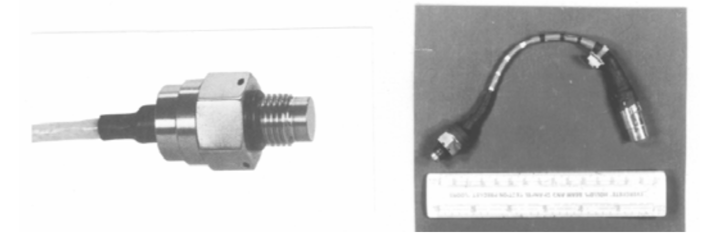


Plate 3.1 - HKM-375-1000-Kulite pressure transducer

Both gauges, were supplied with the calibration factors, but were also statically calibrated and typical results are given in the next Figure. The gauge with the metal diaphragm produced much better and more consistent results and some of the typical traces are shown in the same Figure.

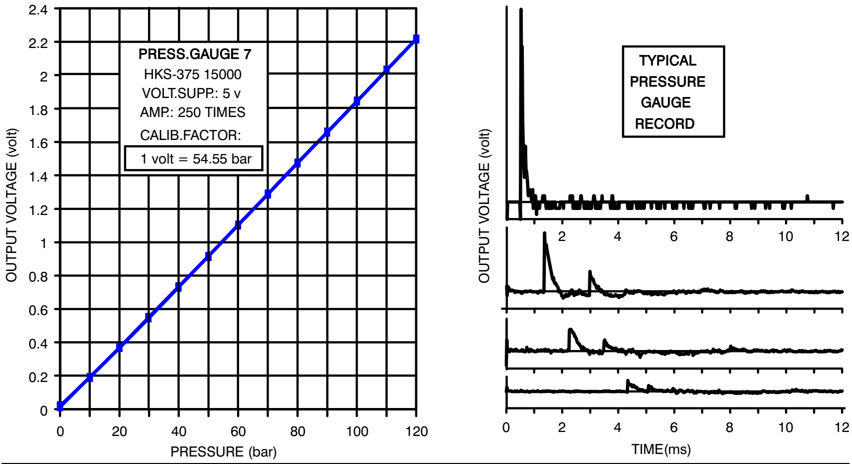


Fig. 3.3 - Pressure gauge calibration and test results

Notes:

The connection circuit is shown in the Figure below.

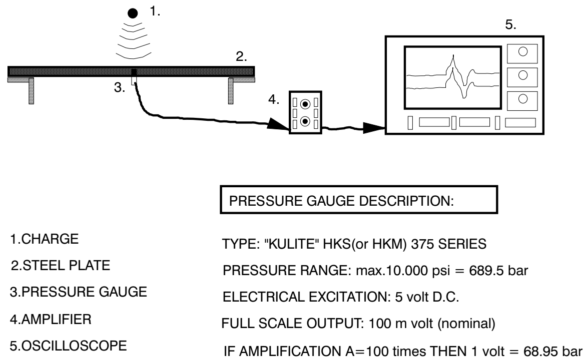


Fig. 3.4 -_ Instrumentation circuit for blast overpressure measurement

Notes:

The blast pulse that produces the dynamic pressure on the slab was quantified using both experimentally obtained measurements, as described above, and the theoretical approach of Henrych, (1979).

If we denote the angle of incidence between the shock front vector and the line perpendicular to the slab surface as α (Fig. 3.5),

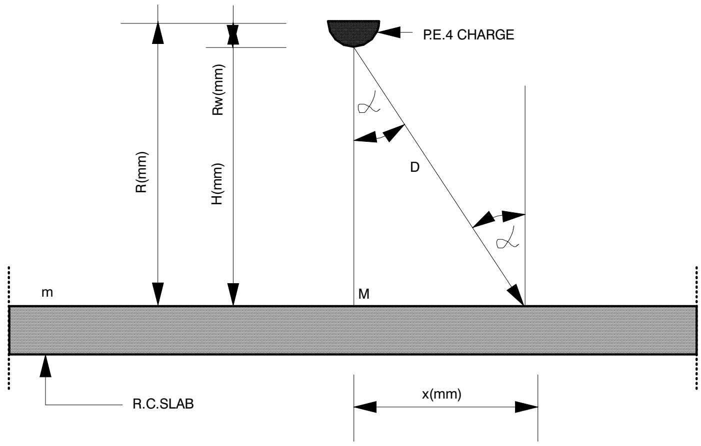


Fig. 3.5 - Loading function parameters

then the pressure function *P(t)* can be obtained in the form of:

$$P(t) = P_{\det} \cdot \left(\frac{R_w}{R}\right)^A \cdot \cos^3\alpha \cdot \left(1 - \frac{t-L}{\tau}\right)$$

where: where $P_{\det}$ is the detonation pressure of a spherical, flat or cylindrical charge of radius R_w and stand-off distance R. t represents the time measured from the arrival of the blast front at the slab and τ is the positive duration of the pressure pulse.. In our case $P_{\det}$ is 26.8 kN/mm^2 , $L = \dfrac{D-H}{V}$, $V = 7.5\,mm/\mu\sec$ (velocity of blast wave propagation for close range charges) and $\dfrac{D-H}{V}$ represent the delay which occurs due to the late arrival of the pressure at different points across the slab. The value of 2.65 for A has been chosen as the best fit to the available experimental results, since the values provided by Henrych correspond to spherical (A = 2), and flat side of the hemi-spherical charge (A = 3). The values for τ were extrapolated from the test results.

Notes:

The pressures on the 1:2.5 scale slab, calculated from these equations, are given in Fig. 3.6. They compare relatively well with experimentally obtained results when calculation is done at every 2mm of the slab. A comparison between the measured and results calculated using modified Henrych relations is given in Table 3.1.

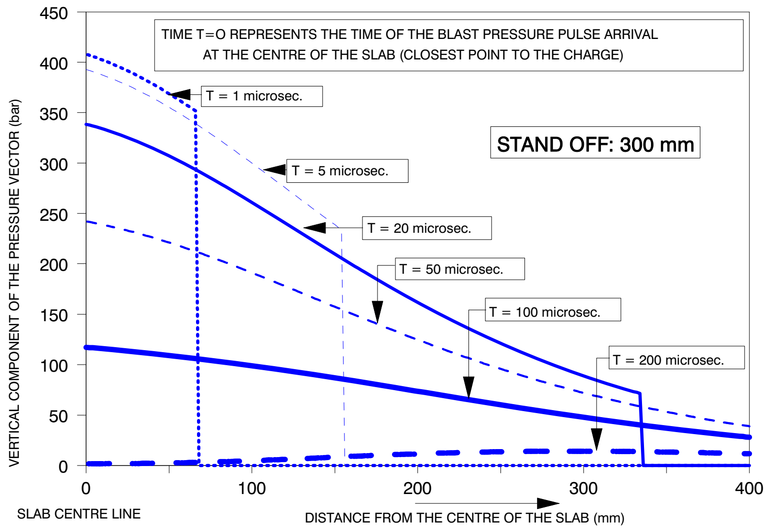


Fig 3.6 - Pressure vs. time profile for 78g PE4 charge according to Henrych (1979)

STAND-OFF (mm)	DISTANCE TO THE EPICENTRE (mm)	PEAK PRESSURES	
		MEASURED VALUE (bar)	CALCULATED VALUE (bar)
600	420	26	21.2
500	0	100 to 140	116.14
400	0	180 to 280	202.2
400	350	45 to 55	48.8
300	0	290 to 320	407.9
300	350	35	63.6
200	350	40 to 52	74.2
100	350	55	57.8

Table 3.1 - Comparison of measured with calculated pressures

It can be seen that all calculated pressures have the same order of magnitude as the measured pressures and most are within 10% of the measured values. The blast function itself is not always consistent, so these small discrepancies can be tolerated.

Notes:

3.3 Strain gauges for dynamic loadings

Electrical resistance dynamic type strain gauges were used to measure the tensile strain in the reinforcement and pressure bars (load cells) in the dynamic tests.

A strain gauge is device which experiences a change in resistance when it is stretched or strained. As strain is applied to the gauge, the shape of the cross-section of the resistance wire distorts, changing the cross-sectional area. As the resistance of the wire per unit length is inversely proportional to the cross-sectional area, there is a consequential change in resistance.

Since:

$$R = \frac{S \cdot L}{A}$$

where: R - electrical resistance
L - length of wire
S - specific resistance
A - cross-sectional area

then: $$\frac{\Delta R}{R} = K \cdot \frac{\Delta L}{L}$$

where : K - the gauge factor (usually varies from 2.0 to 2.2)

It can be seen that this gauge factor represent the input-output relationship for a particular gauge and is defined as the change in resistance for a given value of strain and is, as such, constant.

Notes:

In stress wave type of application the strain gauge length is very important because the strain recorded is the average strain over its length (see figure below). Generally, the shorter the strain gauge the better.

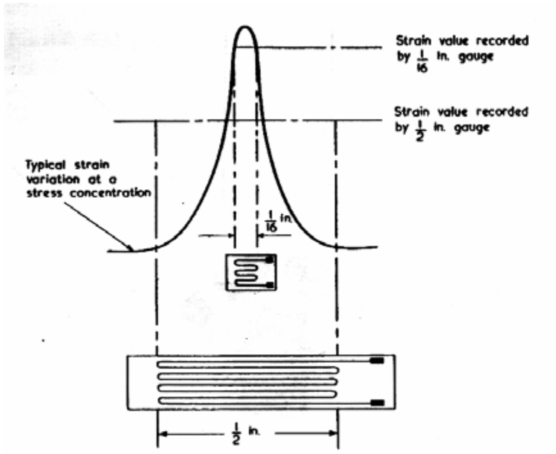


Fig. 3.7 - Effect of using too long strain gauge

Notes:

For each of the impulsive tests, the two bottom layer bars, one in each direction, were equipped with electrical resistance strain gauges placed at the midspan point of the bars.

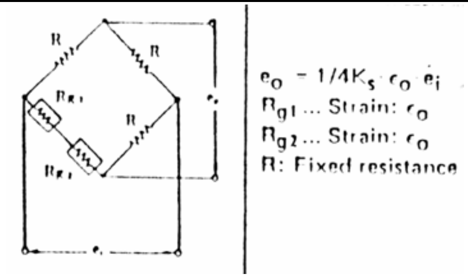


Fig. 3.8 - Wheatstone bridge circuitry for measuring the strain in the reinforcement

For our tests we used "KYOWA" foil type strain gauges and terminals with the typical gauge characteristics being 120 Ω resistance, 5 mm and 30 mm long and gauge factors K = 2.15 or 2.08. The gauges were connected into a Wheatstone Bridge circuit as shown in Figure on the left.

It is noticeable that this is the same arrangement as used in static tests, the only difference being that here the dummy gauges do not need to perform the role of temperature compensators as in static tests.

The gauges were calibrated using the manufacturers gauge factor in the Wheatstone Bridge equation - second type of calibration. For this type of Wheatstone bridge the relation between the output voltage from the system and the strain ε_o is given as:

$$e_o = \frac{1}{4} \cdot K_s \cdot \varepsilon_o \cdot e_i \cdot A$$

where: K_s - gauge factor (given by the gauge manufacturer as, for example, 2.15)
e_i - input voltage
A - amplification of the signal
for: A = 100 times and e_i = 4 volts
e_o = $2.15\varepsilon_o$
so: 1 volt = 0.0046512 strains.

In use, strain gauges are bonded to the object whose displacement or strain is to be measured. It is important to notice that the process of bonding presents a certain amount of difficulties, particularly for the shorter gauges that are usually used in dynamic applications.

Notes:

The typical reinforcement strain vs. time record obtained from the small scale slabs tested by explosive is shown in the figure below.

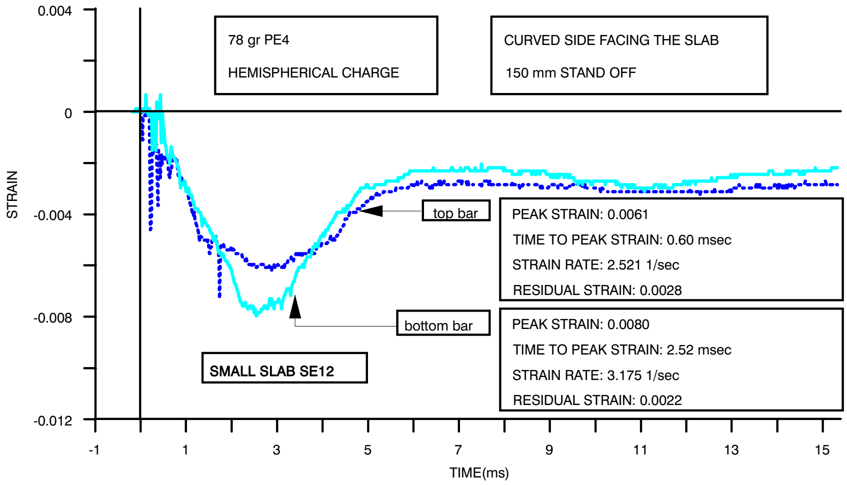


Fig. 3.9 - Typical strain gauge results

Notes:

3.4 Displacement transducers

There are two basic types of displacement transducers which are based on the change of output voltage as a result of specimen displacement. They are LVDT - Linear variable differential transformer and Resistive potentiometers. The main difference between them is that whilst in the case of LVDT the central iron core travels between the primary and secondary wire windings inducing the voltage in secondary windings, the Resistive potentiometers consist of a resistance element and a movable contact - see the figure below.

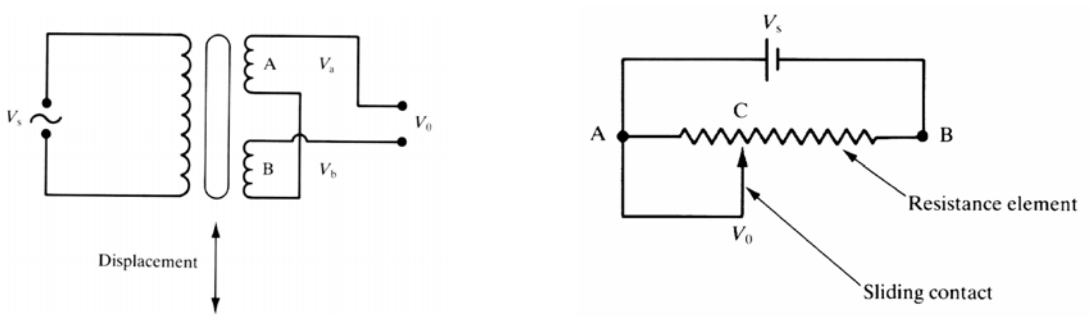


Fig 3.10 - Principle of operation a) LVDT b) Resistance Potentiometer

Notes:

Here, we shall look more closely at the Resistive type displacement transducer.

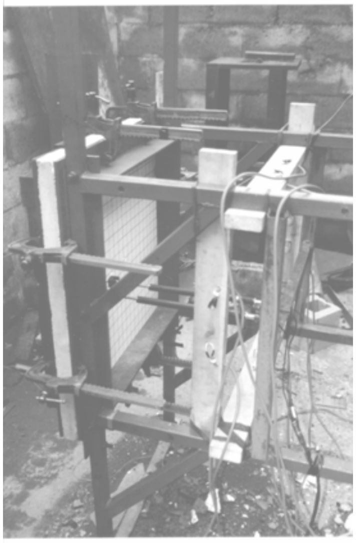


Plate 3.2 - RC Concrete slab ready for testing

The main type of displacement transducers used for the dynamic testing presented here was Penny and Giles' Hybrid Track Rectilinear Potentiometers. These transducers consist of two basic parts. A moving stroke has a two-part conductive plastic wiper whose linear movement across the second main part, a resistive track of infinite resolution, is directly proportional to the voltage difference in the output of the two. In the case of our tests the rectilinear potentiometer displacement transducers, RPDT's, were powered by 10 volt DC and produced good results. Special mountings were provided on both ends of the transducer so enabling good connection between the stiff steel RPDT holder and the specimen itself.

A 3D-cross section of the transducer is given in Fig. 3.11 and typical static calibration traces together with some of the results are shown in Fig. 3.12. All transducers used in the tests were statically calibrated with the same electrical connections as in the dynamic tests. The RPDT static calibration rig consisted of a micrometer screw gauge and a dial gauge that together with the Digital Voltage Meter gave the relation between the voltage output and the displacement of the RPDT's stroke. In Plate 3.2 you can see how RDPT-s were positioned during the tests.

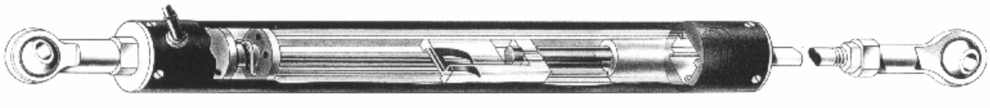


Fig. 3.11 -_ The cross-section of a typical Resistance Displacement Transducer

Notes:

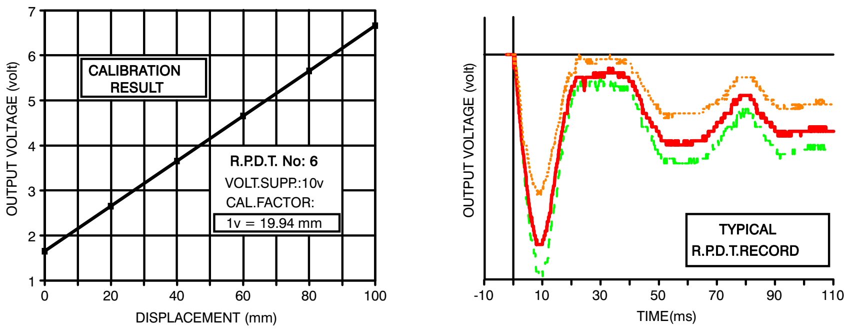


Fig. 3.12 - Displacement transducer calibration

The typical deflection vs. time record obtained from the large scale slabs tested by explosive is shown in Fig 3.13. This is the same record as shown in the previous figure, but here after applying the calibration factors.

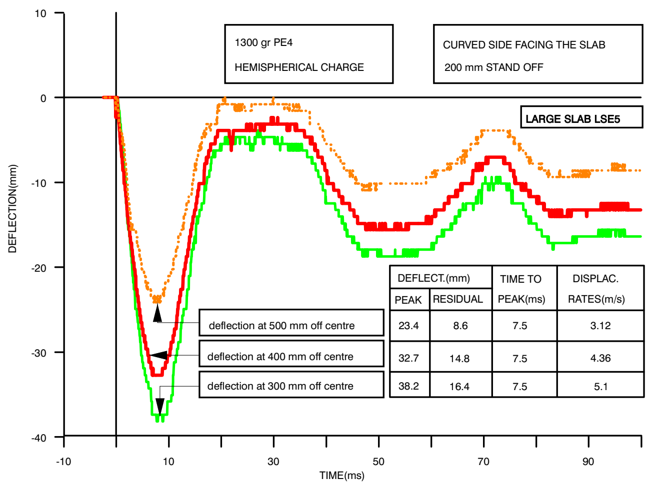


Fig. 3.13 - Displacement transducer test results

Notes:

Some typical deflection - time profiles of the slabs under explosive blast loading are given in Fig. 3.14 . They show the overall deflected shape of the slabs.

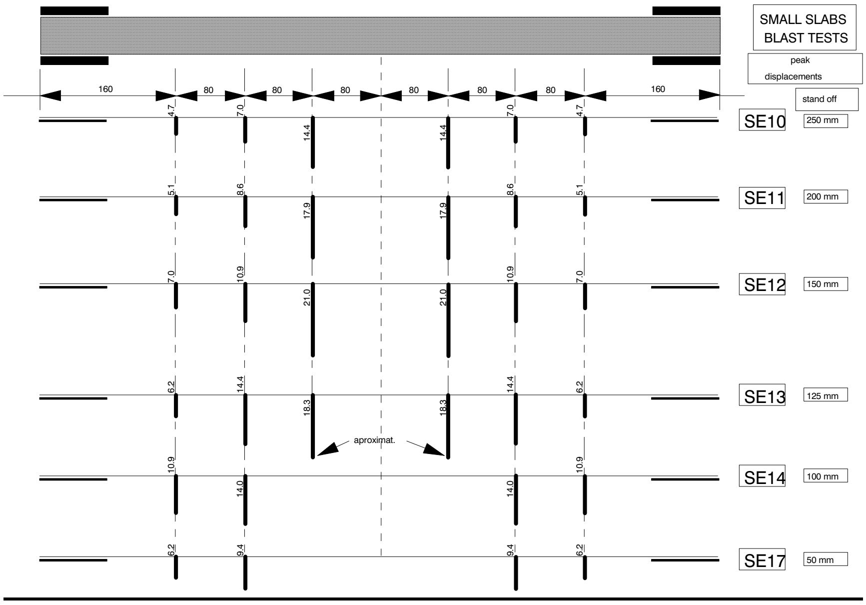


Fig 3.14 - Deflected shapes of the slabs

Notes:

3.5 High Speed Photography

A rotating prism 16 mm high speed camera - Photec IV, Plate 3.3, was used to film the damage on some of the small scale impact and impulse tests. When recording in full frame mode the speed can vary from 100 to 10,000 pictures per second (pps) but half frame and quarter frame shutters are also available and these increase the speed by two and four times respectively. The camera can accommodate from 30 to 150 m of 16 mm film. Very importantly the camera has an internal lighting source that marks the edge of the film with a mark at every millisecond. Two cables are provided with the camera. The Y-cord is used to connect the camera to the event - synchroniser and the remote cord is used for starting the camera. The event-synchroniser can be set to start an electrically controlled event, a blast or impact in our case, at any pre-selected point on the film. It was powered by a 15 volt 2A DC power supply and the amount of film set to pass before triggering the event is set on the control panel of the camera. Illumination of the specimen becomes of major importance when the camera runs in the fastest mode so we used 8000W of light positioned very close to the specimen.

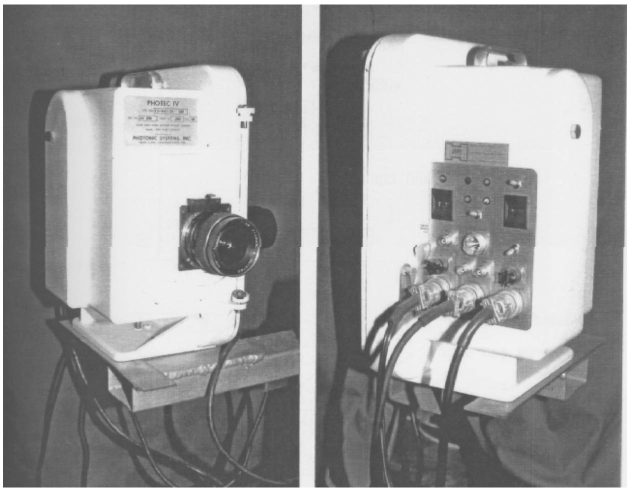


Plate 3.3 - Photec IV - High Speed Camera

In our case a half frame shutter was used so framing rates of up to 10,000 half frames per second were used to record the events. Ilford 400ASA HP5-plus Type 782, 30.5m long 16 mm wide high speed films produced images of very high quality. After processing, the high speed films were analysed with the Vanguard instrumentation motion analyser projector which allows the freezing of single frames and up to 15 times enlargement of the picture and can run the film at variable speed.

Notes:

High speed filming was used on almost all small scale specimens. Photec IV camera was usually set to run at up to 10,000 p.p.s. As mentioned earlier on all small scale slab specimens, meshes were drawn before the test with squares of 36 mm x 36 mm, starting from the central line. In all cases when the Photec IV High speed camera was employed a half frame shutter was used and the size and position of the area that was filmed is approximately shown in Fig. 3.15.

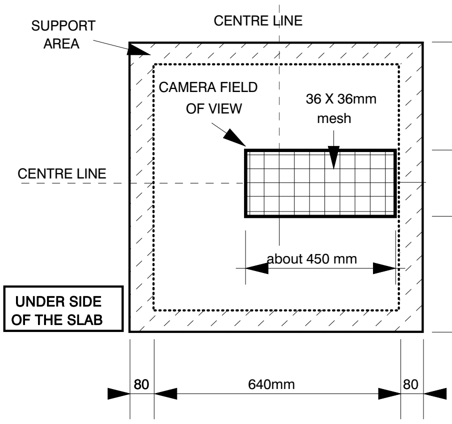


Fig 3.15 - The area that was filmed by the High Speed Camera

In the case of blast test a new rig was designed and built in which the slab was held vertically and the camera placed at about 2.5m behind the wall filming through the protected port hole. The camera arrangement is shown in Fig 3.16.

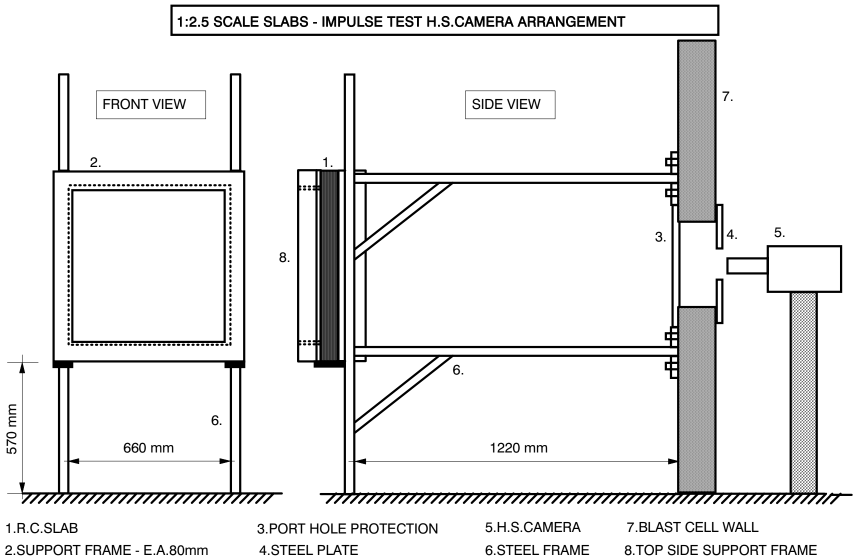


Fig. 3.16 - High speed camera arrangement

Notes:

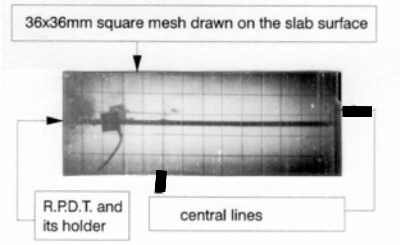


Plate 3.4 - Description of a HS Film frame

The high sped films were used to provide the information regarding the crack propagation in an early stage of the slab response - i.e. before the time of maximum displacement. Typical frames taken from slab No. SE15 are presented in Plate.3.5.

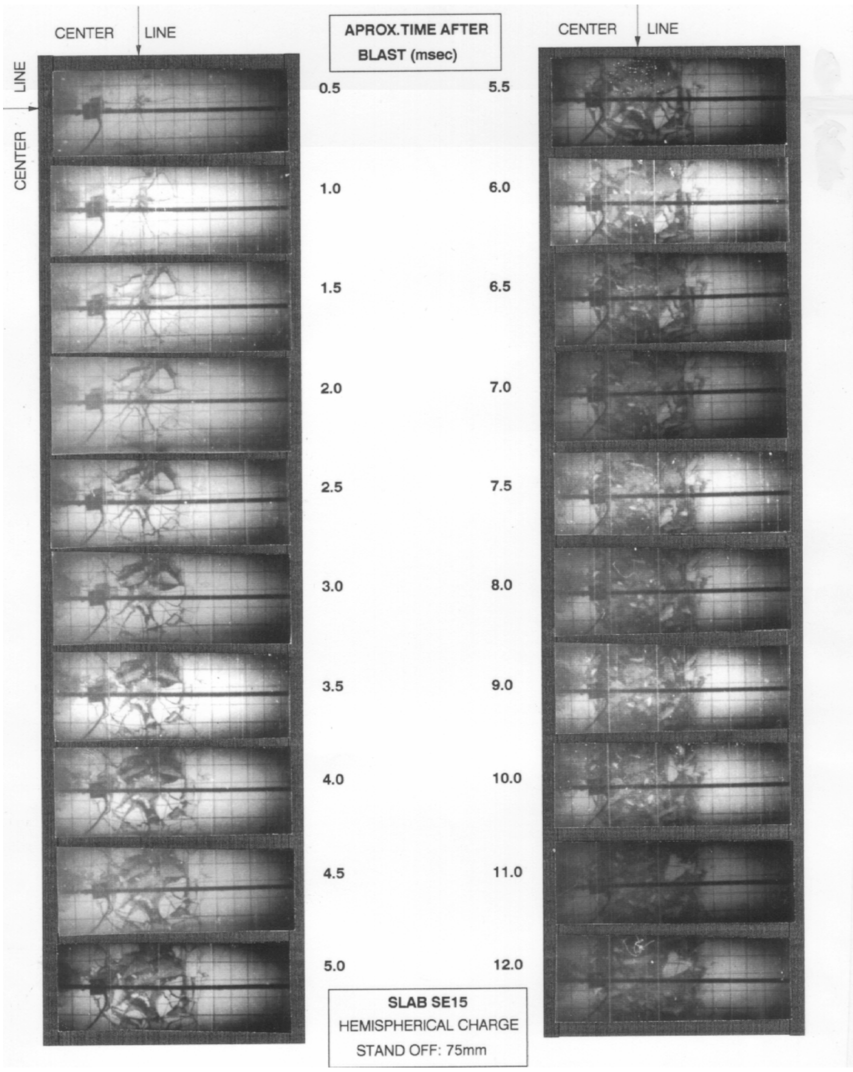


Plate. 3.5 - 16 mm Film frame details- Blast impulse tests

Notes:

It can be seen that:

The initial stage of local response of slab SE15 to an explosive charge at 75 mm stand-off was characterised by the formation of radial or fan shaped cracks on the underside of the slab, propagating from the centre of the slab. These cracks start to form by around 100μsec after detonation. The visible length of the longest crack after 190μsec was about 147 mm measured from the centre of the slab.

In addition to these radial cracks, a set of circular cracks was formed around the epicentre on the underside of the slab early in the response, in a region about 20 mm radius from the centre. This was followed by extensive surface cracking inside that circle.

Another set of circular cracks forming a shear plug, with a radius of about 126 mm on the back face of the slab and close to the future scab region, was completely established by around 860 μsec after the detonation. In about 1.8 msec after detonation the area of local response was fully defined within the circular cracks. Inside that area extensive fan shaped cracking occurred and disintegration was starting to take place. New cracks began to propagate, being initiated at the circular crack that borders the area of a scab.

Symilarities and differences to other tests:

The process that characterised the formation of the local damage in slab SE17 was very similar to that one observed on Slab SE15, the main difference being that slab SE17 was perforated. Extensive radial cracking on slab SE17 first occurred inside the circular crack at about 25 mm radius from the epicentre. About 655μsec later further circular cracks became visible at about 80 mm radius from the epicentre. The establishment of the full circular crack around the epicentre took another 200μsec and the local scab area was then clearly established.

Slab SE13, explosively loaded, did not have any significant scabbing but it was observed that the initiation of fan shaped cracks was almost 3 msec before any visible circular cracks, at about 125 mm from the centre, became obvious. Although the circular cracks closed when the slab recovered, the fan shaped cracks remained open throughout the event and were combined with the scabbing that was observed after the test.

Slab SE14 also explosively loaded, had diagonal cracking inside the area of the future scab before the circular cracks around that area became visible. These fan shaped cracks formed about 800 μsec before the circular cracks and the area of the scab was of square shape with sides about 250 mm long. The boundaries of the square were parallel to the reinforcement.

Notes:

In soft impact test S12, the time difference between the initiation of the diagonal and the circular cracks inside the scab area was about 4.16 msec with the diagonal cracks occurring first. The overall time needed for the formation of the scab area was about 6 msec from the impact. Slab S13 was exposed to a hard impact and was fully perforated by the impact hammer. In this case the formation of radial cracks happened much later than the initiation of the first circular cracks that were formed at a radius of about 100 mm from the impact point. The time difference between the two was approximately 1.6 msec. After another 1.6 msec the circular crack was fully developed while the fan shaped ones were still in the process of forming. Slab S17 was exposed to a soft impact and had no visible damage associated with local response of the specimen.

Conclussions from the High Speed Films:

The formation of a well defined cracked area of a circular shape can be caused by at least two different mechanisms. The concentric rings of identical pressures as the blast wave produced by the explosion of the hemispherical charge, spread across the slab, gave a load function that had radialy varying intensities. This is contributed to further by the curvature of the initial blast front. The other reason may be related to the rate of loading which necessitates the shortest paths of stress relaxation. The circle has the smallest length of circumferential line of all geometrical areas so the first cracks will most likely be initiated along that line.

It is observed from the high speed films, that the boundaries of the local damage are formed early in time and that most of the further damage then forms within that area. The cracks that define the local area are then a limit on the size of the punching shear cone and the energy confined within this area is unable to fracture the surrounding concrete. Typical crack velocities observed from the high speed films were between 420 and 770m/sec.

Notes:

3.6 Ancillary instruments for blast testing

a. Reynolds FS-10 Firing System

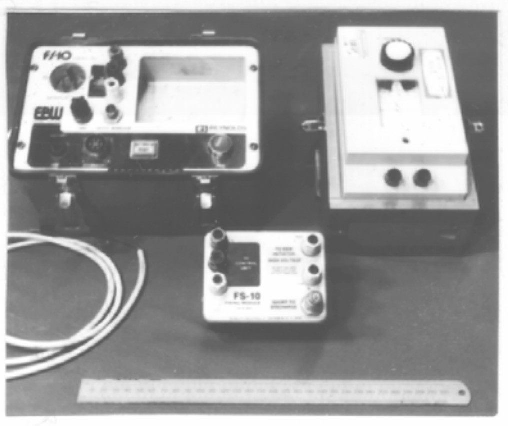


Plate 3.6 - F.S.10 - Firing System

The firing system, Plate 3.6, was used to generate and deliver an electrical pulse to fire the detonator and thus the charge itself. It consists of a control unit, which provides low charging voltage to the firing module and ensures a safe and reliable operation, and a firing module, which provides an input voltage of 3000 volts to the detonator lasting for about 0.2μsec. Peak output current is about 1000 Amps.
All the charges were initiated by the L2A1 type detonators which had operational time of about 50μsec.

b. DC - Bridge Amplifiers

Fylde type DC - Bridge amplifiers FE 359 TA were used to power and amplify the outputs from the electrical resistance strain gauge Wheatstone bridge circuits employed on load cells, pressure gauges and reinforcement bars and so eliminate or reduce disruptions in the output signal caused by the noise produced by damp and radio interference. Analogue voltage signals can be amplified up to 10000 times to give up to 10v full scale output. The control facilities consist of amplification voltage controls (up to 10 mv, 100 mv, and 1V), bridge balancing controls (coarse and fine balancing), calibration controls and input voltage controls. Each amplifier is connected to one channel of a storage oscilloscope. In our case the amplification of the signal varied from 250 for circuits on reinforcing bars to 2500 times for some of the pressure gauge measurements. Circuits were powered from 4 to 10 volts DC.

c. DC Power Supply

DC bench power supplies were mainly used to supply a constant DC voltage to the displacement transducers. The coarse and fine controls allow output voltage to be varied between zero and maximum voltage (20 or 30 volts DC). The supply stability is about 10,000 times better than the stability of the ordinary mains supply. In most of the cases displacement transducers used a 10V supply.

d. H.S. Film analysers

These can “freeze” those frames of H.S film that are of the greatest interest, so they can be analysed in more detail. The analyser also allows films to be run at variable speeds so giving an impression of the real event. The frames of a film appear on the screen separately, one by one, and enlarged about 15 times in both directions. Special light pen allows “marking” the times and distances in real terms, so for example, the analyser will calculate the time between two markings regardless of the speed at which it runs the film. The films can be run in both directions and with pre-set viewing time, if required.

University of Sheffield

Department of Civil and Structural Engineering

Msc Course: Structural Dynamics

CIV 615 - Blast and Impact

Tutorial 2

1. Vehicle impacts on parapets, crash barriers and other structures lying close to highways provide everyday examples of structural impact. Outline the particular characteristics of car impacts.

2. A full-scale car impact test is to be conducted in order to asses the ability of a long mass concrete wall to contain the vehicle. What instrumentation should be selected in order to properly assess the structural response of the wall?

3. How would you expect the wall described in q2. to perform?

4. How could car impact characteristics be replicated in the laboratory?

5. What are the particular advantages and disadvantages of the optical displacement transducers over conventional displacement transducers?

6. Integrating readings obtained from accelerometers twice in order to obtain displacements is problematic. Why?

7. Try to state potential problems when carrying blast load testing. Could you think of any particular example ?

8. a) Explain in you own words the meaning of "instrument calibration" and the main types of calibration. b) In what respect are static load pressure gauge calibration and RPDT calibration similar.

9. What are the main advantages of digital over analogue oscilloscopes ?

10. a) How does the relative position of pressure gauge diaphragm to the flowing pressure stream influences the measured results ? b) Explain the purpose of a strain gauge as a part of a pressure gauge.

11. What is the importance of the strain gauge size when used for stress wave type measurements ?

12. Using the graph No 1 try to establish a) peak deflection and time needed to reach peak displacement, b) peak deflection rate, c) peak residual deflection

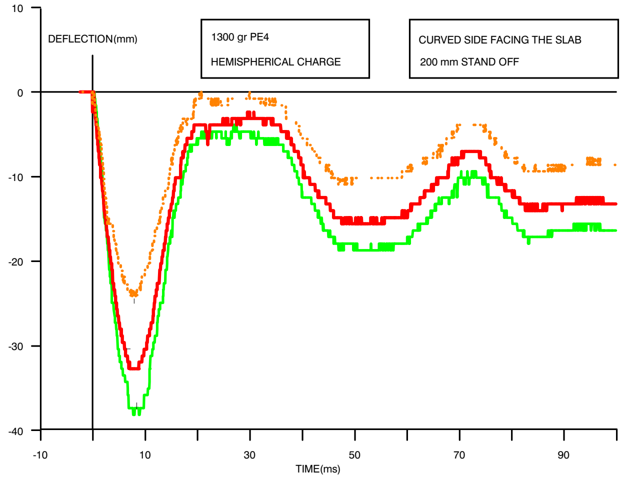


Figure 1

13. Describe the differences between the operation of resistance and inductance type displacement transducers.

Solutions

1. Relatively long duration ('soft'), typically 50 to 200mS duration

   Vehicles often designed to crush up in order to absorb energy (protecting passengers)

   Normally impact will not be head on. In these cases often a tendency for vehicle to rotate, sometimes causing a second impact when the rear of the car impacts.

2. Install accelerometers at centre of gravity of vehicle (allow force-time history to be obtained)

   Consider installation of crack detectors to monitor growth and spread of cracks in impacted wall.

   Use devices to measure movement of wall - e.g. high speed camera from above or displacement transducers behind wall to allow profile of out-of plane movements to be obtained.

   Use conventional or high speed video to monitor position of car - containment criteria include specification that vehicle should not be deflected into oncoming traffic.

3. From known response of unreinforced masonry walls may expect wall to form fracture lines, allowing two short sections of the wall either side of the impacted zone to then undergo gross rotations (effectively a 3-pin arch).

4. Use pendulum, drop hammer/rotating quadrant device or similar. Need to use device to attenuate the applied load (to replicate car crush characteristics). Could use timber or metallic honeycomb crushblock.

5. Advantages- lack of mechanical contact ensures:

   -transducer does not affect results (no mass attached to object)

   -sensed object free to undergo angular displacements without damaging gauge

   -ease of setting up

   Disadvantages -expensive

   -optical path may be obscured by smoke (e.g from explosion)

   -object must be light coloured and non-reflective

6. Very small inaccuracies in the measured accelerations will lead to large inaccuracies in the implied displacement when results are integrated over a long period of time. e.g. cantilever vibrating with max. acceleration of 200g. Zero offset (error) of just 1g (0.5% of full scale) will lead to error in predicted displacement = $at^2/2 = 9.81 \times 0.5^2/2 = 2.45$m after 0.5seconds.

7. Among the potential problems in shock testing are:

(1) Containment of the test item and any debris that may result from the test.

(2) Rugged and reliable data systems which may be required to withstand shock loads as well.

(3) Tailoring the shock pulse to meet the test requirements.

(4) Maintaining alignment of the test rig or test item and the source.

(5) Test system safety for operators and equipment (e.g. interlocks, alarming systems, firing systems).

(6) Adequate transducers and data acquisition systems which accurately read the high frequency shock pulses and measure the responses of the structural system or component.

8. a) Measurement processes depend on the calibrations of the instruments used. Calibration of the instruments relates the inputs they receive to the outputs they indicate. For example, a strain gauge based load cell is subjected to an applied force. The force produces a strain in the sensing portion of the load cell. The output of the load cell's measurement system indicates a voltage change. The voltage change is proportional to the applied force.

Calibration is quantifying and defining the relationships between known inputs and observed outputs and the uncertainties associated with the two measurement processes. In each case it is necessary to have a known reference which is traceable to some accepted standard (for example BS), a calibration procedure which is repeatable and supplies the known condition, and a measurement device calibrated using the reference and accepted procedure

There are two basic approaches to calibration:

(1) relating the operation of a transducer or device and its output to that of a known standard so the history of the instrument can be developed and documented, and

(2) modifying the equations or factors governing the constants used to convert the measured output (e.g. voltage) to the needed indication of behaviour (e.g. strain, acceleration).

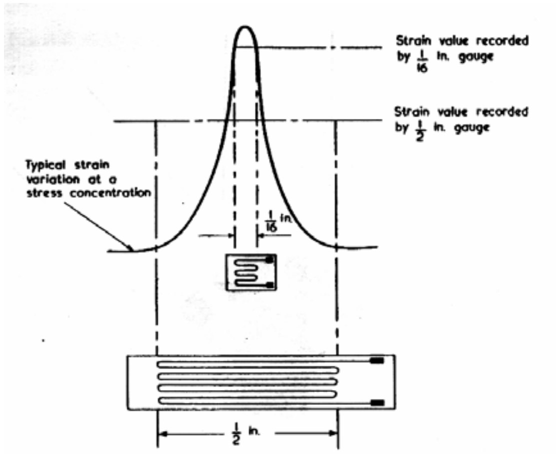
b) They are both conducted against the known quantities - pressure gauge against the static pressure generated by known weights, an RPDT against known lengths

9. Digital oscilloscopes offer significant improvements in accuracy resolution and storage capacity when compared to analogue ones which, in essence, had no storage capacity..... Also the horizontal scale of the Cathode-ray tube screen is not in terms of frequency but is calibrated in terms of time per point of data...... An analogue to digital converter digitises the input signal voltage and stores the bits in a solid-state memory much like a computer. With a 12 bit system the data is measured 2^{12} i.e. 4096 times over a designated time period - vertical resolution. At any time the observer can “freeze” the display by storing the currently displayed “block” of data in a second memory buffer which keeps that “block” of data displayed on the screen. Modern digital oscilloscopes have a resolutions of 16 bits i.e. $1/2^{16}$ or 1.5×10^{-3} %. This is about 5 orders of magnitude better than the analogue oscilloscope.

10. a) The diaphragm may be mounted parallel or perpendicular to the flowing stream. If the stream velocities are large, the mounting direction is important since the parallel diaphragm will sense true steady state pressure and the perpendicular diaphragm will measure total or stagnation pressure (steady state plus velocity head).

b) The strain gauge may be used to measure the “deflection” of the pressure-sensing diaphragm for pressure loading. By deflecting the diaphragm the pressure will induce the strain in the strain gauge wires, which can then be translated in to a voltage difference - i.e. analogue form of the result.

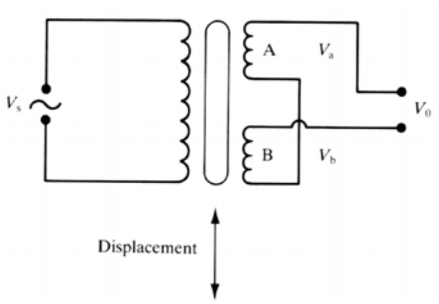
11. In stress wave type of application the strain gauge length is very important because the strain recorded is the average strain over its length. Generally, the shorter the strain gauge the better. This is best demonstrated in the figure bellow.

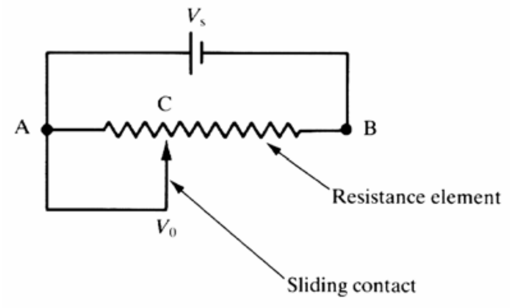


12. a) 38.2 mm in 7.5 msec b) 5.1 m/sec c) 16.4 mm

13. The main difference between them is that whilst in the case of LVDT the central iron core travels between the primary and secondary wire windings

inducing the voltage in secondary windings, the Resistive potentiometers consist of a resistance element and a movable contact - see the figure below.





Principle of operation a) LVDT b) Resistance Potentiometer

University of Sheffield

Department of Civil and Structural Engineering

CIV 615: Blast and Impact

Possible Exam Questions

(Questions and Answers)

by Nebojša Đuranović

Q1:

Try to state potential problems when carrying blast load testing. Could you think of any particular example ?

A1:

Among the potential problems in shock testing are:

(1) Containment of the test item and any debris that may result from the test.
(2) Rugged and reliable data systems which may be required to withstand shock loads as well.
(3) Tailoring the shock pulse to meet the test requirements.
(4) Maintaining alignment of the test rig or test item and the source.
(5) Test system safety for operators and equipment (e.g. interlocks, alarming systems, firing systems).
(6) Adequate transducers and data acquisition systems which accurately read the high frequency shock pulses and measure the responses of the structural system or component.

Q2:

a) Explain in you own words the meaning of "instrument calibration" and the main types of calibration. b) In what respect are static load pressure gauge calibration and RPDT calibration similar.

A2:

a) Measurement processes depend on the calibrations of the instruments used. Calibration of the instruments relates the inputs they receive to the outputs they indicate. For example, a strain gauge based load cell is subjected to an applied force. The force produces a strain in the sensing portion of the load cell. The output of the load cell's measurement system indicates a voltage change. The voltage change is proportional to the applied force.

Calibration is quantifying and defining the relationships between known inputs and observed outputs and the uncertainties associated with the two measurement processes. In each case it is necessary to have a known reference which is traceable to some accepted standard (for example BS), a calibration procedure which is repeatable and supplies the known condition, and a measurement device calibrated using the reference and accepted procedure

There are two basic approaches to calibration:

(1) relating the operation of a transducer or device and its output to that of a known standard so the history of the instrument can be developed and documented, and

(2) modifying the equations or factors governing the constants used to convert the measured output (e.g. voltage) to the needed indication of behaviour (e.g. strain, acceleration).

b) They are both conducted against the known quantities - pressure gauge against the static pressure generated by known weights, an RPDT against known lengths

Q3:

What are the main advantages of a modern day digital over an analogue oscilloscope ?
A3:

Digital oscilloscopes offer significant improvements in accuracy resolution and storage capacity when compared to analogue ones which, in essence, had no storage capacity..... Also the horizontal scale of the Cathode-ray tube screen is not in terms of frequency but is calibrated in terms of time per point of data...... An analogue to digital converter digitises the input signal voltage and stores the bits in a solid-state memory much like a computer. With a 12 bit system the data is measured 2^{12} i.e. 4096 times over a designated time period - vertical resolution. At any time the observer can "freeze" the display by storing the currently displayed "block" of data in a second memory buffer which keeps that "block" of data displayed on the screen. Modern digital oscilloscopes have a resolutions of 16 bits i.e. $1/2^{16}$ or 1.5×10^{-3} %. This is about 5 orders of magnitude better than the analogue oscilloscope.

Q4:

a) How does the relative position of pressure gauge diaphragm to the flowing pressure stream influences the measured results ? b) Explain the purpose of a strain gauge as a part of a pressure gauge.

A4:

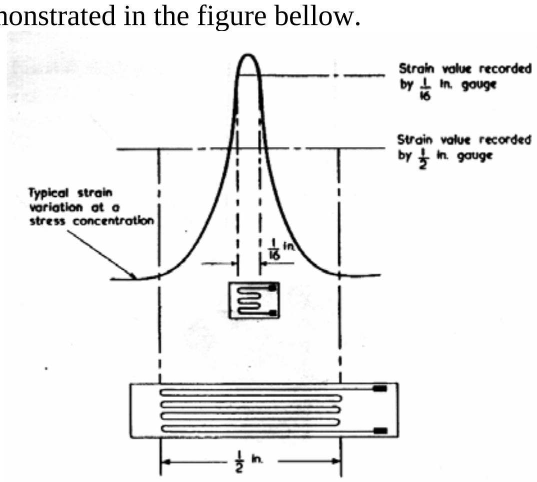
a) The diaphragm may be mounted parallel or perpendicular to the flowing stream. If the stream velocities are large, the mounting direction is important since the parallel diaphragm will sense true steady state pressure and the perpendicular diaphragm will measure total or stagnation pressure (steady state plus velocity head).

b) The strain gauge may be used to measure the "deflection" of the pressure-sensing diaphragm for pressure loading. By deflecting the diaphragm the pressure will induce the strain in the strain gauge wires, which can then be translated in to a voltage difference - i.e. analogue form of the result.

Q5: What is the importance of the strain gauge size when used for stress wave type measurements ?

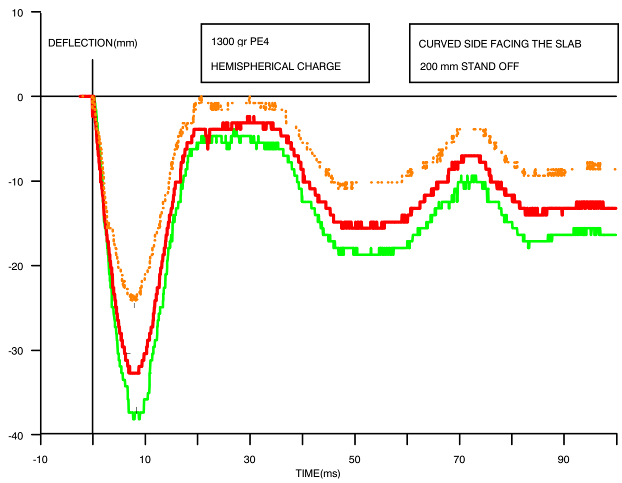
A5:

In stress wave type of application the strain gauge length is very important because the strain recorded is the average strain over its length. Generally, the shorter the strain gauge the better. This is best demonstrated in the figure bellow.



Q6:

Using the graph below try to establish a) peak deflection and time needed to reach peak displacement, b) peak deflection rate, c) peak residual deflection

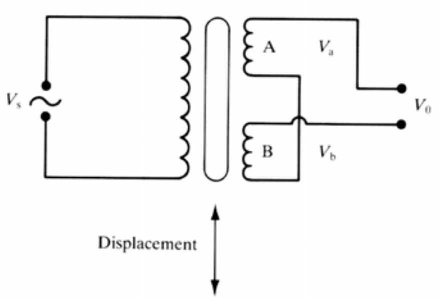


Q7:

Describe the differences between the operation of resistance and inductance type displacement transducers.

A7:

The main difference between them is that whilst in the case of LVDT the central iron core travels between the primary and secondary wire windings inducing the voltage in secondary windings, the Resistive potentiometers consist of a resistance element and a movable contact - see the figure below.



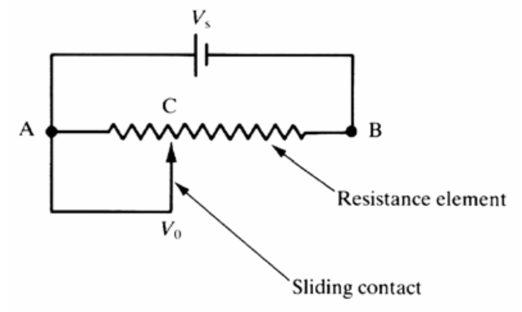


Fig 3.10 - Principle of operation a) LVDT b) Resistance Potentiometer

Real Exam Questions

Q1.

a) Give the operational principles of three types of transducers used to measure the transient response of structures under dynamic loading; identify the important advantages of each type and show how they are used in practice. (30 marks)

b) With reference to one series of laboratory experiments where these types of transducers were used, describe the experiment, typical results obtained from the transducers and the structural behaviour indicated by these results. (20 marks)

A1.

a)

Digital displacement transducers	⇒	termionic emission electron beam deflecting resolution and storage advantage to analogue type oscilloscope used for capturing and temporary storage of blast test data
Pressure gauges	⇒	flash diaphragm type transducers, relative position to blast wave measuring device type (strain gauges, LVDTs. piezo electric,) used formeasuring blast pressure waves (positioning and protecting the gauge, amplifying the signal, establishing pressure profiles)
Strain gauges	⇒	Electrical resistance type S.G. change in resistance (i.e. length) proportional to output voltage importance of the size of the gauge for stress wave type applications used for reinforcement strain measurements
Displacement transducers	⇒	inductive type: travelling core of the transducers induces the current in secondary wire windings resistive type: potentiometric change of output due to movement along the resistive surface used to measure deflection of slab under blast loading
High speed camera	⇒	rotating prism type synchronisation of events motion analysers used for detailed film analysis used for filming underside of blast loaded slabs

b)
Blast Testing on R.C. Slabs

Experiment description:

- Scaled tests (small scale, large scale)
- Close range charges
- Charge scaling (geometrical scaling)
- Features of the test site (open space chamber, debris containment, max. charge size)

Results:

Pressure gauges ⇒	overpressure profiles across the slab surface comparison to theoretical results description of the pressure vs. time curve spatial and transient change in positive duration and peak pressure
Strain gauges ⇒	strain vs. time record peak strain, peak strain rates, residual strain
Displacement transducers ⇒	raw and calibrated results deflection vs. time trace, peak and residual deflection, deflection rate deflection profile difference in deflection profile under close range blast and assumed static deflection i.e. indication of local response
High speed films ⇒	early stages of crack formation crack propagation establishment of crack patterns crack velocity and size monitoring