JAMES COOK CYCLONE STRUCTURAL TESTING STATION

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LOAD AND DEFLECTION INSTRUMENTATION FOR STRUCTURAL TESTING

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LOAD AND DEFLECTION INSTRUMENTATION FOR STRUCTURAL TESTING

G.N. Boughton *

SUMMARY

This publication details the operation of an Instrumentation System to record and process on a computer, load and deflection information obtained during tests on a wide range of building products and assemblies. The system was designed to minimise the accummulation of errors during the test, but to have an adequate sampling rate and resolution. Satisfactory levels of precision have been achieved at surprisingly little cost using custom-built displacement transducers, remote analogue to digital converters and digital data transmission to a micro computer.

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LOAD AND DEFLECTION INSTRUMENTATION FOR STRUCTURAL TESTING

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1. INTRODUCTION

Since 1977, the Cyclone Testing Station has been directly involved in the testing of large number of building components and assemblies ranging from nailed joints to complete houses. The tests have provided answers for manufacturers interested in that specific product, or as part of research projects, contributed to a greater understanding of the way houses resist high winds, but they have all involved the collecting, checking and processing of load and deflection data.

In the past deflections have been measured using dial gauges, and this still proves the most cost effective method for small one-off tests, but for repetetive tests or tests where large amounts of information must be processed the dial gauges have a number of shortcomings.

(i) Many components of structural systems used by the building industry exhibit creep under load. This creep can be significant if the time taken to read all the gauges is of the order of a minute, and the extra deflections can lead to a false picture of the test specimen behaviour.

(ii) As dial gauges have to be viewed to have their readings taken, their location is limited, and movements of people reading the gauges can lead to accidental movement of the specimen or the gauge datum.

(iii) The use of dial gauges allows two sources of transcription errors - one in reading the dial face, and the other in transferring that reading to a data base.

Recognising these short comings, testing programmes have incorporated many checks to ensure that errors are minimised, and that mistakes are eliminated. However the laborious nature of the data collection, checking and reduction processes has consumed many man hours that could have been more productively spent on other assignments.

An instrumentation system was therefore developed that would allow the readings to be taken quickly and transferred directly to a digital computer data base. The system was designed so that many different deflections could be measured within a few seconds, checked and reduced within a fraction of a second and displayed in a way that would enable test personnel to make accurate assessments of the test's progress.

This publication briefly outlines the system developed and the economical displacement transducers built.

2. AIMS AND OBJECTIVES OF THE INSTRUMENTATION SYSTEM

The primary aim was to develop a general purpose instrumentation system that would rapidly and accurately transfer physical measurement to a digital computer at minimal cost. A major requirement was that the system be versatile: in some tests such as nail pull out tests one or two deflection measurement points only would be required, whereas for a cyclic house test, over 50 deflection measurement points, 2 load measurement points and feed back to a load control valve may be required. Thus it was desired that the system was not too cumbersome to easily monitor simple tests yet capable of expansion and easy installation to monitor more sophisticated tests such as the cyclic house tests.

The main physical quantities to be measured, were load and deflection, with expected deflections ranging from one or two to 50 mm, and loads of up to 50 kN per loading point. The large range of expected physical quantities to be measured had to be achieved without unduly sacrificing the accuracy of the system. The measurement system was often used in conjunction with loading machines that have quite high electric power requirements and strong magnetic fields in the vicinity of the motor, and the data acquisition and transmission had to be insensitive to these electro magnetic interferences. The transducers and signal interpretation also had to be stable over a long time span, so that the drift of the instrumentation system between calibrations was minimal.

2.1 Definition of System Properties

The terms used to define the requirements and performance of the complete system will be examined prior to a statement of the system objectives.

(i) Resolution: The smallest interval that can be measured by the system (often expressed as a percentage of full scale measurement), eg. a scale rule, 300 mm long, graduated in mm, can resolve a distance to the nearest mm. Its resolution would be 1 mm or 1/300 of the full scale reading ie. 1/3%.

(ii) Long Term Drift: The deviation from a "true" reading when measured over a long period (one week). eg. if a 200 mm long bar is measured with a rule continuously for one week and the maximum reading obtained was 201 and the minimum was 199, the long term drift over that period was ±1 mm. Again if the full scale measurement of the rule was 300 mm then the long term drift is ±1/3% of full scale reading.

(iii) Deviation from linearity: The deviation from the linear reading when assessed over the full range of the instrument. eg. A car speedometer is usually fairly linear at low speeds, even though it may not necessarily be accurate.

eg. 10 km/hr may indicate 11 km/hr.
20 km/hr may indicate 22 km/hr.
30 km/hr may indicate 33 km/hr.

ie. no deviation from linearity over 0 - 30 km/hr range. However at higher speeds they are usually quite non-linear.

80 km/hr may indicate 92 km/hr instead of 88.
100 km/hr may indicate 118 km/hr instead of 110.

The maximum non linearity over the 0 - 100 km/hr range then is 8 km/hr - ie. 8% of full scale reading.

(iv) Hysteresis: The difference between characteristics for compression of the transducer and those for the release of the transducer. eg. a 100 kN capacity load cell reads 51 kN when a true load of 50 kN is reached while increasing the load, and reads 49 kN when a true load of 50 kN is reached in the unloading cycle the hysteresis is therefore 2 kN or 2% of full scale load.

(v) Sampling rate: The rate at which measurements can be taken. eg. If it takes 10 seconds to read and check a dial gauge and 5 seconds to note and check the reading, the sampling time is 15 seconds and the sample rate is 4 per minute.

(vi) Range: Full scale reading of the measurement instrument. eg. a

300 mm long scale rule has a range of 300 mm.

(vii) Accuracy: The overall accuracy of the measurements obtained in tests is affected by all of the above errors with their effects usually additive. The measurement errors are usually compounded by a mathematical analysis so that measurements accurate to 1% of full scale reading may produce analysed results with an accuracy of only 5%.

2.2 Summary of System Objectives

(i) Resolution: The desired resolution was fixed at better than 1% of full scale reading. This would permit results of most tests to be reported to within 5% after allowing for some mathematical operations.

(ii) Long Term Drift: ±½% of full scale reading.

(iii) Deviation from linearity: ±½% of full scale reading.

(iv) Hysteresis: 1% of full scale reading.

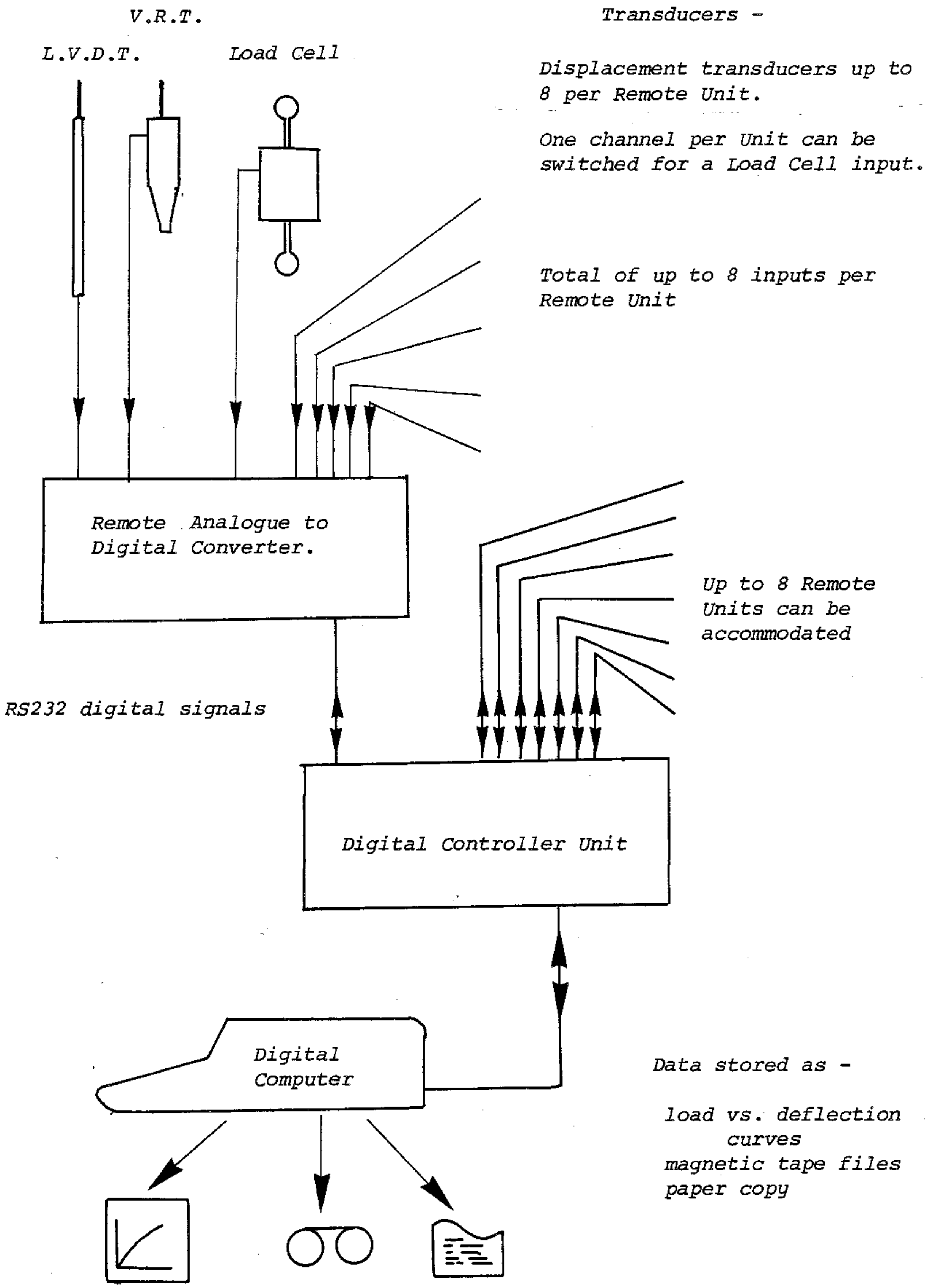
(v) Sampling frequency: more than 5 transducers per second.

(vi) Range - Deflection: variable up to 50 mm.
- Load: variable up to 50 kN.

As can be seen from the above objectives, the resolution sets the criteria for all other properties. The resolution represents the maximum level of accuracy it is possible to achieve, so errors significantly greater in magnitude than the resolution, seriously jeopardise the accuracy of the whole system.

3. THE INSTRUMENTATION SYSTEM

With these objectives in mind, an Instrumentation System has been designed, constructed, tested and used by the Cyclone Testing Station. To date its usage has been primarily for deflection measurement on large research projects and some commissioned testing of building products. A schematic diagram of the complete System is shown in Figure 1. The salient points are treated



Transducers -

Displacement transducers up to 8 per Remote Unit.

One channel per Unit can be switched for a Load Cell input.

Total of up to 8 inputs per Remote Unit

Up to 8 Remote Units can be accommodated

Data stored as -

load vs. deflection curves
magnetic tape files
paper copy

Figure 1. Schematic Sketch of Instrumentation System

in this publication under separate headings. Displacement transducers of two types can be accommodated by the system. These are commercially available "dc output Linear Variable Differential Transformers", abbreviated by LVDTs and the Variable Resistance Transducers (VRTs) manufactured by the Station. Both of these types of transducers are discussed in detail in section 4. Transducers used for load measurement are discussed in section 5, and the remainder of the System is briefly outlined in the remainder of this section. As a complete description of each device is rather long winded each will be abbreviated as follows:

Remote Analogue to Digital Converter Unit - Remote Unit.
Digital Controller Unit - Controller
Digital Micro Computer - Computer

3.1 Remote Analogue to Digital Converter Units

As their name suggests, these devices are located close to the measurement points and convert the sensitive voltage signals output from all of the transducers to more reliable digital signals for transmission over longer distances, and past power leads, motors, lights which could otherwise corrupt the analogue signals. Physcially, each Remote Unit is a black box approximately 250 x 200 x 100 mm in size and is powered by 240 V mains current. It has eight sockets on the front panel to receive the transducer plugs and a plug to connect the digital signals to the computer. On the back of each box is facility to calibrate each transducer individually.

The displacement transducers require a steady 12 V power supply, and the load transducers a steady 2.5 V power supply. The Remote Units incorporate carefully regulated power supplies and protection so that transducer power is independent of mains voltage fluctuations such as often occur when large motors start, or from short circuits in other transducers connected to the same Remote Unit. Given the steady power supply, each transducer returns a voltage proportional to the quantity being measured (displacement or force). These signals, often called analogue voltage or analogue signals are continuously available at the Remote Unit whenever power is turned on. They are only converted to a digital signal when prompted by the computer with a signal on the control line. As each Remote Unit supports up to eight transducers, the control signal from the Computer must identify the transducer to be read. Thus the computer prompts the Remote Unit with the number of the channel of the appropriate transducer. This number is decoded in the Remote Unit, the correct analogue voltage converted to a digital signal and the digital signal returned along the control line. The digital signals are transmitted as a series of zeros and ones along a single wire using an industry standard format designated RS 232, taking just over one thousandth of a second to transmit the data from one transducer. Each signal is a number between 0 and 255, with the full scale reading as 255. This divides the complete range of the transducer into 256 equal spaces and gives a resolution of better than 0.4% of full scale reading. The transmitted number can then be converted to a force or deflection by multiplying by calibration factors within the computer.

3.2 Digital Controller

The RS 232 signals to and from the Remote Units are compatible with most digital computers, but would only give a system capacity of 8 transducers. The Digital Controller provides a means of including other remote units. At present the Digital Controller has the capability of communicating with 8 Remote Units, one of which has been reserved for controlling a cyclic loading system. This leaves the present system with a capacity of 56 transducers through 7 Remote Units.

In operation, the Controller functions largely as does a telephone exchange with one control line to the Computer and a control line connecting it to each Remote Unit. As the Computer reads each transducer in turn, it sends the number of the next transducer to be checked to the Controller. The Controller relays that number to the appropriate Remote Unit only, leaving all of the others disconnected, and it passes the reading sent by the only valid Remote Unit on to the Computer. It too is housed in a 250 x 200 x 100 mm black box and can be mounted close to the Remote Units so that only one control line is necessary to link the measurement system to the Computer.

3.3 Pump Control Unit

One of the Remote Units connected to the Controller is permanently mounted on a hydraulic pump and can be used to control a cyclic loading sequence. Rather than being used to feed information into the Computer it is used to perform functions as directed by the Computer. A summary of the instructions that this unit can respond to is given below.

(i) Turn Pump Motor on.

(ii) Turn Pump Motor off.

(iii) Turn Solenoid Valve on.

(iv) Turn Solenoid Valve off.

(v) Activate Loading Cycle (*)

(vi) Terminate Loading Cycle (*)

(vii) Activate Unloading Cycle (*)

(viii) Terminate Unloading Cycle (*)

The instructions marked (*) give the Computer an indication as to whether the Unit has correctly responded to the instruction within one fortieth of a second.

These instructions can be used in conjunction with load cells to perform the following sequence.

1. Turn Pump on.

2. Activate Loading Cycle.

3. Check load, if it is greater than maximum allowable load, Terminate Loading Cycle.

4. Read Displacement Transducers.

5. Activate Unloading Cycle.

6. Check load, if it is less than the minimum limit of the cyclic load program, Terminate Unloading Cycle.

7. Read Displacement Transducers.

8. Go. to step 2.

A sequence of instructions similar to the one in the above example has been used by the Station to cyclicly apply simulated wind loads to a complete house. With suitable computer controlled safeguards to prevent overloading, the system ran continuously, without fault for over 36 hours.

The solenoid valve can be used to give more flexibility to the pump control unit by allowing two hydraulic circuits to be controlled at once.

3.4 Digital Computer

This device is crucial to the correct operation of the Instrumentation System. The Computer:

- sends the prompts that read each transducer in the correct order.
- converts the digitised transducer reading to a meaningful physical quantity with calibration coefficients.
- presents the data obtained in a useful manner.
- stores the data for further processing.

While the Computer is a very important part of the Instrumentation System, the System has been designed so that many different types of computer could be connected to it if necessary. The use of an industry standard control line configuration (RS 232) means that any Computer fitted with a port for RS 232 connection can be used in conjunction with the Instrumentation System.

Some examples of the types of programs used with the Instrumentation System are given in Section 6.

3.5 Summary of System Specifications

(i)	Resolution	0.4% of full scale reading.
(ii)	Long Term Drift (1 week)	LVDT 0 VRT ±0.4% of full scale reading.

(iii) Deviation from linearity	LVDT 0.4% of full scale reading. VRT 1% of full scale reading.
(iv) Hysteresis	LVDT 0.4% of full scale reading. VRT 1.2% of full scale reading.
(v) Sampling frequency	9 transducers per second.
(vi) Data transmission	8 bit digital number RS 232 format with 1 stop bit, no parity bit, 9600 baud.

It can be seen that the System objectives have generally been exceeded by the LVDTs, and compromised only for hysteresis and linearity by the VRTs. The sampling frequency is particularly pleasing as it reduces the reading time for 40 gauges to just over four seconds and does not allow creep to influence readings to a large extent.

4. DEFLECTION MEASUREMENT

As mentioned in the previous section, two different types of displacement transducers were employed in the Instrumentation System.

4.1 Linear Variable Differential Transformer (LVDTs)

These are commercially produced highly accurate devices that do not use any moving electrical contacts. The displacement of an iron core induces voltage in windings in the annular body of the device. The particular units chosen for this system required a dc voltage to power them, and produced a dc voltage proportional to the displacement of the iron core. The stability and linearity of the LVDTs was very good due to precision in manufacture and the lack of moving electrical contacts contributed to the lack of hysteresis in their response.

Their characteristics were ideally suited to the System but their expense precluded the purchase of many of them. The tendered prices on suitable dc-dc spring loaded LVDTs were of the order of $400 - $500 each. Over the past year, the Station has acquired eight of these devices which will be used as a check on VRT performance and to calibrate the less expensive but more robust VRTs.

4.2 Variable Resistance Transducers (VRTs)

These are devices that operate using a moving contact variable resistor, very similar in principle to the volume controls on hi-fi equipment. These too are commercially available, but the Station has built its own stock of 50 of these units using replacement volume control slider potentiometers for hi-fi amplifiers. Because these sliders were not manufacturered for high precision usage, the linearity of the VRTs is not as impressive as the LVDTs, and friction of the sliding electrical contact contributed to hysteresis in their output. The usable range of the VRTs varies from 32 mm to 45 mm, so they fall marginally short of the project requirements as far as hysteresis and range is concerned but their attraction is their low price. Approximately $5 worth of materials and one hour of technician time each is required to manufacture them.

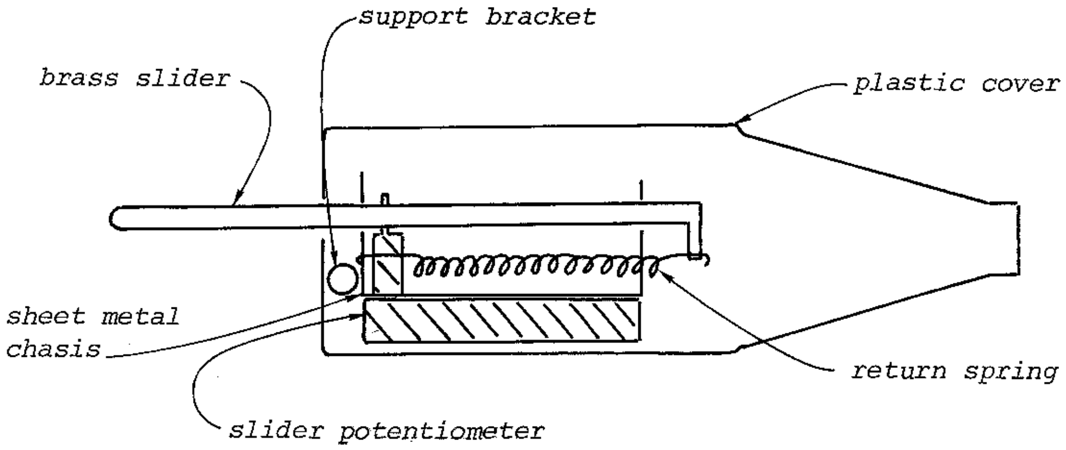


Figure 2 Construction of V.R.T.

A sketch of a VRT as produced by the Station is shown in Figure 2.

This sketch shows the five main parts of the VRT. A sheet metal chasis locates all the other parts of the device. The movement is experienced by the brass slider which moves the slider of the potentiometer. The return spring ensures that the brass rod is in contact with the moving surface at all times, and the plastic cover helps to keep dust and moisture out of the moving electrical contacts.

A series of tests was conducted to determine durability and long term stability of these devices. These included:

(i) Calibration prior to and after 12000 cycles of zero to full scale and back to zero with no change in calibration constant.

(ii) Calibration prior to and after complete saturation of the device, with water yielding no change after allowing 20 minutes to dry out.

(iii) Exposure to direct sunlight, evening dew and a 15°C diurnal temperature variation over a 24 hour period yielding a 0.4% change in reading.

(iv) Exposure to diurnal temperature variations but not to dew over a 1 week period resulting in ±0.4% of fullscale change in reading. Calibration prior to and after dropping the transducer 5 times onto a concrete floor from a height of 3 metres with no change in calibration constant.

(v) Exposure of the slider potentiometer to an extremely dirty environment which resulted in the mechanical failure.

The extremely good performance of the transducers under these conditions has given confidence in their long term performance provided dust is kept out of the sliding contacts.

The VRTs will be used for the majority of displacement measurements in the course of the Station's testing and can be placed in vulnerable positions without fear of substantial loss if damage should occur as a result of a local failure.

Although the electrical characteristics of LVDTs and VRTs were significantly different, the Remote Analogue to Digital Converter Units have sufficient flexibility to operate either device in all eight input channels.

4.3 Calibration of Displacement Transducers

Both VRTs and LVDTs return a number from 0 to 255 which is proportional to displacement from the zero position. For most testing, it was the difference between the final and initial positions that is of importance. This could be found by knowing the numbers returned by the transducer at initial and final position, and the calibration constant of the transducer.

For a 50 mm LVDT the calibration constant was typically 0.20 mm per division and for a VRT with a 30 mm range 0.13 mm per division. These constants could be found by comparing say 30 points in the range of the transducer with known displacements. LVDTs were calibrated against precision dial gauges, and VRTs were calibrated against previously calibrated LVDTs.

Examples of calibration curves and some statistical information on the calibration of the transducers is included in Appendix A.

5. LOAD MEASUREMENT

Provision has been made in each Remote Unit for one channel to be switched to receive input from a strain gauge load cell. These load measurement devices return a voltage proportional to the measured load, but the voltage is very small and needs to be amplified by very high gain, temperature compensated amplifiers. These devices are therefore very much more susceptible to corruption from other power leads, motors and also direct sun on the load cell or the Remote Unit.

The load cells presently used are commercially available tension/compression strain gauge load cells with an impedance of 350Ω, but sufficient flexibility has been built into the Remote Unit to accommodate other types of load cells. Unlike deflection, load is an absolute quantity - zero load does not vary from location to location, however, in performing uplift tests, it is desirable to subtract the weight of the load spreading devices from the load applied to give the true uplift. Thus some zero compensation within the Computer was still neccessary.

5.1 Summary of Specifications of Load Measurement

(i)	Resolution	0.4% of full scale reading.
(ii)	Long Term Drift (24hrs)	±1% of full scale reading.
(iii)	Deviation from Linearity	1% of full scale reading.
(iv)	Hysteresis	0.2% of full scale reading.

In most respects, the properties of this system are similar to those of the VRTs, but the long term drift associated with the load cell and amplifier is larger than for the other transducers because of induced stray currents in leads. However the use of the load measurement system has proved quite satisfactory in practice.

6. CASE EXAMPLES OF INSTRUMENTATION SYSTEM USE

Two case studies will be examined to illustrate the operation of the System in two extreme examples. The first is a simple nail shear test, and the second is the monitoring of a cyclic load test on a complete full scale house. Even though the scale of operation for the two examples is vastly different, the same basic principals apply.

(i) Setting up for the test - positioning of transducers, feeding in calibration information, determining reading sequence.

(ii) Reading and storing the data as required.

(iii) Processing, printing and/or plotting the data for examination.

(iv) Detailed post testing analysis of the data.

Each of the principals listed above depends heavily on the computer for correct sequencing and performance of data storage and transfer operations. The operations are presented in Figure 3. The operations presented in the first two dashed boxes are essential to the operation of the Instrumentation System and those in the last two dashed boxes are necessary to process and

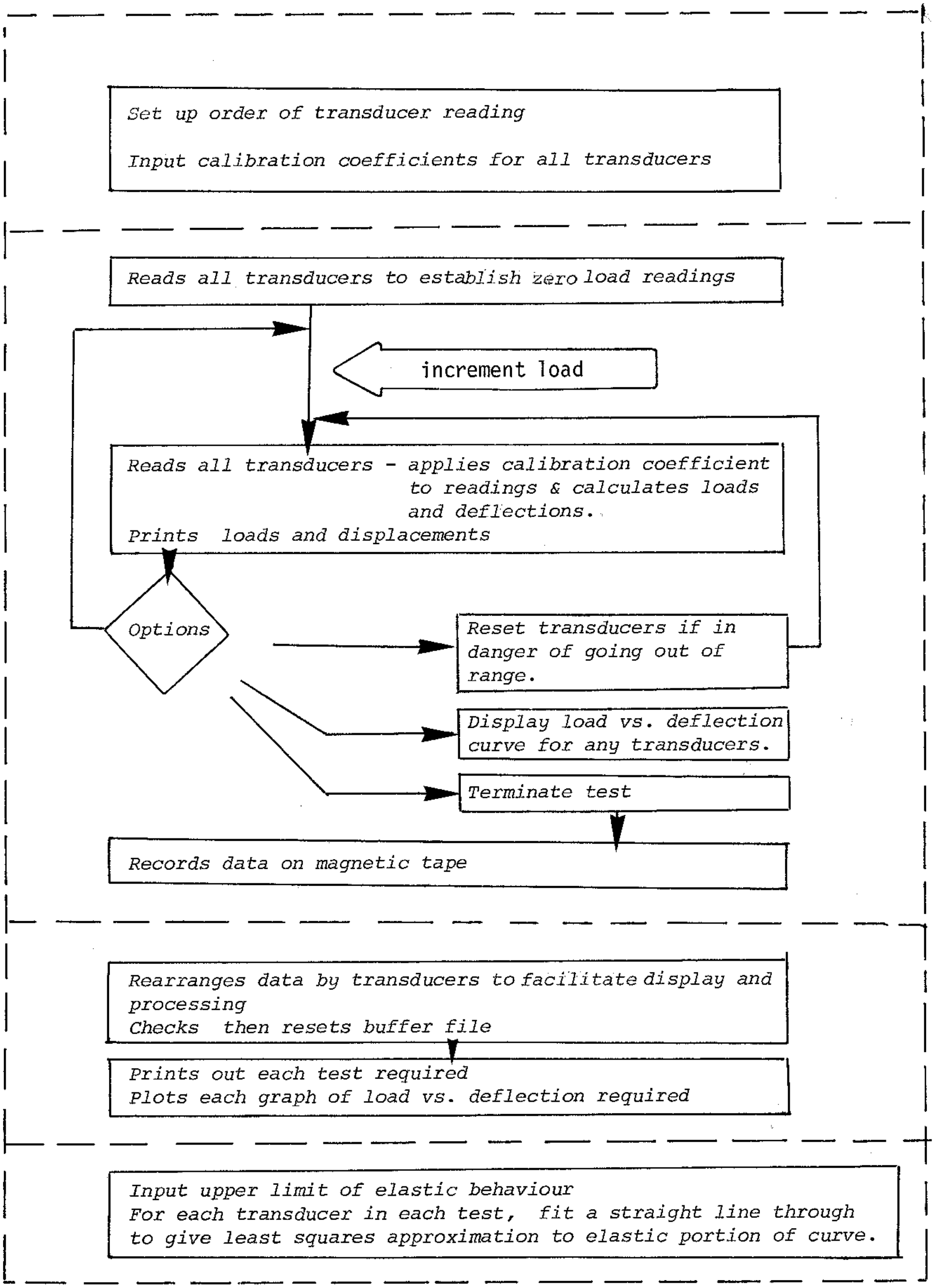


Figure 3 Basic Flow Chart of Computer Programs

check large amounts of data and are as such, options.

6.1 Case Study of Nail Shear Tests

In these tests two pieces of wood were joined using a metal plate with nails driven through it across the grain of the timber and then pulled apart so that the nails acted in shear. The primary objective was to determine the ultimate load of the joint, but if deflections could have been read and plotted against load during the performance of the test without slowing the process, then additional information about mechanisms of failure would also have been made available. Two deflection transducers were used - one on each side of the joint and load was applied in a universal testing machine. As only two deflection transducers were used, one Remote Unit was required and the output from it was fed directly to the Computer. The Controller was not required.

A single computer program was utilized which accomplished the following sequence.

(i) Start - checked position of both transducers - allowed adjustments to be made if necessary.

(ii) Read deflections at zero load, indicated readiness for testing.

(iii) While load steadily increased, the operator input load magnitude and pressed a cue button at the instant the load was reached. The deflections were read within 1/5 of a second giving negligible load increase during the measurement period.

(iv) At the completion of the test, all deflections were printed out individually and as the average of the two measurements for each load increment. The Load vs average deflection curve was also plotted.

(v) Returned to (i) ready for the next test.

The data aquisition took place within the normal time taken for the tests, and plotting and presentation of the data was performed while test specimens were changed in the loading frame. The results were in a form that allowed quick assessment of the test by simply examining a graph and provided very quick documentation of the test. The single program, once written facilitated the data aquisition in this series of tests and will remain available for use in conjunction with other joint tests should they be required.

The setting up of the Instrumentation System involved plugging the Remote Unit in to mains power and the Control Line into the Computer, mounting the two transducers on the test piece and plugging their leads into the Remote Unit. The computer program was then loaded, and the system was ready to work. The total set up time was typically five minutes.

6.2 Case Study of Cyclic Loads on a Full Scale House

In contrast to the previous case study, the Instrumentation System was essential to the retrieval of any information from this test, and indeed to the actual performance of the test.

In this test hydraulic rams applied lateral loads equivalent to wind loads experienced in tropical cyclones to a complete house. The load was applied and released a number of times and at strategic points throughout the test, deflection readings at many locations on the house were taken to enable the determination of response of the building to the loads. The Instrumentation System was employed in the following way.

Over 50 displacement transducers and one load cell were used in the test. Thus all of the Remote Units were utilized and fed information to the Controller. The Controller was then connected to the Computer. Each displacement transducer was mounted on a scaffold erected next to the house, so that all displacement readings obtained could be related to the same datum - ground. In contrast with the nail withdrawal tests, the Instrumentation System took two men two hours to set up for work.

The tasks that the computer performed were divided into the four groups represented by the four dashed boxes shown in Figure 3 with each of these representing a complete program.

The first program assembled all of the calibration data required for each device and established the order in which the transducers were read. It also enabled the starting position of each transducer to be checked so that during the course of the test they stayed within their allowable range. All of the data thus assembled was stored on magnetic tape for access during the actual test and subsequent analysis.

The second program then enabled the test to be performed. At the commencement of the test, all transducers were read to determine their initial zero load positions. Then to facilitate the cyclic loading of the structure, the computer controlled the hydraulic loading system through the Pump Control Unit. Having determined the maximum and minimum loads and the number of cycles together with the places in the cyclic loading sequence at which readings were to be taken, the pump was turned on and the loading cycle activated. As the load increased, it was continually monitored by the load cell until the prescribed load was reached. At this point the loading cycle was terminated and if readings were required, all transducers read. The readings, adjusted by the calibration factors were immediately printed to allow test observers to examine the progress of the test. The unloading cycle was then activated and the load cell monitored until the minimum load was attained. The unloading cycle was then terminated and if necessary, all transducers read again. The System then repeated the load - unload cycle until the required number of cycles had been successfully completed. Numerous safeguards were built into the sequence to prevent accidental overloading of the structure in the event of any equipment malfunction. At the conclusion of the testing sequence, all of the readings - usually over 1000 - were stored on magnetic tape as a permanent easily accessed record of the test results.

The third program utilized in this test series was necessary because of the large number of transducers and readings taken during each test. The stored data was read from the magnetic tape and checked, then stored in a slightly different way so that later analysis was easier. At this point all of the readings taken could have been printed again, and selected key transducers had load vs deflection curves plotted out paper. This gave a good pictorial representation of the test results in a form that could be copied straight into reports.

The fourth program shown in Figure 3, represented by the last dashed box is typical of the first steps in an elastic analysis process. Where the test produced elastic behaviour, the results of that portion of the test gave load vs deflection curves that were nearly straight. A traditional least squares analysis was performed for each transducer over that straight line portion of the curve, and the results condensed to an effective elastic stiffness constants for each transducer. These constants were then used as the starting point of an elastic analysis to determine load sharing mechanisms within the house.

7. CONCLUSIONS

The Instrumentation System that has been described in this document has proved, and will prove to be a means of extracting the maximum information from tests with a minimum of extra effort.

The System has proved versatile in that it can be fully utilised on small scale tests, and also on very large scale tests where thousands of data items can be aquired, checked stored and analysed in a day.

The final System properties compared well with the initial objectives of the system, although a compromise has been reached on linearity of displacement transducers, and long term drift of load transducers, in order to achieve useful results with the money available at present. The total cost of the Instrumentation System as detailed here was less than $6,000 excluding design and development time.

8. ACKNOWLEDGEMENTS

The author is grateful to Dr Baden Best of the Civil and Systems Engineering Department, James Cook University, for his inspiration and encouragement, particularly at the very early stages of development. The author is also appreciative of the help of the Station's Technical Director, Mr Greg Reardon for his support and to Mr Jim Roberts, a Civil and Systems Engineering Department technician who assisted in the assembly of 2 Remote Units and the 50 VRTs.

APPENDIX A CALIBRATION OF TRANSDUCERS

All transducers must be calibrated so that the number that is returned to the computer can be translated into a physical measurement. The procedure for calibrating displacement transducers has been refined and is presented here. The procedure for calibrating load cells is similar.

The displacement transducer was mounted with the tip against a moving metal plate. The reference measurement was placed on the other side of the plate in line with the transducer to be calibrated. In this way, both transducers experienced the same displacement as the metal plate was moved up and down. For one the displacement was positive, the other negative. It was found convenient to mount the moving plate on a drill press as shown in Figure 4.

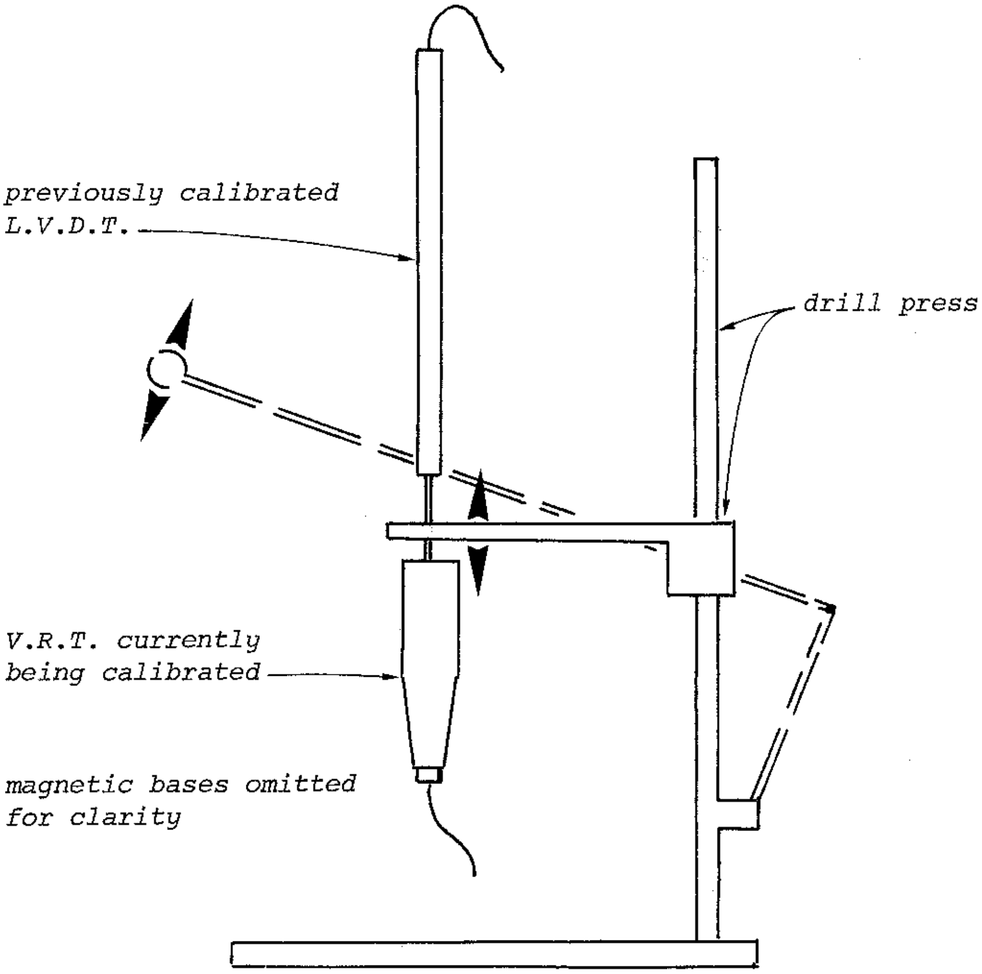


Figure 4 Calibration of V.R.T. against a L.V.D.T

Calibration of LVDTs

These devices were calibrated against precision dial gauges with a resolution of ±0.01 mm. A computer program was written that would accept the dial gauge reading and immediately record the reading on the LVDT. At the completion of the calibration in which a number of readings were taken, a least squares approximation was used to fit a straight line through the points. From this, a correlation coefficient could be calculated and a t-test performed on the calibration coefficient to determine its significance. A sample of the output is shown over.

Calibration of VRTs

These devices were calibrated against a previously calibrated LVDT with a resolution of ±0.10 mm. A different computer program was written, in which as the drill press was slowly moved, the LVDT was continuously monitored by the computer. Every 2 mm of travel, the VRT was read which gave 15 points over each direction of travel of the drill press. Again, at the completion of a downward and upward movement over the full range of the VRT, a least squares approximation was used to fit a straight line through the points, the slope of which gave the calibration coefficient. A correlation coefficient, t-test value and deviation from linearity was calculated for the calibration. A sample of the calibration output is shown over.

Results of the Calibrations

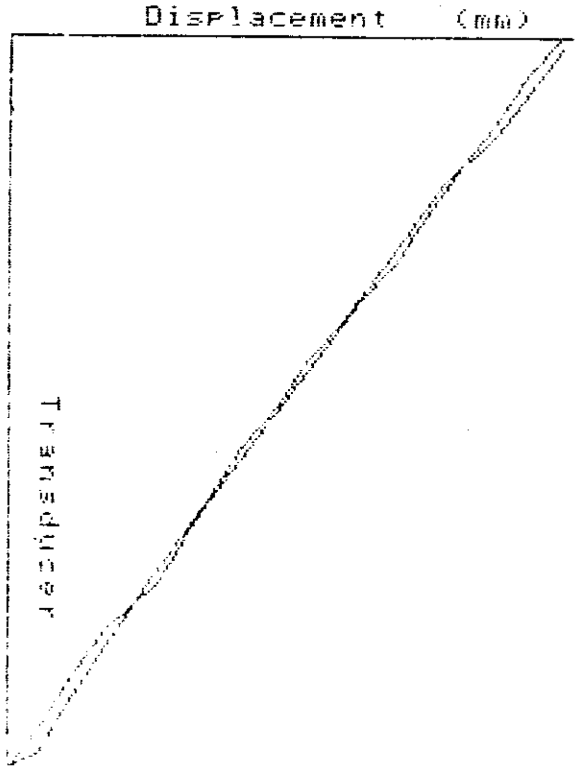
As can be seen for the sample calibration plots, the correlation coefficients were very close to 1 and the t-test indicated a high significance in the calibration coefficient for both types of devices. This gives confidence in the use of a straight line approximation for the two types of transducers. The LVDTs showed no sign of hysteresis at all and the hysteresis could be calculated by hand for the LVDTs. The deviation from linearity obtained for the LVDTs' of ±0.4% reflected the resolution of the data transmission system, while the VRTs introduced further non-linearities themselves and returned deviations of the order of ±0.7% to 1%. This was deemed to be quite satisfactory.

```
CALIBRATION VRT 1  8/6/83

     mm      transducer

   41.45          1
   39.19         13
   37.14         32
   35.09         46
   33.04         64
   30.99         81
   28.93         94
   26.88        109
   24.83        125
   22.78        139
   20.73        155
   18.67        171
   16.62        190
   14.36        206
   12.31        222
   10.26        241
    8.21        255
    9.85        249
   11.90        229
   13.95        212
   16.01        194
   18.06        178
   20.11        161
   22.16        143
   24.21        129
   26.27        113
   28.32        100
   30.37         85
   32.42         68
   34.47         52
   36.53         36
   38.53         20
   40.63          5

CAL FACTOR          -.1291
CORR COEFF          -.9996
REGRESS ER           .0814
CAL FAC ER           .0002
T TEST - T       -575.7867
NO OF RDNG         33.0000
% NON LINY           .8829
```



```
CALIBRATION  LVDT 8L  switch UP

Dial gauge  Reading
    1500      241
    2000      216
    2500      191
    3000      168
    3500      143
    4000      118
    4500       94
    5000       70
    5500       45
    6000       21
    6200       12
    5700       36
    5200       60
    4700       85
    4200      109
    3700      133
    3200      158
    2700      183
    2200      208
    1700      231
    1200      254

CAL FACTOR        -20.5048
CORR COEFF         -1.0000
REGRESS ER        168.9033
CAL FAC ER           .7158
T TEST - T        -28.6050
NO OF RDNG         21.0000
```