

**TRAINING DOCUMENT**  
**GENERAL FORCE METROLOGY**

Prepared By

**Dr. Sinan FANK**

**TÜBİTAK ULUSAL METROLOJİ ENSTİTÜSÜ**  
**FORCE GROUP LABORATORY**

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TÜBİTAK ULUSAL METROLOJİ ENSTİTÜSÜ

Gebze Yerleşkesi P.K. 54. 41470 Gebze KOCAELİ T (262)67950 00 F (262)6795001

[www.ume.tubitak.gov.tr](http://www.ume.tubitak.gov.tr)

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## **i. ABBREVIATIONS**

ASTM	: American Society for Testing and Materials
ISO	: International Standard Organisation
TURKAK	: Turkish Accreditation Agency
FSM	: Force Standard Machine
FPI	: Force Proving Instrument
MTM	: Material Testing machine
UME	: Ulusal Metroloji Enstitüsü (National metrology Institute of Turkey)
SI	: The International System of Units
B-FSM	: Build-up force standard machine

## ii. SYMBOLS

- F** : Standard force value produced by FSM
- X<sub>r</sub>** : Average value of readings on the indicator from rotation position of transducer
- X<sub>wr</sub>** : Average value of readings on the indicator from without rotation position of transducer
- X<sub>N</sub>** : Readings on the indicator at maximum capacity of force transducer
- X<sub>a</sub>** : Calculated readings by third degree polynomial equation
- X** : Readings on the indicator from FPI in any time
- i<sub>0</sub>** : Readings on the indicator before force application
- i<sub>f</sub>** : Readings on the indicator after force application
- X<sub>1,2</sub>** : Readings on the indicator in increasing forces in 0° position of force transducer
- X<sub>3,5</sub>** : Readings on the indicator in increasing forces in 120° and 240° position of force transducer
- X<sub>4,6</sub>** : Readings on the indicator in decreasing forces in 120° and 240° position of force transducer
- f<sub>0</sub>** : Relative zero error
- b** : Relative repeatability error with rotation position of force transducer
- b'** : Relative repeatability error without rotation position of force transducer
- f<sub>c</sub>** : Relative interpolation error
- e** : Relative resolution error
- v** : Relative reversibility (Hysteresis) error
- f<sub>ft-td</sub>** : Relative temperature shift error of force transducer
- m<sub>ft-td</sub>** : Relative temperature error of force transducer given by producer in ist catalogue
- t<sub>2</sub>** : Initial temperature of calibration laboratory before starting of calibration
- t<sub>1</sub>** : End temperature of calibration laboratory after finishing of calibration
- S<sub>ft-lts</sub>** : Long term stability error of force transducer
- X<sub>ft-d1</sub>** : Average value of force transducer for previous calibration
- X<sub>ft-d2</sub>** : Average value of force transducer for present calibration
- S<sub>i-lts</sub>** : Long term stability error of indicator

$X_{i-d1}$  : Average value of indicator for previous calibration

$X_{i-d2}$  : Average value of indicator for present calibration

**c** Relative creep error

$i_{30}$  : Reading on the indicator 30 s after application or removal of the maximum calibration force

$i_{300}$  : Reading on the indicator 300 s after application or removal of the maximum calibration force

**K** : the instrument's temperature coefficient, in reciprocal degrees Celsius ( $^{\circ}\text{C}^{-1}$ );

**W** : The expanded relative uncertainty

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## v. PREFACE

This training document gives detailed knowledge about the force metrology area including force applications. force measurements. force measuring instruments. force calibrations. force standard machines and calibration of force measuring equipments and calculation measurement uncertainty of calibration results

An introduction to force metrology is provided. together with application force measuring devices (force transducers. load cells. dynamometers and etc) to deadweight force standard machines. force transducers. There then follows a recommendation on good practice in the treatment of the uncertainty of measurement as applied to force transducers. This document also provides a more detailed introduction to the characteristics of force transducers and their applications in industry and research.

At same time. calibration of force transducers are explained according to the calibration procedures of international standards (EN ISO 376 ) in detail. To make accurate measurements. the devices are calibrated at regular intervals. The main function of Force Measurement Laboratory in TUBITAK National Metrology Laboratory ensure to traceability of the force measurements.

## INTRODUCTION

Force transducers or load cells are directly used for quality control in production process. weighing systems. material testing systems. safety engineering. in optimal design works. etc.. and also for the check of force measuring systems by the using them as transfer standards. In order to be able to make reliable and accurate measurements with these systems. accurate calibration of the force transducers are necessary. For the calibration of force transducers or load cells. standard forces should be generated by force standard machines (FSMs).

Different type force standard machines are used for calibration of force proving instruments such as force transducers. load cell. proving rings and etc. in many national metrology institutes. Decision about type selection of force standard machines directly depends on the required accuracy of force generation and budget limitation of the institute or country. In this training document general knowledge about force metrology will be given as well.

### 1. FORCE -BASIC CONCEPTS

The manufacture of nearly all industrial products requires the controlled application of forces. In many industries. these forces need to be measured to ensure that the manufactured items will perform correctly. The precision of force measurement varies from a few per cent to a few parts per million. Although the requirements vary. good practice needs to be followed [1].

#### 1.1. Units of Force

The International System of Units (SI) is widely used for trade. science. and engineering. The SI unit of force is the newton (N). The base units relevant to force are [1].:

\_\_the metre. unit of length. symbol m.

\_\_the kilogram. unit of mass. symbol kg.

\_\_the second. unit of time. symbol s.

Force is defined as the rate of change of momentum. For an unchanging mass. this is equivalent to mass \_ acceleration.

Thus  $1 \text{ N} = 1 \text{ kg} \cdot \text{m} \cdot \text{s}^{-2}$

Table 1: Summary of SI prefixes

Multiplying Factor	SI prefix	Scientific Notation
1 000 000 000 000	tera (T)	$10^{12}$
1 000 000 000	giga (G)	$10^9$
1 000 000	mega (M)	$10^6$
1 000	kilo (k)	$10^3$
0.001	milli (m)	$10^{-3}$
0.000 001	micro ( $\mu$ )	$10^{-6}$
0.000 000 001	nano (n)	$10^{-9}$
0.000 000 000 001	pico (p)	$10^{-12}$

The use of abbreviated forms for large and small numbers is encouraged by the SI system. Reducing ninety five million four hundred thousand newtons to 95.4 MN greatly simplifies the reporting of data. SI prefixes represent multiples of  $10^3$  or  $10^{-3}$  as in Table 1. There is an exception to the system caused by adoption of the kilogram as the base unit for mass rather than the gram. The effect of this is that prefixes above 'kilo' are not used for mass. The tonne is  $10^3$  kg [1].

## 1.2. Other Units of Force

Historically there have been a variety of units of force, and some approximate conversion factors to older units are given in Table 2 [1].

Table 2: Some conversion factors from non-SI units

Unit	Symbol	Is approximately equal to
pound-force	lbf	4.448 N
ton-force	tonf	9.964 kN
kilogram-force (or kilopond)	kgf (kp)	9.807 N

### **1.3. Other Related quantities**

In this section related quantities of force such will be described [1].

#### **Mass**

The term mass is used to measure the amount of material in an object. and can be deduced from the number and type of atoms present. Mass is a constant of a body and can only be changed by adding or removing matter (neglecting any relativistic effects of high velocity which are not relevant here).

#### **Weight**

Weight is a term that must be used with care. In everyday life it is often confused with mass. In this document. the term weight will only be used to describe a calibrated mass.

#### **Load**

Load is defined as the force acting on a body.

## **2. MEASUREMENT OF FORCE**

A force measurement system is made up of a transducer and associated instrumentation.

The transducer is subjected to the force to be measured. and some resultant change in the element is measured by the associated instrumentation. In practice a force transducer is a chain of several (usually different) transducers - for example the force may act upon a metal cylinder which is compressed by the force. the change in size alters the electrical resistance of a strain gauge bonded to the surface of the cylinder. and the instrumentation measures this change in resistance.

For many types of force measurement system the term load cell is in common usage in place of force transducer.

A force transducer is frequently built in as an integral part of a structure or machine. and many force calibration devices are themselves machines. It is often therefore difficult to consider the force measurement system separately from the application and this has many effects on the procedures for design. calibration and operation of the system.

### **2.1. Necessity of Force Measurement**

Force is a quantity on which many other quantities such as torque. thrust and pressure are based. Accurate force measurements are required in many applications. These

include the determination of the strength of materials. quality control during production. weighing. and consumer safety. For example. force measurement systems are used to determine when a missile has developed sufficient thrust to be released for takeoff and in auto safety tests. In the aircraft industry. force measurements are required to test the structural integrity of aircraft components and structures. In the picture on the left. force sensors are used to test the structural integrity of the wings. fuselage. and fasteners used in aircraft production.

Similarly. accurate force measurements are required to determine the weight of vehicles. tanks. bins. ladles and hoppers. Automated industrial processes such as rolling mills require accurate force measurement to control roll pressure on bar steel. sheet metal. paper. etc. Other applications include measurement of engine thrust. torque on dynamometer stands. cable tension on winches and elevators. and checking structures for weight. lift. drag and balance. Force sensors are used in electronic balances to measure weight. Such balances include those used to weigh trucks on highways. freight cars on railroads. babies in the doctor's office. puppies at the vet. and the flow of materials in a production process

## **2.2. Importance of Force Metrolog**

Mechanical metrology including force metrology plays a critical role in nearly all sectors of the every country economy and in everyday life. Accurate and traceable measurements of mechanical quantities and standardized metrology methods are crucial to domestic and international trade. to cost-effective manufacture of innovative new products. to distributed and global manufacturing. and to ensuring compliance with regulatory requirements. Country measurement system identified several critical "Measurement Needs" in mechanical metrology areas. These Measurement Needs have been validated by industry and other customers and provide evidence for the importance of accurate and traceable measurements of mechanical quantities. To ensure the competitiveness of the companies and products in world markets. this program provides the metrology infrastructure and associated standards to satisfy current and future needs of the government and industry for SI-traceable measurements of acoustics. force. mass. and vibration. This objective is accomplished through realizing. maintaining. and disseminating the basic SI unit of mass and the quantities of acoustics. force. and vibration to a broad customer base.

## 2.3. Types of Force Transducers used in Force Measurements

There are many types of force transducer and they are used with instrumentation of varying complexity. In designing or specifying a force measurement system for an application, it is useful to understand the basic operation of the transducer to be used and also their broad operating characteristics.

Details of different types of force transducers are given below under the following headings:

- |  |  |
|--|--|
| <b>Strain gauge force transducers</b>        | <ul style="list-style-type: none"> <li>• elastic elements</li> <li>• electrical resistance strain gauges</li> <li>• foil strain gauges</li> <li>• semiconductor strain gauges</li> <li>• thin-film strain gauges</li> <li>• wire strain gauges</li> </ul>              |
| <b>Piezoelectric crystal</b>                 | <ul style="list-style-type: none"> <li>• multi-component piezoelectric force transducers</li> </ul>  |
| <b>Measuring force through pressure</b>      | <ul style="list-style-type: none"> <li>• hydraulic load cells</li> <li>• pneumatic load cells</li> </ul>   |
| <b>Other types of force measuring system</b> | <ul style="list-style-type: none"> <li>• elastic devices</li> <li>• magneto-elastic devices</li> <li>• inductive devices.</li> <li>• capacitive devices.</li> <li>• vibrating elements</li> <li>• dynamic devices</li> <li>• plastic deformation</li> <li>•</li> </ul> |

## 2.4. Extensively Used Force Transducers

### 2.4.1. Strain Gauge Based Force Transducers

The sensing or spring element is the main structural component of the load cell. The element is designed in such a way that it develops a strain, directly proportional to the load applied. Sensing elements are normally made of high strength alloy steels (nickel plated for environmental protection), precipitation - hardened stainless steels, heat treated aluminium alloys, or beryllium copper alloys. By bonding strain gages to a precisely machined element, the force applied can be identified in terms of resistance change. The strain gages, usually four or a multiple of four, are connected into a Wheatstone bridge configuration in order to convert the very small change in resistance into a usable electrical signal. Passive components such as resistors and temperature

depending wires are used to compensate and calibrate the bridge output signal [3]. The rated capacities of strain gauge force transducers (or load cell) range from 5 N to more than 50 MN. They have become the most widespread of all force measurement systems and can be used with high resolution digital indicators as force transfer standards.



Figure 1. Type of strain gauge based force transducers [2]

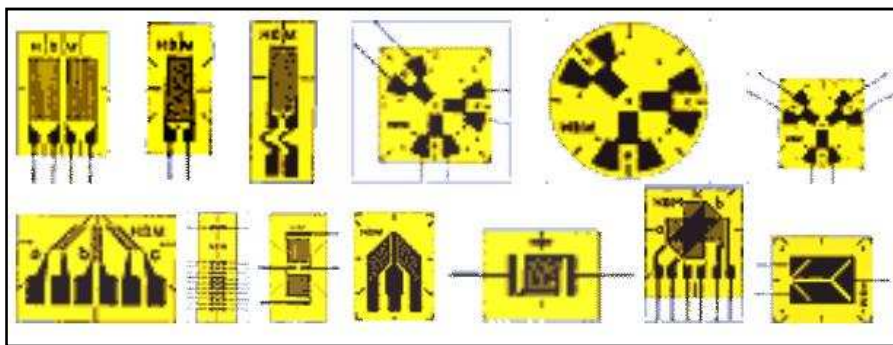


Figure 2. Strain gauge types used in force measurements [2]

In order to measure electrical signal related to change of electrical resistance of strain gauges bonded on elastic element of force transducer. Wheatstone bridge circuit is used in force measuring equipments. The resistance level of each strain gauges are  $350\ \Omega$  indicated as  $R_1$ ,  $R_2$ ,  $R_3$  and  $R_4$  in Fig. 3.

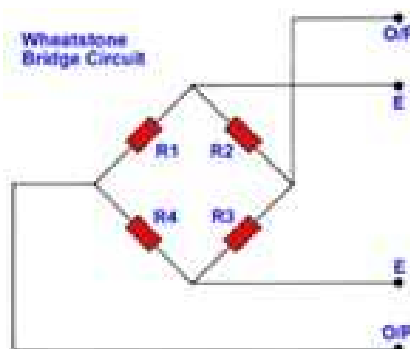


Figure 3 . Wheatstone bridge circuit

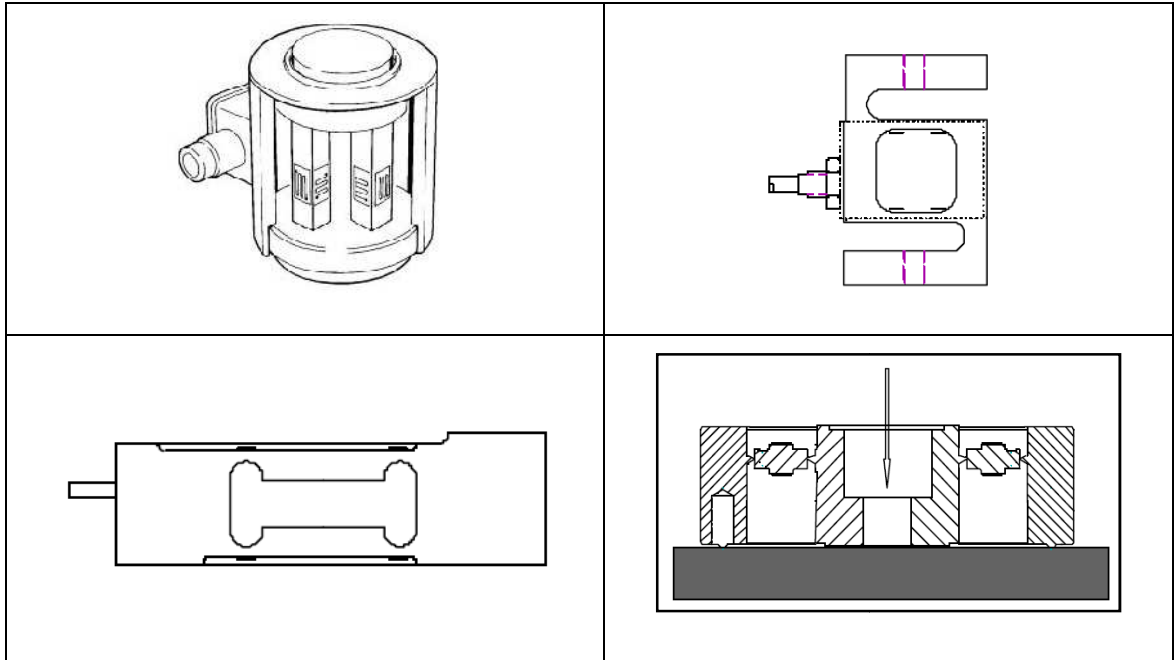


Figure 4. Force transducer Spring Member Design Considerations [3]

### 2.4.2. Piezoelectric Crystal Force Transducers

piezoelectricity: To generate a useful output signal. our sensors rely on the piezoelectric effect. ("Piezo" is a greek term which means "to squeeze.") When the piezoelectric elements are strained by an external force. displaced electrical charge accumulates on opposing surfaces. Figure 5 illustrates the displacement of electrical charge due to the deflection of the lattice in a naturally piezoelectric quartz crystal. The larger circles represent silicon atoms. while the smaller ones represent oxygen. Crystalline quartz. either in its natural or high-quality. reprocessed form. is one of the most sensitive and stable piezoelectric materials available [4]

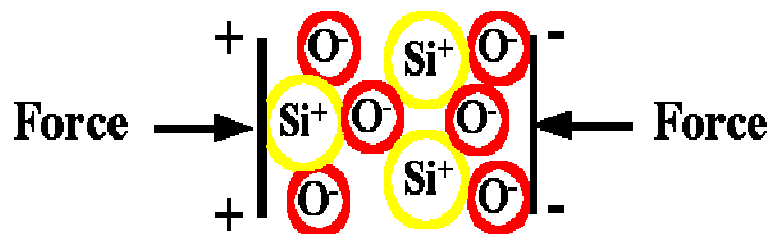


Figure 5. Principle of piezo electric force sensor

Quartz Force Sensors are recommended for dynamic force applications. They are not used as 'load cells' for static applications. Measurements of dynamic oscillating forces. impactor high speed compression/tension under varying conditions may require sensors

with special capabilities. Fast response. ruggedness. stiffness comparable to solid steel. extended ranges and the ability to also measure quasi-static forces are standard features associated with PCB quartz force sensors. There is a small leakage of charge inherent in the charge amplifier. which is called drift of the signal. So while piezoelectric force transducers are ideally suited for dynamic measurements they cannot perform truly static measurements. Measurements can be made over a period of minutes or even hours and piezoelectric transducers are said to take 'quasi-static' measurements [4].



Figure 6. Piezoelectric force sensor [4]

Piezoelectric crystal sensors are suitable for measurements in laboratories as well as in industrial settings. The measuring range is very wide and the transducers survive high overload (typically > 100 % of full-scale output). The sensors small dimensions. large measuring range and rugged packaging make them very easy to use. They can operate over a wide temperature range and survive temperatures of up to 350 °C.

## 2.5. Force Transducer Applications

Force transducers or load cells are widely used in weighing. process control. research. automotive and many engineering applications. In order to explain necessity of force transducer calibration or verification of force measuring systems. force transducer (load cell) application should be presented. The following application gives an overview of different uses for load cells.

- Aerospace Structural Testing and Manufacture
- Automotive Testing
- Roller and Conveyor Belt Scales

- Dual Range Jet Engine Test Stand
- Dynamometer Applications
- Tension Hopper Weighing
- Compression Tank Weighing
- Materials Testing Machines
- Medical Instruments
- Research Centres and Laboratories
- Truck Weighing
- Tension Control
- Aircraft weight set.
- Missile testing system.
- Automotive crash testing system

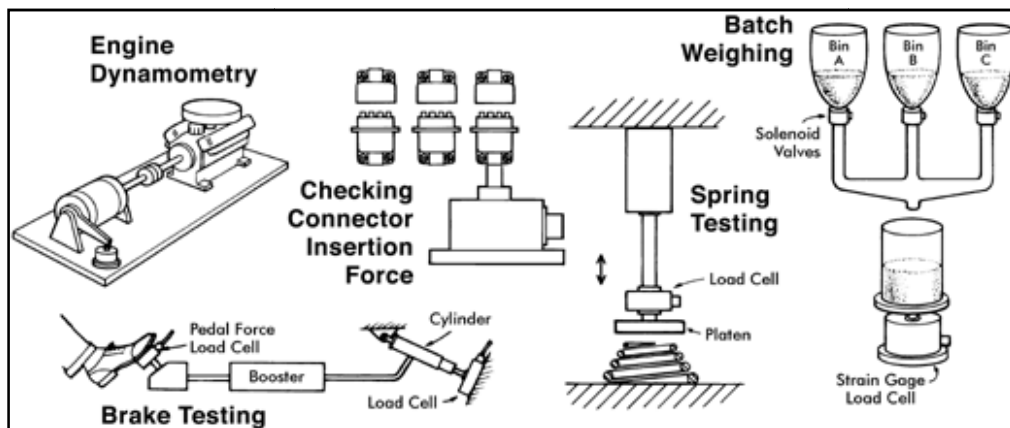


Figure 7. Different applications of load cell

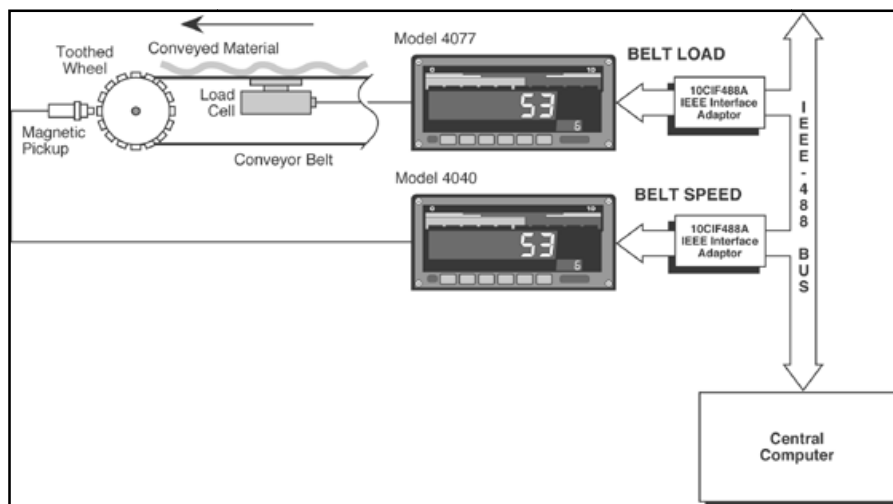


Figure 8. Load cell for process control [5]

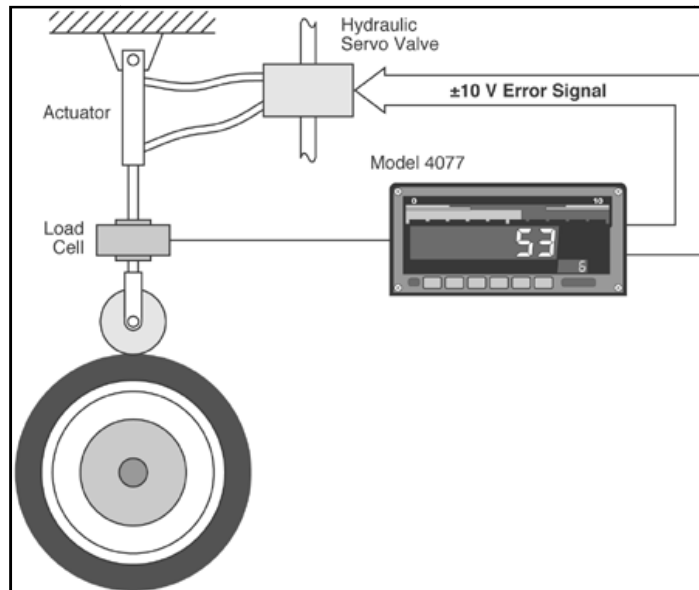


Figure 9. Load cell in tire control unit [5]

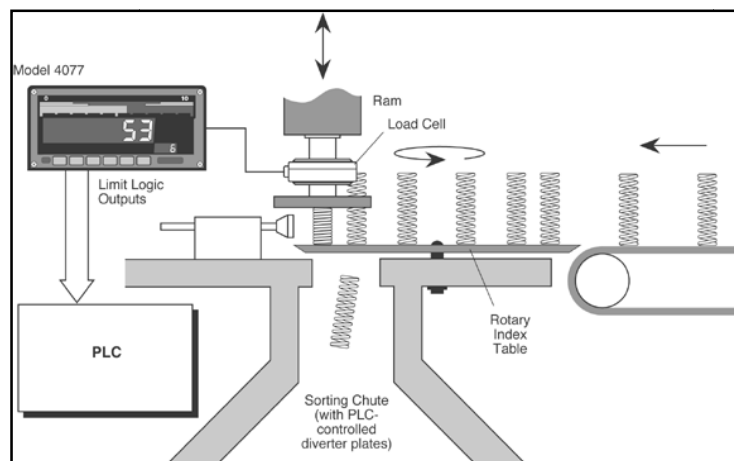


Figure 10. Load cell in spring test system [5]

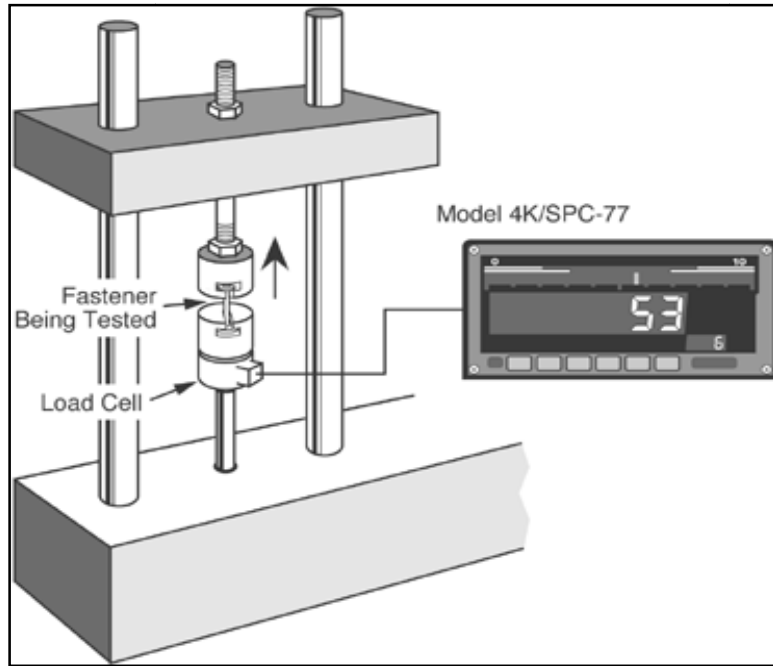


Figure 11. Load cell in material testing machine [5]

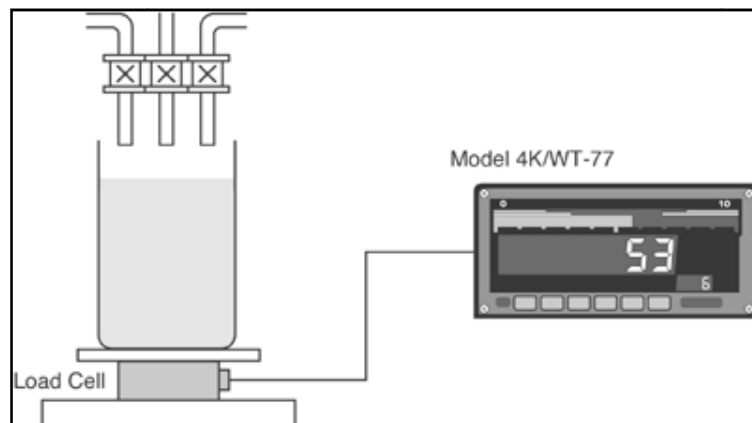


Figure 12. Load cell in chemical process plant [5]

### Force transducer Applications : Aerospace

Load cells are used to measure the load introduced into aircraft structures during static, fatigue and ultimate load testing. The load cell output is stored electronically and retrieved for comparison with analytically determined values to demonstrate the ability of the structure to carry its design limit load. Double and/or triple bridges provide back-up data and permit real-time monitoring of the test loads.

Load cells provide direct measurement and recording of loads applied to individual components that are static and fatigue tested apart from the main airframe [6].

### Industries:

- Aircraft Manufacturers. component manufacturers. aircraft repair centre. aerospace manufacturers

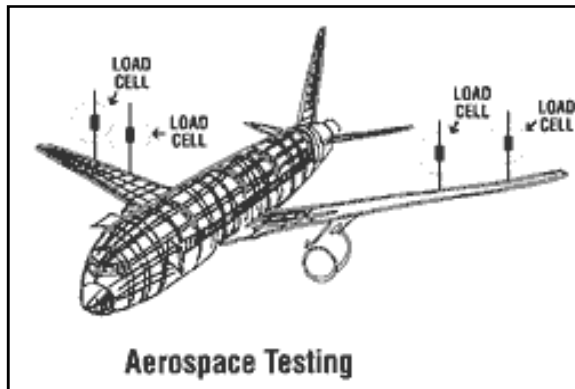


Figure 13. Force transducers for aerospace applications

### Force transducer Applications : Automotive

Load cells are used in the automotive industry for the testing of different components by the automotive manufacturers test laboratories and suppliers. The following are two examples of how these load cells are used in this industry.

- The gear shift is placed under extreme hydraulic force pushing and pulling in and out. back and forth. testing for wear and strength of the shift arm. housing and lock out assembly. Units are tested until there is a failure. The design of the structure and the gear shift is critical to safe operation of the vehicle.
- Load cells are used in testing the breaking forces for the seat belt anchors. This is done by attaching hydraulic cylinders with the load cells. This generates a force that equals the impact of the vehicle in a crash. simulating human body movement. This test determines whether the frame or structure of the vehicle has the strength to hold and not allow the person to be thrown from the vehicle [6].

### Industries:

- Automotive. farm equipment. miscellaneous vehicles

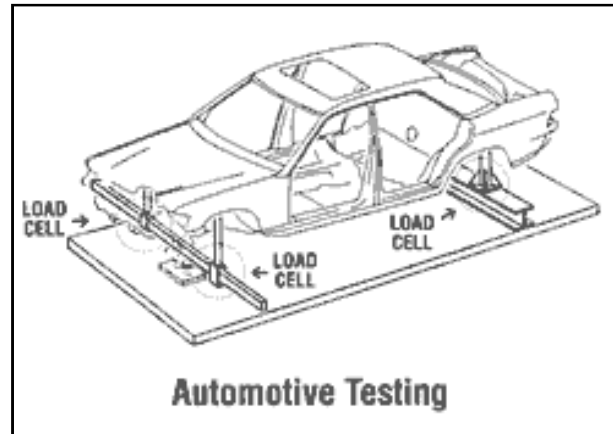


Figure 14. Load cell in automotive testing

**Force transducer Applications: Missile Testing**

Load cells are used in the missile production and development industry for the testing of missile body during design phase by the missile manufacturers and its test laboratories.

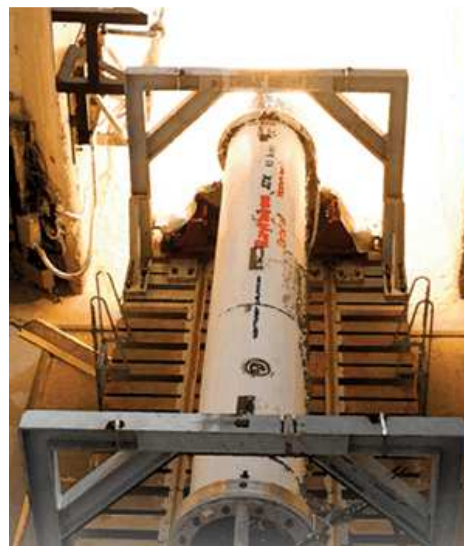


Figure 15. Load cell in missile testing

**Force transducer Applications : Automobile crash testing stands**

Automobile developers set high quality standards for force measurement in crash tests. The new mobile calibration test stand covers loads up to 500 kN. The calibration process can be interrupted at any stage to dovetail with the crash test sequence so it is never delayed. Laborious dismantling of the crash barriers for return to the manufacturer is not necessary [6].



Figure 16. Force Transducers in automobile crash testing stands

**Force Transducer Applications : Dual Range Jet Engine Test Stand**

Load cells can be supplied assembled in a stack configuration, using two load cells having different ranges. These stacks are ideally suited as compression thrust sensing elements in aircraft engine test stands which are designed to test many engines of widely different ratings, or to provide higher accuracy at the low end when an engine must be qualified over a broader range of thrust.

Industries / Test Applications:

- Engine manufacturers: Qualification and acceptance test.
- Commercial / Military aircraft users: Jet engine overhaul facilities

**Force Transducer Applications : Dynamometer**

Load cells are used to measure torque in dynamometers by sensing force on a fixed moment arm attached to the stationary member of the dynamometer. The torque is generated in the stationary member by the rotating member of the dynamometer. The load cell is typically mounted with hardware on both ends which accommodates a small amount of motion, such as rod end bearings. Applications are found anywhere rotating machinery is being manufactured or tested.

**Industries:**

- Automotive
- Aircraft
- Marine
- Electrical Power

**Testing Activities:**

- Petrol Engines
- Diesel Engines
- Transmissions
- Gear Box

- Farm Equipment
- Bus and Truck
- Military
- Aerospace
- EPA Emissions
- Vehicle Emissions
- Brake and Clutch
- Wheels. Axles. Tyres

### **Force Transducer Applications : Materials Testing**

Material testing machines (MTM) are used to test the strength, elasticity, yield points and fatigue life of metal, plastic and various other materials in both tension and compression. MTMs provide a versatile and accurate method of applying tensile and compressive forces. Across the globe, quality control and product design centres, as well as research and education laboratories, use the MTM for their Tension and compression test requirements. Applied load is measured by load cells. Load cells are used to test the properties of materials.



Figure 17. Force Transducers in different test

### **Force Transducer Applications : Concrete Testing**

Concrete testing machines are used to test the concrete crash strength, elasticity, yield points in compression for safe construction of buildings, bridges and roads. The main part of this machine is accurate load cells to measure crash load value to determine concrete characteristics.



Figure 18. Force Transducers in concrete testing machines

**Force Transducer Applications : Medical Instruments**

Load cells are used in medical instrumentation for fluid monitoring/management, fluid weighing, mixing and separation, purification, stress management and patient weighing. The load cells measure or detect differences in the capacity of a reservoir, flow of fluids and weight measurement by the deflection of the flexure which in turn changes the resistive load of the proprietary strain gauge resulting in a mV/V signal output to a microprocessor, signal conditioners or other electronic readouts [6]. The total sub-assemblies are available with or without; overload protection, integral electronic connectors and mounting brackets and structure components.

Industries:

- Medical Instrument OEM's
- Pharmaceutical
- Blood Grouping
- Haematology
- Therapeutic Rehabilitation Systems
- Fluid Management / Monitoring
- Orthopaedic-stress, monitoring
- Blood Bank / Donor Machines
- Blood Separation - Automated
- Mixing Devices

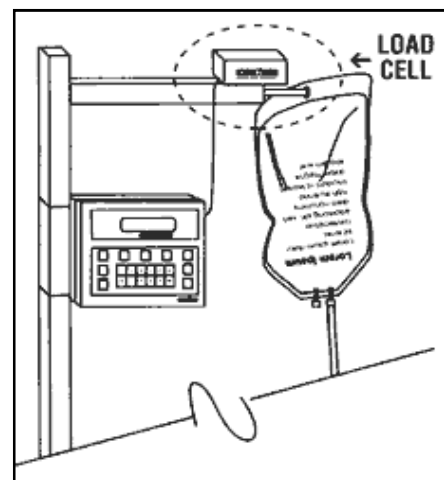


Figure 19. Load cell in flow control application of blood

- Purification
- Auto Transfusion
- Dialysis Machines
- Hospital Beds

### **Force Transducer Applications : Research Centres / Laboratories**

Load cells are used to test the properties of materials. perform research and general force measurements.

Industries:

- Material Testing Labs .Calibration Labs. Research Centres
- Biomedical Research Centres. Universities

### **Force Transducer Applications : Roller and Conveyor Belt Scales**

Load cell can be used in tension and compression. Suspending the conveyor in a tension mode is recommended to eliminate alignment problems.

- Roller Scale: Weighing of packaged goods prior to shipping
- Belt Scale: Weighing of bulk material during processing or shipping

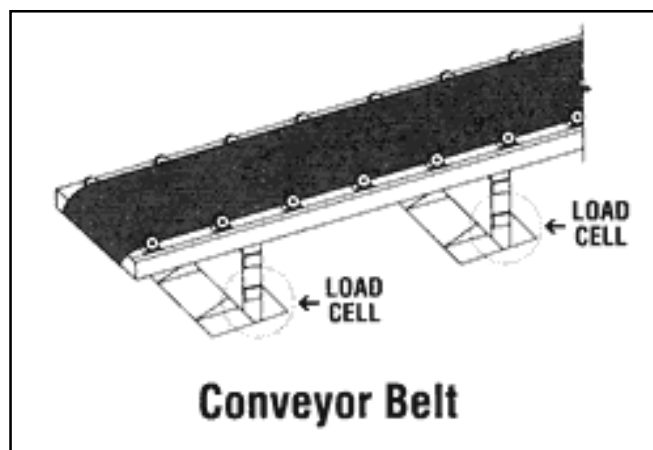


Figure 20. Load cell for weighing control in conveyor belt

### **Force Transducer Applications : Tank Weighing - Compression**

Generally three to four low profile load cells are used. Three load cells are ideal to simplify installation. Top and bottom mounting plates are available to make mounting easy. The WeighCheck system is ideal for long horizontal tanks which would have a lot of thermal expansion [6].

**Industries:**

- Chemical Manufacturing
- Food Processing
- Batch Weighing
- Process Control
- Storage Facilities

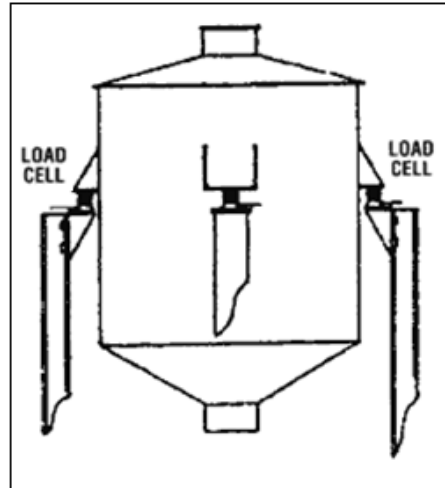


Figure 21. Load cell for liquid tank weighing

**Force Transducer Applications : Tension Control**

Load cells are used in the steel and non-ferrous metals industries for flat rolled products. i.e. sheet and strip. They are specially used on guide rollers to measure tension. The load cells are typically installed under the bearing pad on each end of the roller. By summing the load cell outputs, the installation will provide readings which are proportional to tension. This general application is used in the following specific areas [6]:

- Sheet and Strip Lines
- Cleaning Lines
- Galvanising Lines
- Slitting Lines
- Temper Mills
- Cold Reduction Mills

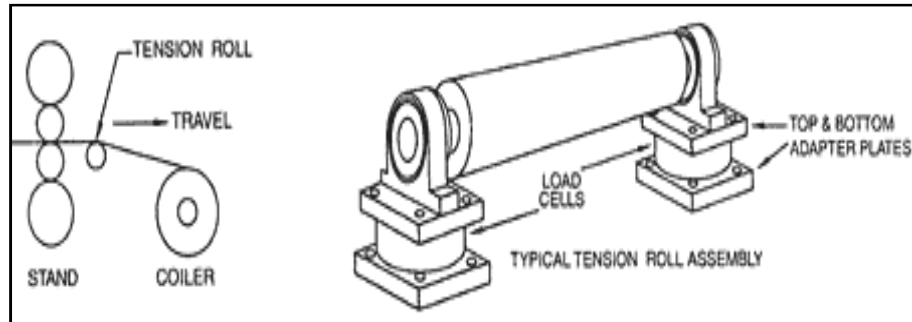


Figure 22. Load cell for roller and tension of steel

### Force Transducer Applications : Truck Weighing

A truck scale is generally located in a pit and would use from 4-12 (Load Check) load cells. along with a summing box and a digital indicator. Load Check load cells are ideally suited for truck and rail scales where outdoor installation and resulting temperature changes as well as dynamic loading normally occurs [6].

For use in all industries that require vehicle load control and measurement. Weighing applications include; sand and gravel suppliers. mines. concrete batching plants. milk producers. moving. storage companies. chemical manufacturers landfills etc.

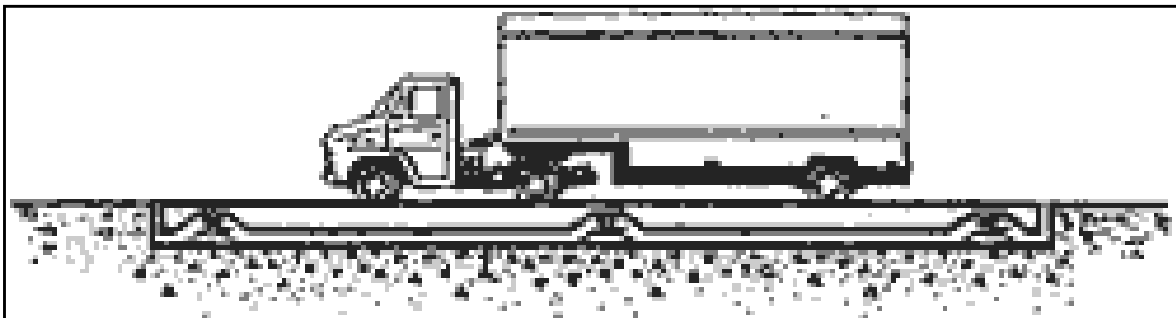


Figure 23. Load cell for truck weighing

### Force Transducer Applications : Suspended Hopper Scales

Ideal for any hopper suspended above the centre of gravity. Normally a rod end bearing is used on top and bottom of load cell.

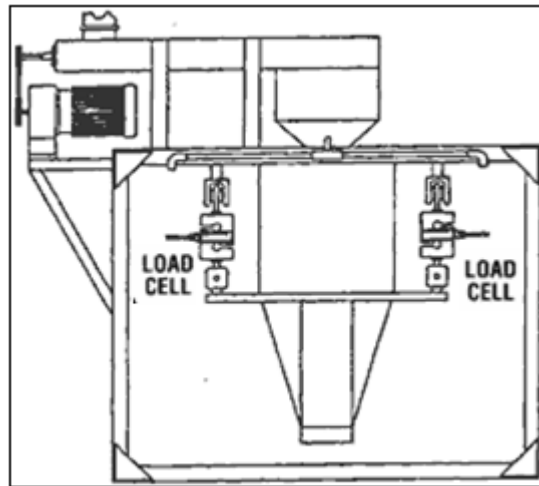


Figure 24. Load cell for suspended hopper scales

### 3. GENERATION OF FORCE

This section describes the common types of force Standard machines used for generating forces. The machines offering the lowest uncertainty use deadweights. They are known as primary machines because they are traceable to base units. Deadweight machines capable of generating large forces are expensive, and it is unusual to find deadweight machines with capacities above a few hundred kilonewtons outside national standards laboratories. There are very few deadweight machines in the world with capacities much above 1 MN.

Larger forces are usually generated using hydraulic or lever machines. These are known as secondary force standard machines because they have indirect traceability to the measurement standards of mass, length, and time [1].

Different type force standard machines are used for calibration of force proving instruments such as force transducers, load cell, proving rings and etc. in many national metrology institutes. Decision about type selection of force standard machines directly depends on the required accuracy of force generation and budget limitation of the institute or country. The most accurate forces can be generated by dead weights with direct application. But direct application of dead weights requires considerable building space, when capacity of forces exceeds 100 kN. Dead weight force standard machines are quite expensive due to their high production cost. Cheaper solutions can be found for establishment of force scale in the country depending on the required accuracy and capacity. Some of these solutions are lever or hydraulic amplification of dead weights and build-up force standard machines, which amplifies the forces by hydraulic ram [7].

### 3.1. Deadweight Force Standard Machine

A deadweight machine has a series of weights that can be applied to a device. The masses of the weights are known. together with  $g$ . the local acceleration due to gravity. After a correction for the buoyancy force acting upwards on the weights. the forces generated by the weights can be calculated [1].

The resultant downward force experienced by a weight in air in the Earth's gravitational field is given by

$$F = m \cdot g_{local} \cdot \left(1 - \frac{\rho_{air}}{\rho_{mass}}\right)$$

where  $m$  is the conventional mass of the weight.  $\rho_{air}$  is the air density of air.  $\rho_{mass}$  is the density of the weight and  $g_{local}$  is the local gravity of acceleration.

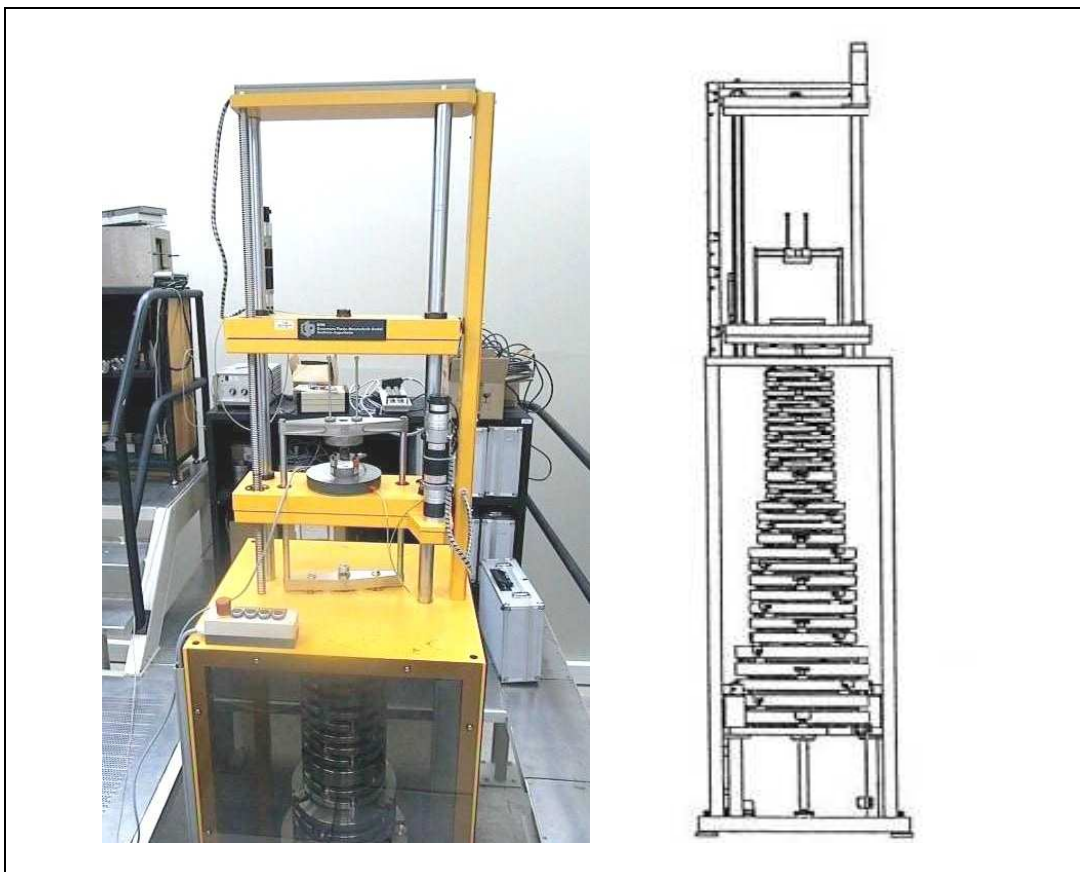


Figure 25. TUBITAK UME 11 kN Dead weight force standard machines

### 3.2. Lever Amplification Force Standard Machine

A lever amplification force machine normally comprises a series of weights with an arrangement of levers to generate larger forces. Although there may be an arrangement

of more than one lever. the amplification of the force is given by the overall lever ratio. These machines have some of the advantages of a deadweight machine without the expense of large weights.

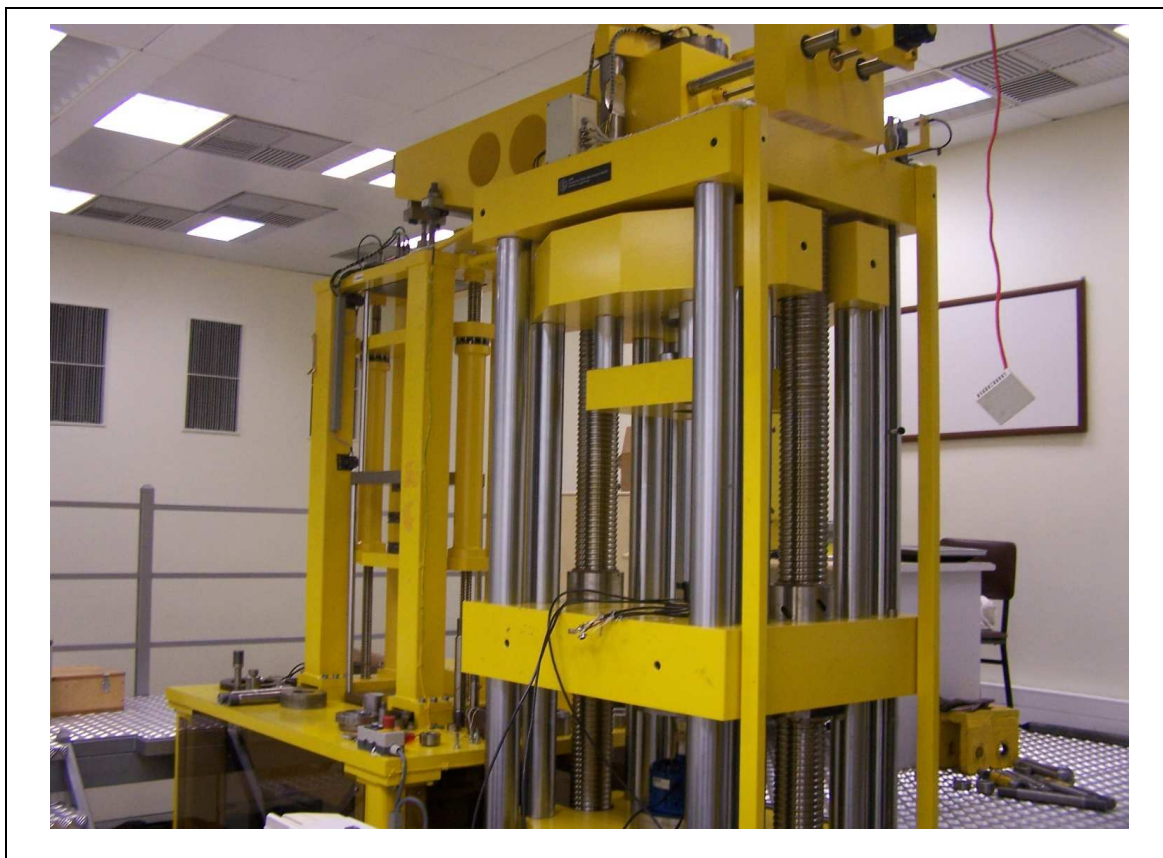


Figure 26. TUBITAK UME 110 kN / 1.1 MN Dead weight lever ampl. machine

### 3.3. Hydraulic Amplification Force Standard Machines

Hydraulic amplification machines use a deadweight stack to apply forces to a small piston-cylinder assembly connected hydraulically to a much larger piston-cylinder assembly. The larger piston cylinder is mounted in a testing-machine frame.

An example of this design is the NPL 5 MN machine (Figure 27). A 22 kN deadweight stack is connected to a 5 MN frame that can operate in both compression and tension. Neither of the piston-cylinder assemblies has a mechanical seal; instead, there is a continual leakage of oil between piston and cylinder to minimise frictional losses. The cylinder of the small assembly is rotated about the piston to reduce the friction further. A servo-valve controls the hydraulic pressure so that the scalepan and selected weights of the 22 kN machine are maintained at a datum position [1].

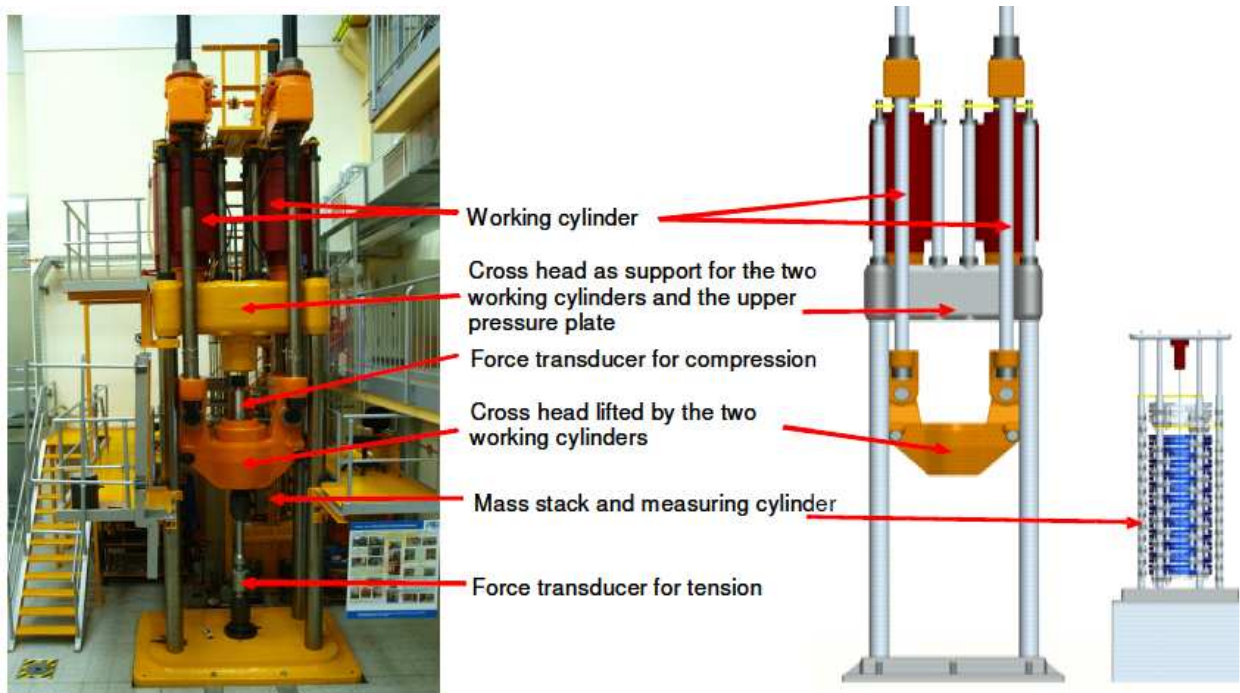


Figure 27: PTB's 5 MN dead weight hydraulic amplification machine

### 3.4. Transducer-based (single or build-up) force standard machines

Transducer- force standard machines can be based on single or multiple (build-up) reference force transducers for hydraulically generated force control. Build-up force standard machine (B-FSM) uses three or power of three ( $3^n$ ) transducers, which are disposed in parallel. This method is called the build-up method or force transducers pyramid, which has great advantages and economy for the establishment of force standard machines of high capacity [7].

The UME B-FSM consists of a mechanical construction, a servo-hydraulic system, and a control unit. The framework of the machine is designed on a three-column principle and is composed of a loading table and a lower base. A force-generating hydraulic cylinder is located on the loading table, and the reference force transducers are mounted on top of this cylinder, providing the signal used as the reference value for calibration as well as the system control. The machine generates forces by a piston-cylinder arrangement, which is driven by a servo-hydraulic system instead of a hydraulic pump and servo valve combination. This system reduces noise, vibration, and maintenance costs caused by a hydraulic pump system. A servo-hydraulic system enables precise pressure control to reduce pressure fluctuations during force application.

As a result, measurement uncertainty of the system is minimized. A general view of the machine is shown in Fig. 28.



Figure 28: TUBITAK UME 3 MN Build-up force st. machine

## **4. CALIBRATION OF FORCE**

### **4.1. The Meaning of Calibration**

Many people do a field comparison check of the transducers, and call them “calibrated” if they give the same reading. This isn’t calibration. It’s simply a field check. It can show you if there’s a problem, but it can’t show you which transducers is right. If both transducers are out of calibration by the same amount and in the same direction, it won’t show you anything. Nor will it show you any trending you won’t know your instrument is headed for an “out of cal” condition.

For an effective calibration, the calibration standard must be more accurate than the instrument under test. Most of us live in places where we change the clocks at least twice a year, plus again after a power outage. When you set the time on that appliance,

what do you use as your reference timepiece? Do you use a clock that displays seconds? You probably set the time on the “digitschallenged” appliance when the reference clock is at the “top” of a minute (e.g., zero seconds). A metrology lab follows the same philosophy. They see how closely your “whole minutes” track the correct number of seconds. And they do this at multiple points on the measurement scales.

Calibration typically requires a standard that has at least 10 times the accuracy of the instrument under test. Otherwise, you are calibrating within overlapping tolerances and the tolerances of your standard render an “in cal” instrument “out of cal” or vice-versa.

Calibration, in its purest sense, is the comparison of an instrument to a known standard. Proper calibration involves use of a National metrology Institute-traceable standard — one that has paperwork showing it compares correctly to a chain of standards going back to a master standard maintained by the National Metrology Institute.

If the calibration report shows gross calibration errors, you may need to go back to the work you did with that instrument and take new measurements until no errors are evident. You would start with the latest measurements and work your way toward the earliest ones. In nuclear safety-related work, you would have to redo all the measurements made since the previous calibration.

Calibration can be defined shortly as ‘The process of determining experimentally the absolute values corresponding to the graduations on an arbitrary or inaccurate scale of measurement’. There are four types of calibration relevant to force metrology [1].

- Calibration of a primary force standard machine
- Calibration of a secondary force standard machine
- Calibration of a force transducer
- Calibration of a materials testing machine

Primary force standard machines are calibrated without a measurement of force. A primary deadweight machine is calibrated by measuring the mass of a weight and the acceleration due to gravity, and determining the buoyancy correction.

The mass of a weight can be measured with a low uncertainty. The local value of  $g$  can also be measured and the air density monitored. Combining the uncertainties gives an overall uncertainty of applied force as low as 1 part in 200 000. Because they can have

such a low uncertainty. deadweight machines form the foundation for force measurement throughout the world [1].

To calculate the uncertainty associated with the generated force. it is necessary to determine the contribution of the individual terms to the total standard deviation. surfaces. The effect on the performance of a load cell will be much greater than the cosine term.

## **4.2. Importance of Calibration**

Calibration is simply the comparison of instrument performance to a standard of known accuracy. It may simply involve this determination of deviation from nominal or include correction (adjustment) to minimize the errors. Properly calibrated equipment provides confidence that your products/services meet their specifications.

Calibration:

- Increases production yields.
- Optimizes resources.
- Assures consistency and
- Ensures measurements (and perhaps products) are compatible with those made elsewhere.

By making sure that your measurements are based on international standards. you promote customer acceptance of your products around the world. But if you're still looking to justify that the cost of calibration does add value. check-out some of the calibration horror stories that have been reported.

## **4.3. Necessity of Force Laboratory**

In order to give force transducer calibration service for a country needs. a calibration laboratory should have force standard machines which generate the reference forces for the calibration of force transducer (load cell) calibrating from 0.5 N through 5 MN in either tension or compression under controlled conditions featuring Deadweight calibrations up to 100 kN or 500 kN with weights directly calibrated by national metrology institute such as NIST-USA. PTB-Germany. NPL-England and TUBITAK-UME-Turkey. The calibration of all of equipment should be traceable to the national standards. All force standards should comply with EN ISO 376 or ASTM E 74 and ISO

guide 17025. National force laboratory should be accredited ASTM E74 calibrations as well as ISO 376 calibration.

The force calibration facilities and procedures are documented in a controlled Quality Assurance Program Manual that provides for the requirements of the following:

- Accredited certificate according to EN ISO 376 or ASTM specification E 74
- ISO GUIDE 17025 – General requirements for the competence of calibration and testing laboratories.

#### **4.4. Importance of Force Metrology**

Mechanical metrology including force metrology plays a critical role in nearly all sectors of the every country economy and in everyday life. Accurate and traceable measurements of mechanical quantities and standardized metrology methods are crucial to domestic and international trade. to cost-effective manufacture of innovative new products. to distributed and global manufacturing. and to ensuring compliance with regulatory requirements. Country measurement system identified several critical “Measurement Needs” in mechanical metrology areas. These Measurement Needs have been validated by industry and other customers and provide evidence for the importance of accurate and traceable measurements of mechanical quantities. To ensure the competitiveness of the companies and products in world markets. this program provides the metrology infrastructure and associated standards to satisfy current and future needs of the government and industry for SI-traceable measurements of acoustics. force. mass. and vibration. This objective is accomplished through realizing. maintaining. and disseminating the basic SI unit of mass and the quantities of acoustics. force. and vibration to a broad customer base.

#### **4.5. Force Traceability to National Measurement System**

Traceability is the ability to link a measurement back through the calibration chain to base SI units. The national measurement system for force is illustrated below. It shows the traceability of measurements back from the materials testing laboratory to the NMI (national metrology institute)

The base units for time. length and mass are realised at NMIs with uncertainties of approximately 1 part in  $10^{13}$  for the second. 3 parts in  $10^{11}$  for the metre. and 2 parts in  $10^8$  for the kilogram. NMI’s deadweight machines. maximum capacity 4.45 MN (at

NIST). have been calibrated directly against standards for these base units with an uncertainty of 1 part in 200 000. Furthermore. NMI's deadweight machines have been intercompared with deadweight machines at several other national standards laboratories. using portable force transfer standards. thereby ensuring agreement with other national standards for force.

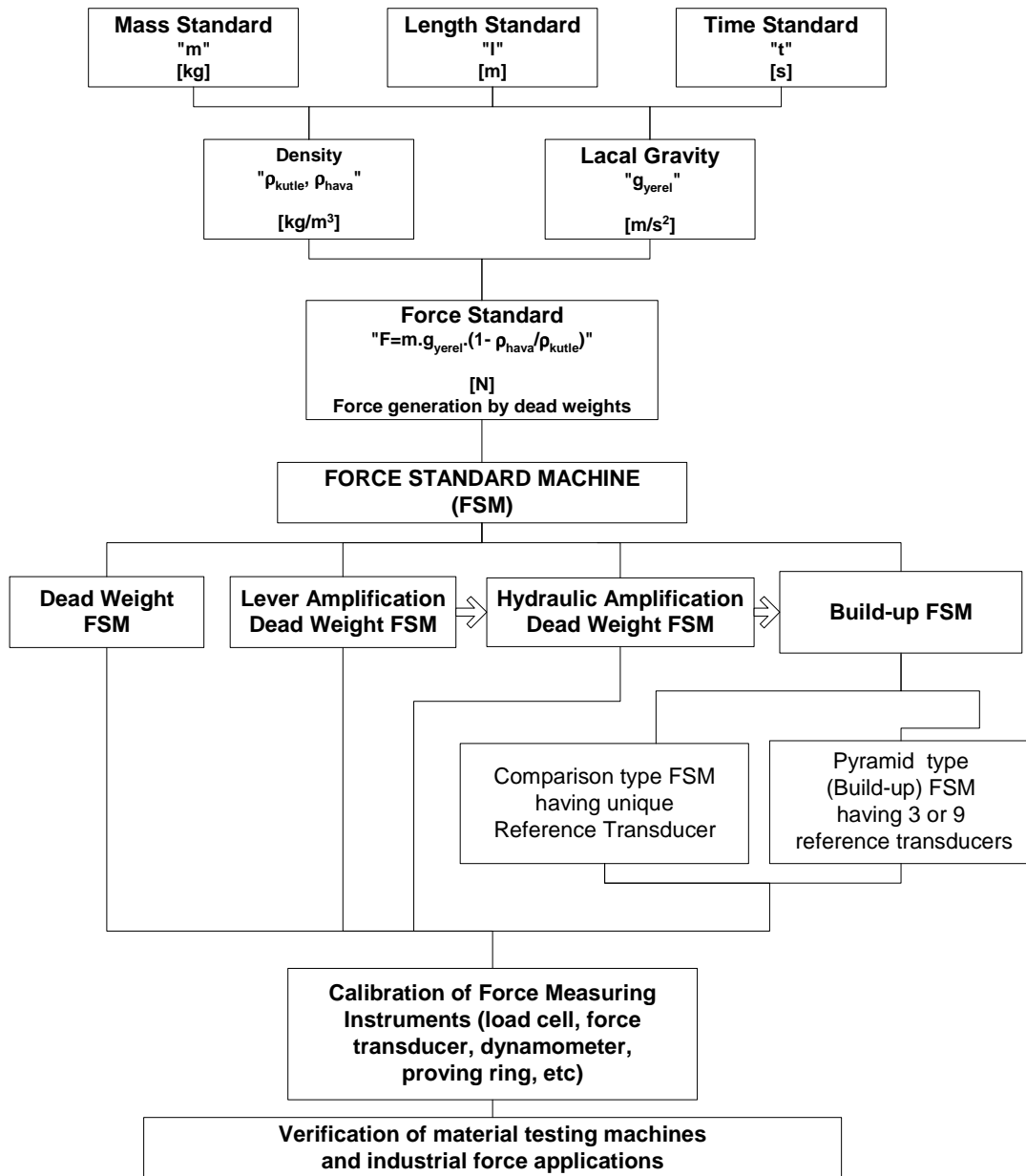


Figure 29: Force Traceability to national standards

There is a rapid increase in uncertainty. indicated by the scale on the left hand side of the diagram. as the number of steps from the base units increases. Provided that appropriately certified force transfer standards have been used. and the relevant

standards have been strictly adhered to. traceability to the base SI units can be claimed [1].

#### **4.6. Characteristics of Force Transducer**

The characteristics of strain gauge load cells that limit their accuracy. Various techniques are described to reduce the errors from these characteristics. enabling force standard machines to be intercompared with an uncertainty better than 0.005 % [1].

During the past 20 years. strain gauge load cells have been used with high resolution digital indicators as high accuracy force transfer standards for the international intercomparison of force standard machines. The uncertainties of the forces applied by these machines are in the region of 0.001 % to 0.002 % and it has been found possible using strain gauge load cells to show agreement between different machines within 0.005 %. As well as the intercomparison of force standard machines. there are other applications of load cells that require high accuracy force measurement. These include the calibration of precision lever and hydraulic machines. the measurement of rocket thrust and the weighing of aircraft. In each case. the accuracy obtained will be limited by the conditions of use of the load cell and its performance characteristics. Some of the characteristics of a load cell that are known to be important are summarised in later sections. together with measurement techniques that enable the resulting errors to be reduced [1].

##### **4.6.1. Repeatability**

Repeatability is a measure of a load cell's ability to give the same output under the same conditions. OIML define it as the agreement between successive measurements of the differences of load cell output for given applications of the same force. This force should be in the same direction and in the range of the load cell's calibration. The tests should be made by the same observer. with the same measuring equipment. on the same occasion and without mechanical or electrical disturbance. i.e. calibration conditions such as temperature. axiality of loading and the timing of readings should be held constant as far as possible. Although many manufacturers quote a value for repeatability as a basic characteristic of a load cell. it can be seen from the definition that repeatability should not be considered as such. The value obtained for a given load cell in a given force standard machine will depend on the true characteristics of the load

cell such as its creep, sensitivity to bending moments and temperature gradients. It will also depend on the resolution and repeatability of the electrical measuring equipment and the degree to which the conditions of the tests, which are characteristics of the test procedure, are held constant. The value of repeatability obtained is important as it limits the accuracy to which the characteristics of the load cell can be measured [1].

By using high stability digital indicators which have resolutions better than 0.001 % (currently 0.000 1 % is obtainable) and by carefully controlling the calibration conditions, it is possible to achieve a transfer of the standard of force within 0.005 %, which is better than the repeatability of the load cells claimed by the manufacturer. Such a low uncertainty could not be claimed for a force standard machine which used an in built strain gauge load cell as the means of defining the force applied, because the general conditions of use of the load cell would not be so well defined in practice.

#### **4.6.2. Non-Linearity**

There are several ways of defining non-linearity. The following definition, however, is one which defines it in a simple way that is not open to misinterpretation: the non-linearity is the deviation of the measured output, obtained for increasing forces only, from the straight line passing through the outputs at zero and the rated force. For high accuracy force measurements, corrections should always be applied for non-linearity, either directly or within the instrumentation. The relationship between the output of a load cell and the force applied can generally be expressed by a third order polynomial equation such that the maximum residual - the magnitude of the difference between a measured output and the corresponding output determined by the equation - is close to the repeatability of the measurements. This will reduce errors due to non-linearity to a level that will not be significant. Nevertheless, for force measurement of the highest accuracy, the load cell should be calibrated and subsequently used at the same nominal values of force [1].

#### **4.6.3. Creep**

The creep of a load cell is usually defined as the change of output with time following a step increase in force from one value to another. Most manufacturers specify the creep as the maximum change of output over a specified time after increasing the force from zero to the rated force (e.g. 0.03 % of rated output over 30 minutes). Creep recovery is the change of output following a step decrease in the force applied to the load cell, usually from the rated force to zero. For both creep and creep recovery, the results will

depend on how long the force applied has been at zero or the rated value respectively before the change of force is made [1].

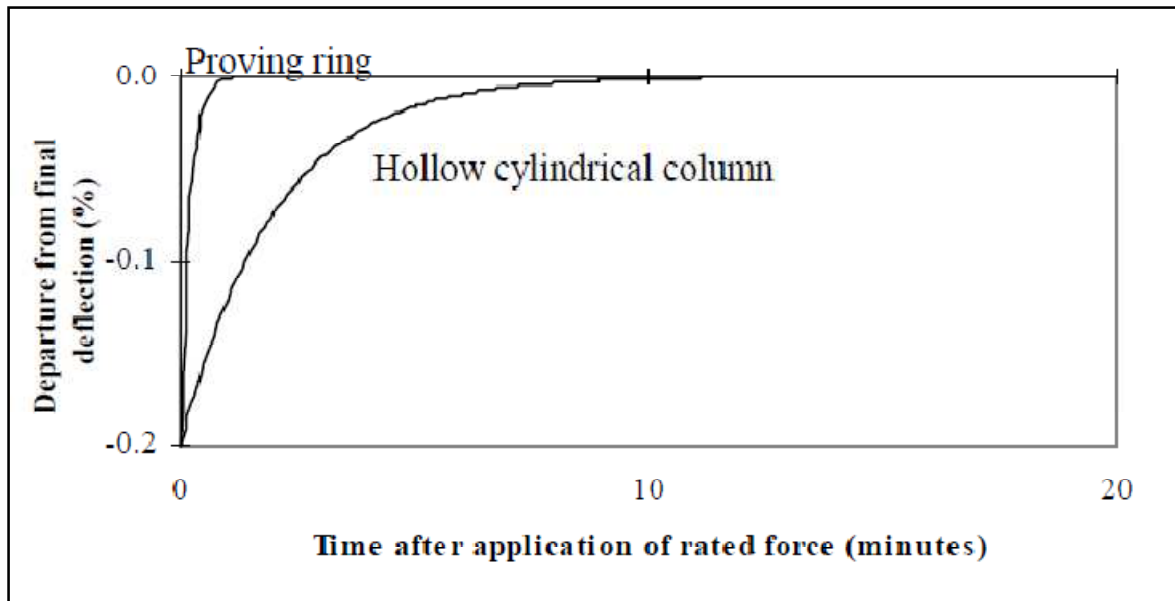


Figure 30. Creep curve of different force transducers [1]

A creep test requires a machine that can hold the force constant within close limits; generally a deadweight or a lever machine is required although some of the precision hydraulic machines at the various national institutes of metrology are suitable. For a creep recovery test, the force can be held within 1 % by a hydraulic testing machine and then reduced to zero very quickly. The creep recovery characteristic can usually be measured more accurately than the creep characteristic because it is easier to determine the moment at which the force is completely removed than that at which it is applied [1].

Several different factors contribute to the overall creep behaviour of a strain gauge load cell, each factor arising from the performance of one of the several components of the load cell that undergo a change of strain when the force applied is changed. These components will include some or all of the following:

The basic load-carrying elastic element together with any supporting diaphragms and outer case.

The resistance strain gauges, each comprising a metal foil grid with an appropriate backing and adhesive layer.

Wire connecting the strain gauges to form a complete bridge circuit and any precision resistors used to adjust the bridge sensitivity and the temperature coefficients of zero and sensitivity.

When a force is applied, the components that are deformed will undergo a change of temperature due to the change of internal energy with applied strain. As thermal equilibrium is regained, the temperatures of the different components will change, resulting in possible changes in the output of the load cell. The magnitudes of these changes depend on the component's function and the amount of its temperature change. This depends on the magnitude and direction of the strain as well as the material of the component. For steel, a tensile strain will cause a fall in temperature and a compressive strain a rise in temperature of about  $0.19\text{ }^{\circ}\text{C}$  for a strain of 0.001 [1].

Figure 28 shows the change of deflection with time, following the application of the rated compression force, for two elastic elements commonly used in load cells - a hollow steel column and a proving ring. The deflection measurements were made by displacement transducers that were isolated from any temperature change. In the case of the steel column, the application of a compression force causes an increase in the temperature of the column, resulting in an immediate thermal expansion. Thus the deflection immediately after loading, the adiabatic deflection, will be equal to the deflection due to the applied force less the thermal expansion. As the temperature falls as thermal equilibrium is regained, the thermal expansion reduces to zero and the deflection of the column increases until the isothermal value is reached (this increase will not be exactly equal to the thermal expansion as the Young's modulus of the steel will also fall slightly with the fall in temperature). If the column is then unloaded, a reverse sequence of events takes place [1].

#### **4.6.4. Hysteresis**

The hysteresis of a load cell is usually defined as the difference between measurements of load cell output for the same applied force, one measurement obtained by increasing the force from zero and the other by decreasing the force from the rated force. Most load cells exhibit the conventional cigar-shaped hysteresis loop (see Figure 29), the width of the loop being dependent on the amplitude of the load cycle which must therefore be specified when quoting the magnitude of the hysteresis. As the amplitude of the load cycle tends to zero, the hysteresis tends to a value which is less than can currently be measured electrically. If a universal load cell is used from maximum

compression force to maximum tension force. the maximum hysteresis. occurring near zero. will be much larger than the hysteresis quoted for a force applied in one mode only [1].

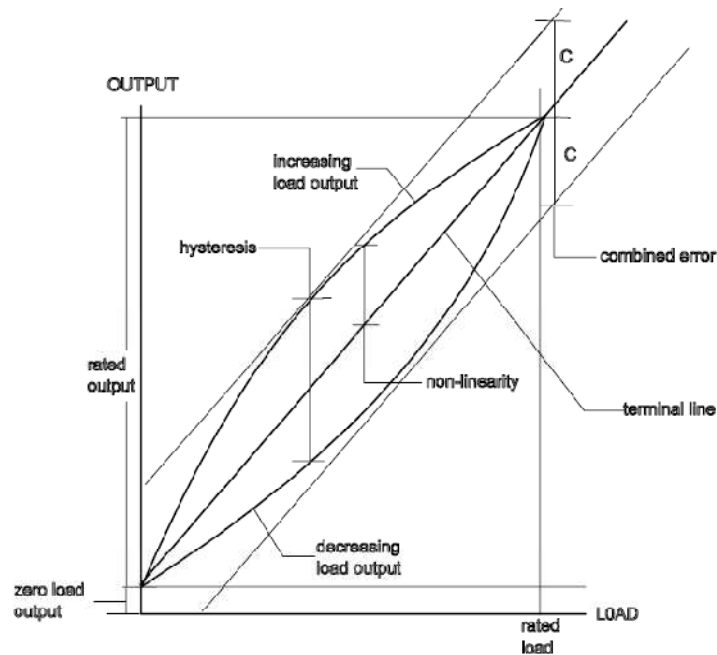


Figure 31: Hysteresis and terminal line of force transducer [1]

The hysteresis of a load cell can only be measured by reference. either directly or indirectly. to a force standard machine which has no hysteresis itself. The only machine of this type at present is the deadweight machine. It is interesting to note that a force applied by a deadweight machine is not truly static. A load cell with a deadweight force applied is essentially a mass spring system with very low damping and there will therefore be a constant oscillation of force due to the general level of ground vibration. The amplitude of force oscillation. however. will generally be small enough not to affect the measurement of the hysteresis characteristic. With any deadweight machine it is not possible to calibrate a device through zero. i.e. to go from tension to compression or vice versa. without involving the force due to the mass of the device itself. At present. the best that can be done is to calibrate a device in one mode and then carefully reposition the device in the machine to continue the calibration directly in the other mode. The forces due to the mass of the different fittings needed for each mode will have to be taken into account together with the force due to the mass of the device itself [1].

When measuring hysteresis. there will always be some masking due to creep and creep recovery. Normally. a hysteresis test is completed in a short time. consistent with smooth operation of the deadweight machine. At the beginning and end of the test. the

output voltage at minimum force was measured and its value corresponding to each force in the test was calculated assuming any change to be uniform with time. The calculated output voltage at minimum force was subtracted from the output voltage at each force to give the difference of output voltage for that force; the hysteresis was then determined by subtracting the difference of output voltage for increasing force from that for decreasing force. The results obtained confirm that, for the load cell tested, the maximum hysteresis in a given cycle is approximately proportional to the amplitude of the cycle.

For high accuracy force measurement, the loading cycle has to be well defined in order to minimise errors due to hysteresis. The hysteresis characteristic of load cells used as force transfer standards is sufficiently repeatable, for a given load cycle, to enable the hysteresis in precision lever and hydraulic machines to be measured.

#### **4.6.5. Temperature Coefficients of Zero and Sensitivity**

The temperature coefficients of the output at zero force and the sensitivity of a precision load cell, over a temperature range of about 50 °C, can be made very small by choosing appropriate values for compensating resistors used in the bridge circuit. Typically, within the range -10 °C to 50 °C, the change of sensitivity can be made to be less than 0.001% per °C and the change of the output at zero less than 0.001% of rated output per °C. It is usually the temperature coefficient of sensitivity that is more important for high accuracy force measurement as the output of the load cell at zero force can be measured at regular intervals in the loading sequence. Each difference of output voltage was calculated by subtracting the average output voltage at zero, before and after the application of a force, from the output voltage with that force applied. The results show that the temperature coefficient is less than 0.001% per °C and that the relationship between sensitivity and temperature, within the repeatability of the measurements, is reversible. As it is normally possible, when undertaking intercomparisons of force standards, to control the temperature within 1°C of a reference value (21°C at UME), errors due to differences of ambient temperature should not be significant. This will only be true, however, if there is no significant temperature gradient in the load cell. Depending on the material of the elastic element and the type of strain gauge used, a temperature difference of 0.1°C between the elastic element and the resistors compensating for the change of sensitivity with temperature will cause an error of about

0.003%. To avoid such errors when obtaining the results, the load cell was left overnight to stabilise following a change of temperature [1].

The temperature of a load cell will increase slightly and a small temperature gradient be induced after the strain gauge bridge is energised. due to energy dissipation in the strain gauges. For high accuracy work, a load cell should be set-up and left energised overnight to reach a state of thermal equilibrium before being used. An insulating box surrounding the load cell reduces the magnitude of any thermal gradients caused by short-term changes of the ambient temperature.

It is possible to use a load cell which has not been compensated for change of sensitivity with temperature provided the change with temperature is reversible and the temperature coefficient has been determined with sufficient accuracy. The temperature of the load cell in use will also have to be measured with sufficient accuracy, generally better than 0.1 °C, and a check will need to be made that thermal gradients are within acceptable limits. In this latter respect, the same accuracy of temperature measurement is required for both a compensated and an uncompensated load cell.

#### **4.6.6. End Loading Conditions**

In general, a load cell has two interfaces through which a force is applied. These may be the upper and lower loading surfaces of a compression load cell or the upper and lower screw threads of a tension load cell. In some load cells, one or both interfaces are part of the elastic element to which the strain gauges are bonded; in other load cells the interfaces are remote from the elastic element, e.g. a permanently attached base pad for a low profile, shear force load cell. At each interface, there will be a force distribution which will depend on the end loading conditions. A change in these conditions, therefore, may cause a change in the force distribution resulting in a change of the sensitivity of the load cell, even though the resultant force at the interface remains unchanged [1].

For compression load cells, the end loading conditions will be determined by:

Properties of the materials in contact at the loading surface of the load cell such as hardness and coefficient of friction.

The shape of the surfaces in contact at the interface.

Deformation of the surfaces under load.

For tension load cells with interfaces at screwed threads, the end loading conditions will be determined by the accuracy of the screw threads of the load cell and the tension adapters and the amount of thread engagement. For beam load cells, the type of support bracket and loading saddle determine the end loading conditions [1].

The International Standards concerned with the calibration of proving devices for the verification of materials testing machines recognises the importance of end loading conditions by requiring compression proving devices to pass a bearing pad test. In this test, a device is loaded through a flat steel pad and then through each of two steel pads that are conically convex and concave respectively by 1 part in 1 000 of the radius. The maximum permitted difference between the sensitivity obtained at maximum force on either conical pad and that obtained on the flat pad is 0.2 % for a Class 1 proving device with a capacity of 500 kN or less.

Depending on the design of load cell, the change of sensitivity caused by a change of end loading conditions can be quite large; some precision compression load cells with low creep, hysteresis and temperature coefficients can show differences of sensitivity in the bearing pad test of 0.3 %, others less than 0.05 %

For tension and compression load cells with a columnar type of elastic element having strain gauges bonded at its mid-length, the length to diameter ( $l/d$ ) ratio is the main parameter that determines the magnitude of the influence of end loading conditions: as the  $l/d$  ratio increases, the influence of end loading conditions is reduced. NPL 500 kN compression load cells having a  $l/d$  ratio of 3.7 (well below the buckling ratio for the design of element) show changes in the bearing pad test of less than 0.005 %. Some commercial load cells with  $l/d$  ratios near unity show changes greater than 1 %. In many designs of compression load cell, the load sensing element is located in a base plate and supported at the top by a diaphragm which is mounted on a robust outer case integral with the base. If the lower loading surface of the base plate is larger than the cross-section of the element, there is the possibility that the base and casing will distort when the load cell is loaded on a conically depressed surface and cause a change of the sensitivity. This change may be reduced if the base plate is machined so that the force is concentrated beneath the element [1].

Many load cells, especially with capacities less than 200 kN, do not have columnar elements. Instead, the element may be of ring form, where bending strains are measured, or may be of a more complicated design where shear strains are measured.

Some designs may be less sensitive to changes of end loading conditions, especially where the strain measurement is made at a point that is well removed from the loading interfaces. It is important, however, to undertake specific tests to show that this is the case. These tests should be applied not only to each type of load cell, but also to different capacity load cells of the same type. The sensitivities of some of the low profile, shear force load cells that are claimed to be insensitive to changes in end loading conditions depend on whether a compression force is applied through the screw thread in the central boss or through its flat upper loading surface [1].

For high accuracy force measurement, the end loading conditions during calibration should represent, as closely as possible, the conditions for the subsequent use of the load cell. Load cells for intercomparison measurements are used with specially designed loading pads that have ground loading surfaces and are sufficiently rigid for the forces applied.

#### **4.6.7. Sensitivity to Moments and Side Forces**

Load cells used to measure a single force component are designed to be insensitive to the orthogonal force components and corresponding moments, provided these are within specified limits. The output of such a load cell should depend only on the magnitude of force along or parallel to a given datum axis. For compression load cells, the datum axis is usually the axis which is perpendicular to the lower loading face and passes through its centre. For a typical beam load cell, a flat surface at the fixed end of the beam may define the direction of the datum axis and a scribed mark on the beam the position of the axis [1].

For a load cell to be sensitive to the magnitude of force in one direction only, it is important to ensure symmetry in both the machining of the elastic element and the positioning of the strain gauges. In practice, there is a limitation to the degree of symmetry that can be achieved and all load cells are sensitive, to some degree, to moments and side forces superimposed on the main force component. The magnitude and sign of the sensitivity of a load cell to a moment or side force, in a given direction relative to the load cell, is not predictable and will vary from one load cell of the same type and capacity to another. The maximum sensitivity in any direction, for a given design and capacity of load cell, will, however, be limited by the tolerances in the machining of the element and the positioning of the strain gauges. The design and capacity of a load cell are important factors. For example, if the external diameter of a

loadcell with a hollow cylindrical element is fixed. the larger the internal diameter. the more sensitive the load cell is likely to be to bending moments. This is because for a given absolute concentricity tolerance. a larger internal diameter can shift the neutral axis further from the nominal position [1].

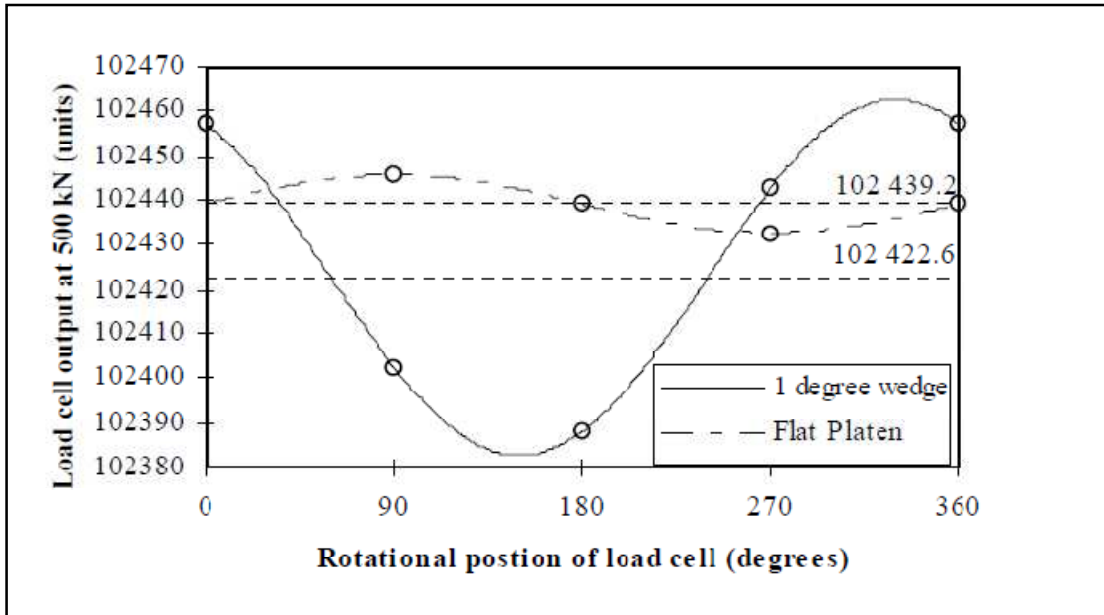


Figure 32. Effect of rotation on load cell output [1]

In addition to the main component of force. force standard machines apply small moments and side forces to load cells being calibrated. In a deadweight machine. there may be uneven distortion of the framework supporting the device and also some uncertainty regarding the positions of the centres of gravity of the weights relative to the assumed loading axis of the machine. Friction in alignment fixtures used to apply the deadweight force to the load cell permits the application of bending moments. The result may be. as well as an insignificant cosine error in the magnitude of the nominal force applied. small moments and side forces which may be significant. To show the significance of any side force or bending moment applied during the calibration and subsequent use of a load cell. measurements should be made for different positions of the load cell in the machines involved. Figure 30 shows the effects of rotating a 500 kN compression load cell about its longitudinal axis in the NPL 500 kN deadweight machine. Results are given with the load cell and its loading pads on the flat platen of the machine and also on a 1 wedge placed between the platen and the lower loading pad. During such rotational tests. it is important to rotate the load cell without introducing a translational movement; special jigs at NPL provide an accurate rotation with translational movements less than 0.1 mm [1].

If it is assumed that the sensitivity of a load cell to side forces and bending moments is linear and that these have a magnitude and direction which are independent of the rotational position of the load cell, there will be a sinusoidal relationship between the load cell's output and its rotational position. The amplitude will be determined by the maximum sensitivity of the load cell in any direction to side forces and moments and also the magnitude of these applied by the machine. The mean value of the sinusoidal relationship is theoretically the value that would be obtained if no side force or bending moment was applied in addition to the main component of force. This is confirmed by the results in Figure 30 where the mean value obtained on the 1° wedge is 0.016% less than that obtained on the flat platen; the expected difference, due to the concurrent cosine error in the magnitude of the applied force, is 0.015%. The good agreement of the results at 360° with those at 0° indicates that no significant translation of the load cell has occurred during its rotation and that the side forces and moments applied by the machine are repeatable [1].

Different force standard machines will apply side forces and moments that differ both in magnitude and direction and it is therefore important, when comparing the magnitudes of nominal forces applied by different machines, to complete a rotational test at each force and obtain the mean output of the load cell. Theoretically, any number of equispaced positions will give a satisfactory mean, two positions being the minimum. For a qualitative comparison of the side forces and moments applied by different machines, four or more positions of rotation are required. An attempt at a quantitative comparison may be made by obtaining results, as shown in Figure 30, with the load cell on a known wedge. Such a comparison, however, must inevitably be of limited accuracy due to the low sensitivity to side forces and bending moments of the load cell [1].

#### **4.6.8. Long Term Stability**

The long-term stability of the sensitivity of strain gauge load cells is clearly important if they are to be used in an intercomparison exercise which may span a period of several weeks or even months. The long-term stability will be determined by several factors including the stability of the load cell's many components, the protection of the strain gauges against humidity and the conditions under which the load cell is stored, transported and used. One important factor for a load cell with a four-way connection is the stability of the lead resistance and contact resistance at the end connections of the lead; where possible, a six-way connection should be used to avoid this problem [1].

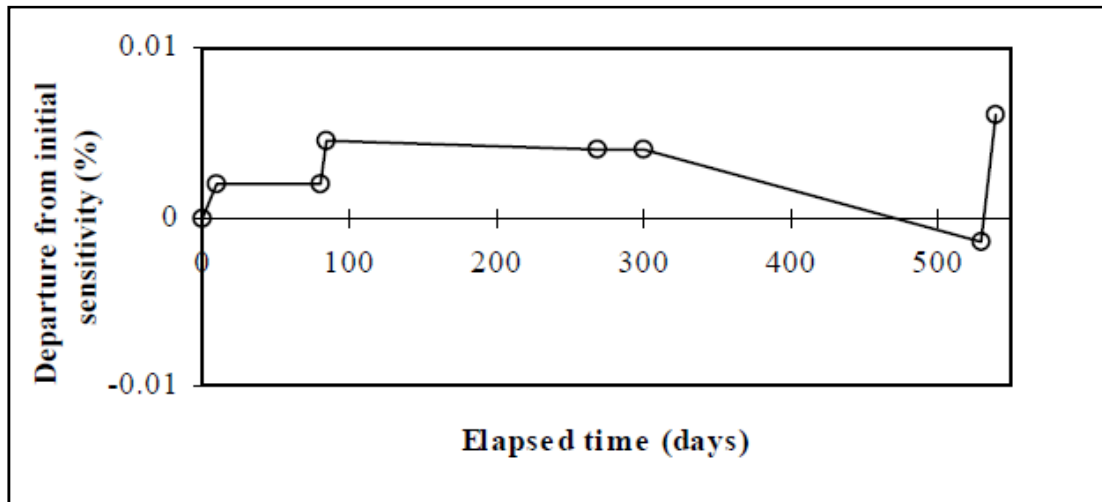


Figure 33. Long term sensitivity of a 500 kN load cell [1]

The long-term stability of the sensitivity of strain gauge load cells used for intercomparison work can be very good. Figure 31 shows all the results obtained over a period of over 500 days for a 500 kN load cell calibrated in the NPL 500 kN deadweight machine. During this period, the load cell was transported to different locations, including one abroad. There does not appear to be any consistent drift with time. Instead, short-term changes following the dismantling and re-assembly of the calibration equipment appear to be more significant [1].

As a conclusion, the characteristics of strain gauge load cells that are known to be important in determining the accuracy obtainable with them have been discussed. These should always be considered when using load cells as force transfer standards. Other characteristics may be found to be important, especially if accuracy requirements are increased.

These factors are also relevant to applications of load cells where accuracies of an order or so less than those discussed are required. In such applications, it is likely that both the performance characteristics of the load cells and their conditions of use will be inferior to those described in this paper, giving rise to greater errors [1].

#### 4.7. Calibration of Force Measuring Instruments

Force measurement is of fundamental importance to many industrial sectors including aerospace, automotive, and offshore. Product liability and safety issues demand that force measurements are traceable to national standards in areas such as the use of seat belts and airbags in vehicles. Competitive advantage can be gained from accurate force measurement, e.g. stress resistance of wing struts and landing gear. Force

measurement is also an essential part of materials testing and weighing, and the need for traceable measurements to a national standard features prominently in the certification to ISO 9000 for both industrial and regulatory force measurements.

To meet this need, national force laboratory should offer wide range of accredited force calibration services using the national force standards machines. This service covers the calibration of most commercially available force transducers (including load cells, proving rings, and shear beams) to the EN ISO 376 (2011), and ASTM E 74-06 (2006) standards, and to a documented in-house procedure.

Measurement range and uncertainties using the following methods are:

- Handweights from 1 N to 200 N at  $\pm 0.005$  %.
- Deadweight machines from 20 N to 4.45 MN at  $\pm 0.002$  %.
- Lever-Hydraulic amplification machine or build-up machine ranging from 100 kN to 30 MN at  $\pm 0.05$  %.

Calibration of force proving instruments (FPI) (force transducer, load cell, dynamometer, proving ring, etc.) are made by using Force Standard Machines. Detail information about calibrated in force standard machines which generate the known force to apply on FPI as the calibration procedure of FPI given in below [8-11]. Force proving instruments are shown in Fig.32

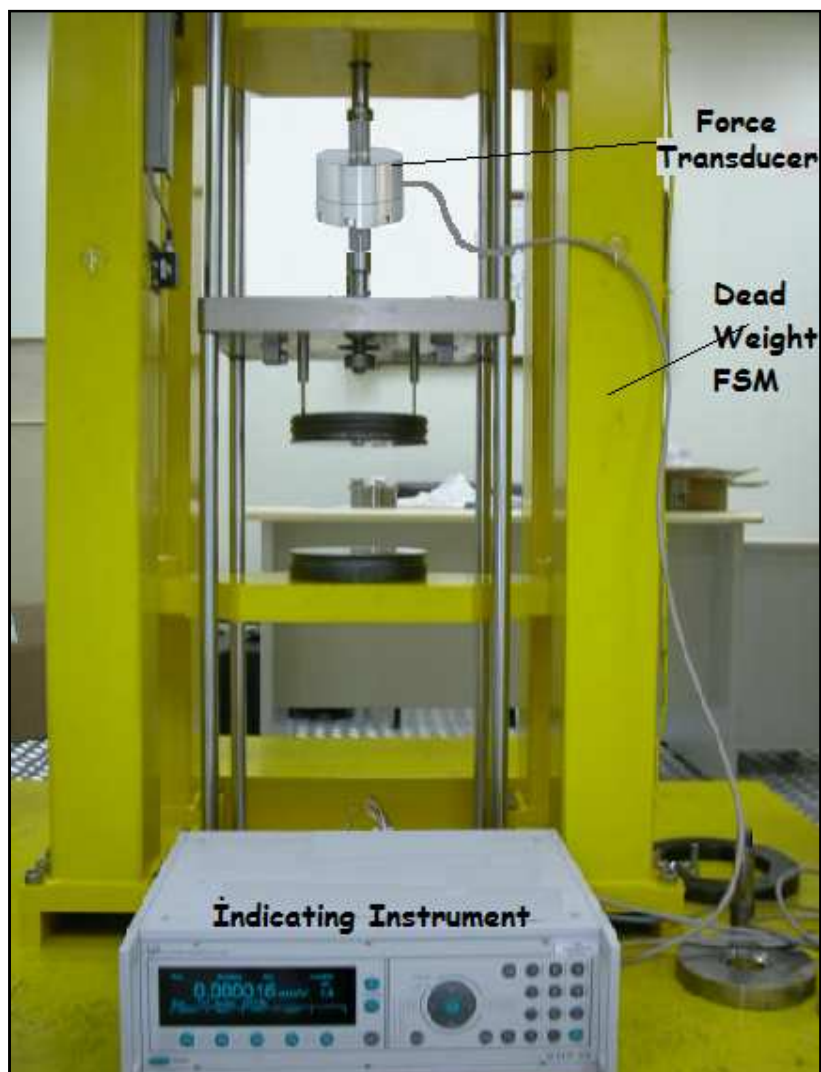


Figure 34. Calibration of Force Proving Instruments in FSM [8]

The calibration shall be performed at a temperature stable to within  $\pm 1$  °C. this temperature shall be within the range 18 °C to 28 °C and shall be recorded. In order to decrease air buoyancy effect. laboratory should be climatized to control humidity level of laboratory air as  $45 \pm 10$  % relative humidity. If the lab. temperature and humidity values are between 19°C and 23°C. 30% RH and 70% RH. you can continue to calibration. Because these value influence the air buoyancy and cause only  $5 \times 10^{-6}$  uncertainty. This value can be neglected compared to uncertainty of force transducers (best one has  $5 \times 10^{-5}$ ).

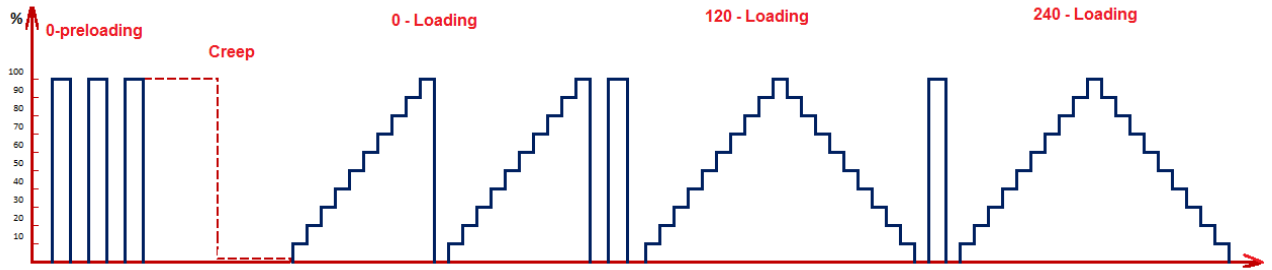


Fig.35. Loading schedule for force transducer calibration

In order to calibrate force proving instruments below rules should be obeyed step by step as below:

**Please make sure that you verified the setup and the concordance of the system as a whole before you get started with the calibration measurement these are;**

- Verification of the correct choice of FSM. depending on the capacity of the instrument to be calibrated.
- Verification to see if there is any anomaly i.e. non-central location of the balance of the chosen FSM.
- Verification to see if our force measurement instrument is adequately centered onto the FSM.

**Then please proceed with pre-tests (exactitude check). These are;**

- Verification to see if repeatability values on the gauge are read while the Force Standard Machine (FSM) is switched on
- Verification to see if the instrument to be calibrated really gives distant values through the realization of a measurement in between some mid values

**Proceed with the calibration after you made sure of everything.**

- Select an FSM (Force Standard Machine) or an FSS (Force Standard System) appropriate to the force measurement ranges of the Force Proving Instrument-FPI.
- Place the Force Measuring Instrument onto the Force Standard Machine in a manner suitable for the application of axial force.
- Center the instrument to be calibrated on the Select an FSM or FSS adequate for the force measurement ranges of the FPI.

- Before you get started with the calibration process. indicate the model. serial number. type. manufacturer's name. outlet voltage. cable length. environmental temperature. pressure. humidity. etc. of the force transducer and the gauge element on the instrument info and environmental conditions on the calibration form.
- Divide into ten equal steps of force values. following the specifications on EN ISO 376 (2011). to reach the maximum capacity. otherwise into at least eight equal steps. For example. an instrument of 100 kN maximum capacity can be calibrated in ten steps as 10 kN. 20 kN. 30 kN. .... 100 kN.
- Make the force measurements. following the specifications on EN ISO 376 (2011). twice on an increasing force series. and twice as an increasing and decreasing force series. and thus in four series in total. During the force measurement sets. the waiting period is at least 30 seconds.
- Make one pre-loading (load and unload of the maximum force value of the instrument). three times before the two increasing series. and once before each of the two increasing and decreasing series. During these pre-loading operations. the waiting period is at least 60 seconds.
- Creep test can be done under full load or onload condition of the force transducers. It can be loaded or unloaded in any rotational position of the transducers. It can also be applied during preloading condition. In this case. before application of third preloading force. creep test is applied combining the third preloading force and registered the load readings in 30 seconds and 300 seconds for the calculation of creep error. Or. it can be applied the maximum (nominal) force on the transducer in 60 seconds (or more) then unloaded the applied force. Then registered the zero readings in 30 seconds and 300 seconds for the calculation of creep error. In this case at 60 seconds. the data is registered for completing the preloading test.
- Before making the pre-loading operation before the increasing and decreasing series after the two increasing series. rotate the transducer 120° (by wearing a pair of gloves). Before the next increasing and decreasing series. apply a rotating degree of 240° compared to the point of start.

- Proceed with the calculations (error, variance, uncertainty calculation and FPI class designation) after saving, on the Force proving instruments calibration form, the calibration data. The execution method of the calculations is explained on EN ISO 376 standard. In the uncertainty calculation, the declared value of the instrument is set forth among the values between 50% and 100%.
- All ambient conditions (temperature and humidity) are registered before and finish of the calibration in the calibration form by hand or by computer.

#### 4.8. Calculations the Calibration Data

On the basis of the input data obtained at the end of the calibration, the below mentioned error values are calculated as well.

##### 4.8.1. Relative reproducibility and repeatability errors. b and b'

These errors are calculated for each calibration force and in both cases, i.e. with rotation of the force-proving instrument (b) and without rotation (b'), using the following equations:

$$b = \left| \frac{X_{\max} - X_{\min}}{\bar{X}_r} \right| \times 100$$

where;

$$\bar{X}_r = \frac{X_1 + X_3 + X_5}{3}$$

$$X_{\max} = \max [X_1, X_3, X_5].$$

$$X_{\min} = \min [X_1, X_3, X_5].$$

and

$$b' = \left| \frac{X_2 - X_1}{\bar{X}_{wr}} \right| \times 100$$

Here,

$$\bar{X}_{wr} = \frac{X_1 + X_2}{2}$$

#### 4.8.2. Relative interpolation error. $f_c$

This error is determined using a third-degree equation giving the deflection  $X_r$  as a function of the calibration force.

The equation used shall be indicated in the calibration report. The relative interpolation error shall be calculated from the equation

$$f_c = \frac{\bar{X}_r - X_a}{X_a} \times 100$$

#### 4.8.3. Relative zero error. $f_0$

The zero reading shall be recorded before and after each series of tests. The zero reading shall be taken approximately 30 s after the force has been completely removed.

The relative zero error is calculated from the equation:

$$f_0 = \frac{i_f - i_0}{X_N} \times 100$$

The maximum relative zero error evaluated should be considered.

#### 4.8.4. Relative reversibility (hysteresis) error . $v$

The relative reversibility error is determined at each calibration. by carrying out verification with increasing forces and then with decreasing forces.

The difference between the values obtained for both series with increasing forces and with decreasing forces enables the relative reversibility error to be calculated using

$$v_1 = \left| \frac{X'_4 - X_3}{X_3} \right| \times 100$$

$$v_2 = \left| \frac{X'_6 - X_5}{X_5} \right| \times 100$$

$v$  is calculated as the mean value of  $v_1$  and  $v_2$ :

$$v = \frac{v_1 + v_2}{2}$$

#### 4.8.5. Relative creep error. $c$

Calculate the difference in outputs  $i_{30}$  obtained at 30 s and  $i_{300}$  obtained 300 s after removal of the maximum calibration force and express this difference as a percentage of maximum deflection:

$$c = \left| \frac{i_{300} - i_{30}}{X_N} \right| \times 100$$

#### 4.8.6. Force transducer temperature shift error. $f_{ft-td}$

$$f_{ft-td} = m_{ft-td} \cdot (t_2 - t_1)$$

As the errors against the temperature shifts of the strain gage based force transducers are appr. 0.001 % /°C and any possible temperature shift during a calibration operation of 2 to 3 hours in the calibration laboratory can be 0.2 °C at the most. this value remains too low. and is being neglected.

#### 4.8.7. Relative resolution error. $e$

$$e = \frac{r}{X_r} \times 100 \quad \text{is the formula applied.}$$

#### Digital scale

The resolution is considered to be one increment of the last active number on the numerical indicator. If the readings fluctuate by more than the value previously

calculated for the resolution (with no force applied to the instrument). the resolution shall be deemed to be equal to half the range of fluctuation.

### **Analogue scale**

The thickness of the graduation marks on the scale shall be uniform and the width of the pointer shall be approximately equal to the width of a graduation mark.

The resolution,  $r$ , of the indicator shall be obtained from the ratio between the width of the pointer and the centre-to-centre distance between two adjacent scale graduation marks (scale interval). the recommended ratios being 1:2, 1:5 or 1:10. a spacing of 1.25 mm or greater being required for the estimation of a tenth of the division on the scale.

A vernier scale of dimensions appropriate to the analogue scale may be used to allow direct fractional reading of the instrument scale division.

### **4.8.9. Classification of Force Proving Instrument**

The range for which the force-proving instrument is classified is determined by considering each calibration force, one after the other, starting with the maximum force and decreasing to the lowest calibration force. The classification range ceases at the last force for which the classification requirements are satisfied. The force-proving instrument can be classified either for specific forces or for interpolation, and for either incremental-only or incremental/decremental loading directions [9]

#### **Classification criteria**

The range of classification of a force-proving instrument shall at least cover the range 50 % to 100 % of  $F_N$ . The class of the force-proving instrument is declared for covering the range 20 % to 100 % of  $F_N$  in the certificate.

**Case A:** For instruments classified only for specific forces and incremental- only loading, the criteria which shall be considered are:

- the relative reproducibility, repeatability and zero errors;
- the relative creep error.

Classification for Case A shall be declared in the certificate only for special request of the customer.

**Case B:** For instruments classified only for specific forces and incremental / decremental loading, the criteria which shall be considered are:

- the relative reproducibility, repeatability and zero errors;
- the relative reversibility error.

Classification for Case B shall be declared in the certificate only for special request of the customer.

**Case C:** For instruments classified for interpolation and incremental-only loading, the criteria which shall be considered are:

- the relative reproducibility, repeatability and zero errors;
- the relative interpolation error;
- the relative creep error

Classification for Case C shall be declared in each the certificate for all case.

**Case D:** For instruments classified for interpolation and incremental/decremental loading, the criteria which shall be considered are:

- the relative reproducibility, repeatability and zero errors;
- the relative interpolation error;
- the relative reversibility error.

Classification for Case D shall be declared in each the certificate for all case.

Table 2 gives the maximum allowable values of these parameters for each class of force-proving instrument and the uncertainty of the calibration forces.

Table 2 — Characteristics of force-proving instruments

Class	Relative error of the force-proving instrument						Expanded uncertainty of applied calibration force (95 % level of confidence) %
	of reproducibility	of repeatability	%		of reversibility	of creep	
	<i>b</i>	<i>b'</i>	of interpolation <i>f<sub>c</sub></i>	of zero <i>f<sub>0</sub></i>	<i>v</i>	<i>c</i>	
00	0,05	0,025	±0,025	±0,012	0,07	0,025	±0,01
0,5	0,10	0,05	±0,05	±0,025	0,15	0,05	±0,02
1	0,20	0,10	±0,10	±0,050	0,30	0,10	±0,05
2	0,40	0,20	±0,20	±0,10	0,50	0,20	±0,10

The same calibration procedure is applied during calibration according to ASTM E74-06 standard. The evaluation is done using to check of uncertainty of force transducers. If the uncertainty is  $\leq 0.05$ . the force measuring instruments is Class (AA) declared in the certificate. If the uncertainty is  $\leq 0.25$ . the force measuring instruments is Class (A) declared in the certificate.

#### 4.9. Uncertainty in Calibration Measurements

##### 4.9.1. Model function of force proving instruments

$$\bar{F} = F_{fsm} + (\delta F_{ft-f_0} + \delta F_{ft-b} + \delta F_{ft-b'} + \delta F_{ft-f_c} + \delta F_{ft-v} + \delta F_{i-e} + \delta F_{ft-td})$$

$\bar{F}$ : Measured force value

$F_{fsm}$ : Applied reference force value produced by force standard machine (FSM)

$\delta F_{ft-f_0}$ : Zero shift effect of force transducer

$\delta F_{ft-b}$ : Repeatability effect of force transducer with rotation

$\delta F_{ft-b'}$ : Repeatability effect of force transducer without rotation

$\delta F_{ft-f_c}$ : Interpolation effect of force transducer

$\delta F_{ft-v}$ : Reversibility (Hysteresis) effect of force transducer

$\delta F_{ft-td}$ : Temperature shift effect of force transducer

$\delta F_{i-e}$ : Resolution effect of indicator

#### 4.9.2. Model Function of Force Standard Machine (FSM)

$$F_{\text{fsm-dw}} = m \cdot g \cdot \left(1 - \frac{\rho_h}{\rho_k}\right) \Rightarrow \text{Uncertainty value is. (for } k=2 \text{ ) } U_{\text{fsm-dw}} = 2 \times 10^{-5} \text{ (for}$$

dead weight machine)

$$F_{\text{fsm-la}} = m \cdot g \cdot \left(1 - \frac{\rho_h}{\rho_c}\right) \cdot Q \Rightarrow \text{Uncertainty value is. (for } k=2 \text{ ) } U_{\text{fsm-la}} = 1 \times 10^{-4} \text{ (for}$$

lever amplification machine)

$$F_{\text{fsm-bu}} = F_{\text{rfmi}} \cdot Q \Rightarrow \text{Uncertainty value is. (for } k=2 \text{ ) } U_{\text{fsm-bu}} = 4 \times 10^{-4} \text{ (for hydraulic}$$

built-up force standard machine)

Q: effects based on lever amplification ratio and/or lever amplification machine

Here. sample uncertainty calculation is given below for dead weight force standard machine for 10 kN dead weight force value;

m: mass of dead weight

g: local gravity

$\rho_h$ : air density

$\rho_k$ : density of mass material

$$m=1020.324 \text{ kg. } g=9.802298 \text{ kgm/sn}^2. \quad \rho_h=1.2 \text{ kg/m}^3. \quad \rho_k=7900 \text{ kg/m}^3 \text{ (for steel )}$$

Sensistivity coefficient calculations;

$$C_m = \frac{\partial F_{\text{fsm}}}{\partial m} = g \cdot \left(1 - \frac{\rho_h}{\rho_k}\right) = 9.800809 \text{ m/sn}^2$$

$$C_g = \frac{\partial F_{\text{fsm}}}{\partial g} = m \cdot \left(1 - \frac{\rho_h}{\rho_k}\right) = 1020.169 \text{ kg}$$

$$C_{\left(\frac{1-\rho_h}{\rho_k}\right)} = \frac{\partial F_{fsm}}{\partial \left(\frac{1-\rho_h}{\rho_k}\right)} = m \cdot g = 10001.52 \text{ kg.m/sn}^2$$

Combined uncertainty of dead weight force standard machine

$$u_{fsm} = \sqrt{c_m^2 \cdot u_m^2 + c_g^2 \cdot u_g^2 + c_{\left(\frac{1-\rho_h}{\rho_k}\right)}^2 \cdot u_{\left(\frac{1-\rho_h}{\rho_k}\right)}^2}$$

$$u_{fsm} = 0.103199 \text{ N .}$$

$$U_g = k \cdot u_{fsm-dw} \text{ (extended uncertainty)}$$

k=2 is coverage factor and confidence level is % 95

$$U_g = 2 \cdot u_{fsm}$$

It is calculated as

$$U_g = 0.206398 \text{ N or } 2.06 \times 10^{-5} \text{ for dead weight force standard machine}$$

Similarly. the uncertainty caused by the lever amplification ratio of the lever amplification machines can only be measured. on an annual basis. through comparative measures held in UME by a machine having a dead load up to 100 kN. or through comparative measurements in foreign institutes held in every 3 to 7 years. The uncertainty value of  $1 \times 10^{-4}$  thus obtained for the force standard machine with lever amplification ratio.

As for the hydraulic force standard machine having reference force transducer with 3 MN capacity. the uncertainties of the three reference force transducer with 1 MN capacity. calibrated by the 1 MN capacity force standard machines. have the biggest effect on built-up FSM. However. the possible measurement uncertainty when they are linked on a parallel basis and then joint. can also be measured on an annual basis.

through comparative measures held in UME by a machine having a dead weight lever amplification machine up to 1000 kN. or through comparative measurements in foreign institutes held in every 3 to 7 years. The uncertainty value of this machine is calculated as  $4 \times 10^{-4}$ .

### 4.9.3. Uncertainty Calculations of Force Proving Instruments

For instruments classified for interpolation. the calibration uncertainty is the uncertainty in the force value calculated from the interpolation equation. at any deflection. for increasing forces only. For instruments classified for specific forces only. the calibration uncertainty is the uncertainty in the force corresponding to any deflection equal to one of the mean deflections obtained during the calibration. for increasing forces only. At each calibration force.  $F$ . a combined standard uncertainty.  $u_c$ . expressed in units of force. is calculated from the readings obtained during the calibration. These combined standard uncertainties are plotted against force. and a least-squares fit covering all the values is calculated. The coefficients of this fit are then multiplied by the coverage factor  $k = 2$  to give an expanded uncertainty value.  $U$ . for any force within the calibration range. An expanded relative uncertainty value.  $W$ . can also then be calculated.

#### The expanded relative uncertainty. $W$

The expanded relative uncertainty  $W$ . may also be calculated from a combination of relative standard uncertainties.  $w_i$ :

$$w_c = \sqrt{\sum_{i=1}^8 w_i^2}$$

and

$$W = k \times w_c$$

and

$$U = W \times F$$

where

$w_1$  is the relative standard uncertainty associated with applied calibration force;

- w<sub>2</sub>** is the relative standard uncertainty associated with reproducibility of cal. results;
- w<sub>3</sub>** is the relative standard uncertainty associated with repeatability of cal. results;
- w<sub>4</sub>** is the relative standard uncertainty associated with resolution of indicator;
- w<sub>5</sub>** is the relative standard uncertainty associated with creep of instrument;
- w<sub>6</sub>** is the relative standard uncertainty associated with the drift in the zero output;
- w<sub>7</sub>** is the rel. standard uncertainty associated with the temperature of the instrument;
- w<sub>8</sub>** is the relative standard uncertainty associated with interpolation.

**NOTE 1** The interpolation component ( w<sub>8</sub>) is not taken into account in the calibration uncertainty with instruments classified for specific forces only.

**NOTE 2** The relative uncertainty can be expressed as a percentage by multiplying by 100.

**Calculation of calibration force uncertainty. w<sub>1</sub>**

u<sub>1</sub> is simply the standard uncertainty associated with the forces applied by the calibration machine. expressed in units of force. and w<sub>1</sub> is the same expressed as a relative value.

**Calculation of reproducibility uncertainty. w<sub>2</sub>**

u<sub>2</sub> is the standard deviation associated with the mean incremental deflections obtained during the calibration. expressed in units of force. and w<sub>2</sub> is the same expressed as a relative value.

$$w_2 = \frac{1}{|\bar{X}_r|} \times \sqrt{\frac{1}{6} \times \sum_{i=1,3,5} (X_i - X_r)^2}$$

where X<sub>i</sub> is the deflection obtained in the incremental series 1. 3. and 5.

**NOTE** This is not the reproducibility of a measured force during the force-proving instrument's subsequent use.

### Calculation of repeatability uncertainty. $w_3$

$u_3$  is the uncertainty contribution due to the repeatability of the measured deflection. expressed in units of force. and  $w_3$  is the same expressed as a relative value. It can be assumed that. at each force.  $F$  :

$$w_3 = \frac{b'}{100 \times \sqrt{3}}$$

where  $b'$  is the relative repeatability error as defined in 4.8.1.

### Calculation of resolution uncertainty. $w_4$

Each deflection value is calculated from two readings (the reading with an applied force minus the reading at zero force). Because of this. the resolution of the indicator needs to be included twice as two rectangular distributions. each with a standard uncertainty of  $r$ . where  $r$  is the resolution. expressed in units of force:

$$w_4 = \frac{1'}{\sqrt{6}} \times \frac{r}{F}$$

### Calculation of creep uncertainty. $w_5$

This uncertainty component is due to the fact that. at a given force. the measured deflection can be influenced by the previous short-term loading history. One measure of this influence is the change in transducer output in the period from 30 s to 300 s after application or removal of the maximum calibration force. This effect is not included in the reproducibility because. generally. the same calibration machine is used for all measurement series and the time/loading profile will be the same.

This effect can be estimated as follows:

$$w_5 = \frac{c}{100 \times \sqrt{3}}$$

If the creep test is not performed, the creep uncertainty can be estimated by dividing the hysteresis by a factor of 3. Therefore, the following equation can be used to calculate this uncertainty contribution for increasing forces:

$$w_5 = \frac{v}{100 \times 3\sqrt{3}}$$

#### Calculation of zero drift uncertainty. $w_6$

This uncertainty component is due to the fact that the instrument's zero output can vary between measurement series and that the measured deflections could be a function of the time spent at zero force between series. This effect is not included in reproducibility because, generally, this time will be the same for all measurement series. One measure of this variation is the zero error,  $f_0$ , so this effect can be estimated as follows:

$$w_6 = \frac{f_0}{100}$$

#### Calculation of temperature uncertainty. $w_7$

This uncertainty is the contribution due to the variation of temperature throughout the calibration, together with the uncertainty in the measurement of the calibration temperature. The sensitivity of the instrument to temperature needs to be estimated, either by tests or from the manufacturer's specifications or by theory or by experience. Expressing this component in units of force or as a relative value, we have:

$$w_7 = K \times \frac{\Delta T}{2} \times \frac{1}{\sqrt{3}}$$

where

$K$  is the instrument's temperature coefficient, in reciprocal degrees Celsius ( $^{\circ}\text{C}^{-1}$ );

$\Delta T$  is the calibration temperature range, allowing for the uncertainty in the measurement of the temperature.

## Calculation of interpolation uncertainty. $w_8$

This component is not taken into account in the calibration uncertainty for instruments classified for specific forces only.

It is the contribution due to the plotted force/deflection points not all falling on the best-fit line. leading to an uncertainty in the interpolation equation. Either of the two methods given in ISO 376 in the section C.1.9.2 and C.1.9.3.

It is preferred to use second method given in C.1.9.3 named in “Deviation Method” in this calculations.

### **DEVIATION METHOD**

The component is the difference between the mean measured deflection and the value calculated from the interpolation equation:

$$w_8 = \left| \frac{\bar{X}_r - X_a}{\bar{X}_r} \right|$$

### **Combined standard uncertainty and expanded uncertainty as relative values**

For each calibration force. calculate the combined standard uncertainty.  $w_c$ . by combining the individual standard uncertainties in quadrate:

$$w_c = \sqrt{\sum_{i=1}^8 w_i^2}$$

Plot a graph of  $w_c$  against force and then determine the coefficients of the best-fit least-squares line through all of the data points.

The form of the fitted line (e.g. linear. polynomial. exponential) will depend on the calibration results. If this results in values lower than the minimum combined uncertainty value. a more conservative fit should be employed and/or a minimum value for the uncertainty should be specified for the relevant parts of the calibration range. It is suggested that this be equal to the minimum combined standard uncertainty obtained.

The expanded uncertainty.  $W$ . is given by the equation whose coefficients are twice those of the best-fit equation. For any force within the calibration range. an expanded uncertainty can then be calculated. expressed as a relative value.

Combined relative measurement uncertainty of force measuring instrument is defined as below ( $W_c$ ). Calculation of  $w_i$  are given in detail in section between 6.2.1 and 6.2.10;

$$w_c = \sqrt{\sum_{i=1}^8 w_i^2}$$

$$W_c = \sqrt{W_1^2 + W_2^2 + W_3^2 + W_4^2 + W_5^2 + W_6^2 + W_7^2 + W_8^2}$$

Extenden measurement uncertainty of calibrated force measuring instruments is written as below;

$$W = k \times w_c$$

$k=2$  is coverage factor and confidence level is % 95

The relative measurement uncertainty of the calibration. “W”. shall be calculated in accordance with the “Guide to the Expression of Uncertainty in Measurement (GUM 1995- **JCGM 100:2008.**)” and **EA-4/02 “Expression of the Uncertainty of Measurement in Calibration:1999”**. U representing the enlarged value of uncertainty. the scope factor of the combined uncertainties is calculated on the basis of;  $k = 2$ . Reliability rate is 95%.

## Uncertainty components

Uncertainty components and distributions		
Uncertainty parameters	Probability Distributions	Variances. $w^2$
Uncertainty of force standard machine	Normal Distributions	$w_1 = \frac{W_{fsm}}{2}$
Reproducibility error. $b$	Normal Distributions	$w_2 = \frac{1}{ \bar{X}_r } \times \sqrt{\frac{1}{6} \times \sum_{i=1,3,5} (X_i - \bar{X}_r)^2}$
Repeatability error. $b'$	Rectangular Distributions	$w_3 = \frac{b'}{100 \times \sqrt{3}}$
Resolution error. $e$	Triangular Distributions	$w_4 = \frac{1'}{\sqrt{6}} \times \frac{r}{F}$
Creep error. $c$	Rectangular Distributions	$w_5 = \frac{c}{100 \times \sqrt{3}}$
Zero error. $f_0$	$\delta$ Distributions	$w_6 = \frac{f_0}{100}$
Temperature error. $f_{td}$	Rectangular Distributions	$w_7 = K \times \frac{\Delta T}{2} \times \frac{1}{\sqrt{3}}$
Interpolation error. $f_c$	$\delta$ Distributions	$w_8 = \left  \frac{\bar{X}_r - X_a}{\bar{X}_r} \right $
Sensitivity coefficient for all parameters $c = 1$		

#### 4.10. Sample Error and Uncertainty Calculations of Calibration Data

##### Preloading Data (Readings)

F [kN]	0	10.0	0
	$i_0$ [mV/V]	$X_N$ [mV/V]	$i_f$ [mV/V]
3 preloadings before 1. serie	- 0.003980	2.002530	- 0.003960
	- 0.003960	2.002535	- 0.003955
	- 0.003955	2.002540	- 0.003945
1 preloading Before 3. serie	- 0.003880	2.002615	- 0.003875
1 preloadings before 4. serie	- 0.003885	2.002615	- 0.003875

##### Creep data (Readings)

(at 30 and 300 seconds after unloading of the last 3. preloading)

kN	$i_{30}$ [mV/V]	$i_{300}$ [mV/V]
0 kN	- 0.003955	-0.004005

##### Measuring Series (Readings)

F [kN]	1. Serie	2. Serie
	$i$ [mV/V]	$i$ [mV/V]
0	- 0.003960	- 0.003920
1.0	0.196670	0.196715
2.0	0.397320	0.397360
3.0	0.598000	0.598035
4.0	0.798690	0.798725
5.0	0.999380	0.999420
6.0	1.200070	1.200105
7.0	1.400745	1.400775
8.0	1.601385	1.601420
9.0	1.802000	1.802010
10.0	2.002575	2.002600
0	- 0.003905	- 0.003870

F [kN]	3. Serie		4. Serie	
	i [mV/V]	i' [mV/V]	i [mV/V]	i' [mV/V]
0	- 0.003900	- 0.003865	- 0.003895	- 0.003855
1.0	0.196730	0.196820	0.196735	0.196825
2.0	0.397380	0.397510	0.397390	0.397525
3.0	0.598055	0.598215	0.598065	0.598225
4.0	0.798750	0.798915	0.798755	0.798925
5.0	0.999440	0.999600	0.999450	0.999615
6.0	1.200125	1.200270	1.200140	1.200280
7.0	1.400795	1.400915	1.400810	1.400920
8.0	1.601440	1.601520	1.601450	1.601545
9.0	1.802055	1.802095	1.802065	1.802105
10.0	2.002625	--	2.002635	--

### Preloading Data (zero-ed data)

F [kN]	0	10.0	0
	X [mV/V]	X <sub>N</sub> [mV/V]	X [mV/V]
3 preloadings before 1. serie	0.000000	2.006510	0.000020
	0.000000	2.006495	0.000005
	0.000000	2.006495	0.000010
1 preloading before 3. serie	0.000000	2.006495	0.000005
1 preloadings before 4. serie	0.000000	2.002500	0.000010

### Data of Measuring Series (zero-ed data)

	1. Serie	2. Serie
F [kN]	X <sub>1</sub> [mV/V]	X <sub>2</sub> [mV/V]
0	0.000000	0.000000
1.0	0.200630	0.200635
2.0	0.401280	0.401280
3.0	0.601960	0.601955
4.0	0.802650	0.802645
5.0	1.003340	1.003340
6.0	1.204030	1.204025
7.0	1.400705	1.404695
8.0	1.605345	1.605340
9.0	1.805960	1.805930
10.0	2.006535	2.006520
0	0.000055	0.000050

	3. Serie		4. Serie	
F [kN]	X <sub>3</sub> [mV/V]	X <sub>4</sub> [mV/V]	X <sub>5</sub> [mV/V]	X <sub>6</sub> [mV/V]
0	0.000000	0.000035	0.000000	0.000040
1.0	0.200630	0.200720	0.200630	0.200720
2.0	0.401280	0.401410	0.401285	0.401420
3.0	0.601955	0.602115	0.601960	0.602120
4.0	0.802650	0.802815	0.802650	0.802820
5.0	1.003340	1.003500	1.003345	1.003510
6.0	1.204025	1.204170	1.204035	1.204175
7.0	1.404695	1.404815	1.404705	1.404815
8.0	1.605340	1.605420	1.605345	1.605440
9.0	1.805955	1.805995	1.805960	1.806000
10.0	2.006525	--	2.006530	--

### Calculation of Relative Repeatability . b

$$b = \frac{|X_{\max} - X_{\min}|}{\bar{X}_r} \times 100$$

$$\bar{X}_r = \frac{X_1 + X_3 + X_5}{3}$$

$$X_{\max} = \max [X_1, X_3, X_5], \quad X_{\min} = \min [X_1, X_3, X_5]$$

F [kN]	X <sub>1</sub> [mV/V]	X <sub>3</sub> [mV/V]	X <sub>5</sub> [mV/V]	$\bar{X}_r$ [mV/V]	b [%]
1.0	0.200630	0.200630	0.200630	0.200630	0.000
2.0	0.401280	0.401280	0.401285	0.401282	0.001
3.0	0.601960	0.601955	0.601960	0.601958	0.001
4.0	0.802650	0.802650	0.802650	0.802650	0.000
5.0	1.003340	1.003340	1.003345	1.003342	0.000
6.0	1.204030	1.204025	1.204035	1.204030	0.001
7.0	1.404705	1.404695	1.404705	1.404702	0.001
8.0	1.605345	1.605340	1.605345	1.605343	0.000
9.0	1.805960	1.805955	1.805960	1.805958	0.000
10.0	2.006535	2.006525	2.006530	2.006530	0.000

### Calculation of Relative Reproducibility Error. b'

$$b' = \frac{|X_2 - X_1|}{\bar{X}_{wr}} \times 100$$

$$\bar{X}_{wr} = \frac{X_1 + X_2}{2}$$

F [kN]	X <sub>1</sub> [mV/V]	X <sub>2</sub> [mV/V]	$\bar{X}_{wr}$ [mV/V]	b' [%]
1.0	0.200630	0.200635	0.200633	0.002
2.0	0.401280	0.401280	0.401280	0.000
3.0	0.601960	0.601955	0.601958	0.001
4.0	0.802650	0.802645	0.802648	0.001
5.0	1.003340	1.003340	1.003340	0.000
6.0	1.204030	1.204025	1.204028	0.000
7.0	1.404705	1.404695	1.404700	0.001
8.0	1.605345	1.605340	1.605343	0.000
9.0	1.805960	1.805930	1.805945	0.002
10.0	2.006535	2.006520	2.006528	0.001

### Calculation of Relative Zero Error

$$f_0 = \frac{i_f - i_0}{X_N} \times 100$$

F [kN]	0	10.0	0	
	$i_0$ [mV/V]	$X_N$ [mV/V]	$i_f$ [mV/V]	$f_0$ [%]
Before 1.Serie	- 0.003980	2.002530	- 0.003960	0.001
	- 0.003960	2.002535	- 0.003955	0.000
	- 0.003955	2.002540	- 0.003945	0.000
Before 3.Serie	- 0.003880	2.002615	- 0.003875	0.000
Before 4.Serie	- 0.003885	2.002615	- 0.003875	0.000
1.Seri	- 0.003960	2.002575	- 0.003905	0.003
2. Seri	- 0.003920	2.002600	- 0.003870	0.002
3.Seri	- 0.003900	2.002625	- 0.003865	0.002
4.Seri	- 0.003895	2.002635	- 0.003855	0.002

### Calculation of Relative Interpolation Error

Using the Least-Square and Gauss-Jordan Elimination methods. a. b. c coefficients of third degree interpolation equation will be calculated as below.

#### Least-Square method :

In order to obtain third degree equations.

$e_i$  = error term

S = sum of square

$$x = F[\text{kN}]$$

$$y = X[\text{mV} / \text{V}]$$

$$y_i = a \cdot x_i + b \cdot x_i^2 + c \cdot x_i^3$$

$$S = e_i^2 = \sum_{i=1}^n (Y_i - y_i)^2 = \sum_{i=1}^n (Y_i - a \cdot x_i - b \cdot x_i^2 - c \cdot x_i^3)^2$$

$$\frac{\partial S}{\partial a} = 0 \quad \Rightarrow \quad \sum_{i=1}^n 2 \cdot (-x_i) \cdot (Y_i - a \cdot x_i - b \cdot x_i^2 - c \cdot x_i^3) = 0$$

$$a \sum_{i=1}^n x_i^2 + b \sum_{i=1}^n x_i^3 + c \sum_{i=1}^n x_i^4 = \sum_{i=1}^n x_i \cdot Y_i$$

$$\frac{\partial S}{\partial b} = 0 \quad \Rightarrow \quad \sum_{i=1}^n 2 \cdot (-x_i^2) \cdot (Y_i - a \cdot x_i - b \cdot x_i^2 - c \cdot x_i^3) = 0$$

$$a \sum_{i=1}^n x_i^3 + b \sum_{i=1}^n x_i^4 + c \sum_{i=1}^n x_i^5 = \sum_{i=1}^n x_i^2 \cdot Y_i$$

$$\frac{\partial S}{\partial c} = 0 \quad \Rightarrow \quad \sum_{i=1}^n 2 \cdot (-x_i^3) \cdot (Y_i - a \cdot x_i - b \cdot x_i^2 - c \cdot x_i^3) = 0$$

$$a \sum_{i=1}^n x_i^4 + b \sum_{i=1}^n x_i^5 + c \sum_{i=1}^n x_i^6 = \sum_{i=1}^n x_i^3 \cdot Y_i$$

<b>F</b>	$\bar{X}_R$	<b>F<sup>2</sup></b>	<b>F<sup>3</sup></b>	<b>F<sup>4</sup></b>	<b>F<sup>5</sup></b>	<b>F<sup>6</sup></b>	<b>F · <math>\bar{X}_R</math></b>	<b>F<sup>2</sup> · <math>\bar{X}_R</math></b>	<b>F<sup>3</sup> · <math>\bar{X}_R</math></b>
<b>x</b>	<b>y</b>	<b>x<sup>2</sup></b>	<b>x<sup>3</sup></b>	<b>x<sup>4</sup></b>	<b>x<sup>5</sup></b>	<b>x<sup>6</sup></b>	<b>x·y</b>	<b>x<sup>2</sup>·y</b>	<b>x<sup>3</sup>·y</b>
0	0.000000	0	0	0	0	0	0.00000	0.00000	0.00000
1.0	0.200630	1.0	1.0	1.0	1.0	1.0	0.20063	0.20063	0.20063
2.0	0.401282	4.0	8.0	16.0	32.0	64.0	0.80256	1.60513	3.21025
3.0	0.601958	9.0	27.0	81.0	243.0	729.0	1.80587	5.41763	16.25288
4.0	0.802650	16.0	64.0	256.0	1024.0	4096.0	3.21060	12.84240	51.36960
5.0	1.003342	25.0	125.0	625.0	3125.0	15625.0	5.01671	25.08354	125.41771
6.0	1.204030	36.0	216.0	1296.0	7776.0	46656.0	7.22418	43.34508	260.07048
7.0	1.404702	49.0	343.0	2401.0	16807.0	117649.0	9.83291	68.83038	481.81267
8.0	1.605343	64.0	512.0	4096.0	32768.0	262144.0	12.84275	102.74197	821.93579
9.0	1.805958	81.0	729.0	6561.0	59049.0	531441.0	16.25363	146.28263	1316.54363
10.0	2.006530	100.0	1000.0	10000	100000	1000000	20.06530	200.65300	2006.53000

<b>Σ</b>	<b>385.0</b>	<b>3025.0</b>	<b>25333</b>	<b>220825</b>	<b>1978405</b>	<b>77.25514</b>	<b>607.00238</b>	<b>5083.34363</b>
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$$385.0 \cdot a + 3025.0 \cdot b + 25333.0 \cdot c = 77.255140$$

$$3025.0 \cdot a + 25333.0 \cdot b + 220825.0 \cdot c = 607.002383$$

$$25333.0 \cdot a + 220825.0 \cdot b + 1978405.0 \cdot c = 5083.343630$$

$$\begin{bmatrix} 385.0 & 3025.0 & 25333.0 \\ 3025.0 & 25333.0 & 220825.0 \\ 25333.0 & 220825.0 & 1978405.0 \end{bmatrix} \cdot \begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} 77.255140 \\ 607.002383 \\ 5083.343630 \end{bmatrix}$$

**Gauss-Jordan Elimination methods:**

3 unknown term of equation can be be calculated as below ;

$$[S]^0 = \left[ \begin{array}{ccc|c} s_{11}^0 & s_{12}^0 & s_{13}^0 & s_{14}^0 \\ s_{21}^0 & s_{22}^0 & s_{23}^0 & s_{24}^0 \\ s_{31}^0 & s_{32}^0 & s_{33}^0 & s_{34}^0 \end{array} \right]$$

$$s_{ij}^k = s_{ij}^{k-1} - \frac{s_{ik}^{k-1}}{s_{kk}^{k-1}} \cdot s_{kj}^{k-1}$$

$k = 1 \rightarrow 2$   
 $j = 2 \rightarrow 4$   
 $i = 2 \rightarrow 3$

$$[S]^0 = \begin{bmatrix} 385 & 3025 & 25333 & 77.25514 \\ 3025 & 25333 & 220825 & 607.00238 \\ 25333 & 220825 & 1978405 & 5083.34363 \end{bmatrix}$$

$$[S]^1 = \begin{bmatrix} 385 & 3025 & 25333 & 77.25514 \\ 0 & 602580 & 8385300 & -0.8822 \\ 0 & 8385300 & 119925036 & -17.1641 \end{bmatrix}$$

$$[S]^2 = \begin{bmatrix} 385 & 3025 & 25333 & 77.25514 \\ 0 & 602580 & 8385300 & -0.8822 \\ 0 & 0 & 1951172102000 & -2945232 \end{bmatrix}$$

$\mathbf{c} = -0.00000150947 \text{ mV}/(\text{V} \cdot \text{kN}^3)$   
 $\mathbf{b} = 0.0000195412085 \text{ mV}/(\text{V} \cdot \text{kN}^2)$   
 $\mathbf{a} = 0.200608486 \text{ mV}/(\text{V} \cdot \text{kN})$

$$X_a = 0.2006082298 \cdot F + 0.00001961995722241 \cdot F^2 - 0.000001514973881657748 \cdot F^3$$

Using this equation below table is established;

F [kN]	0.0	0.1	0.2	0.3	0.4
	$X_a$ [mV/V]				
1.0	0.200626	0.220691	0.240756	0.260821	0.280886
1.5	0.300951	0.321017	0.341083	0.361150	0.381216
2.0	0.401283	0.421350	0.441417	0.461484	0.481552
2.5	0.501620	0.521687	0.541755	0.561824	0.581892
3.0	0.601960	0.622029	0.642098	0.662166	0.682235
3.5	0.702304	0.722373	0.742442	0.762511	0.782581
4.0	0.802650	0.822719	0.842788	0.862858	0.882927
4.5	0.902996	0.923066	0.943135	0.963204	0.983273
5.0	1.003342	1.023411	1.043480	1.063549	1.083618
5.5	1.103687	1.123755	1.143824	1.163892	1.183960
6.0	1.204028	1.224096	1.244164	1.264232	1.284299
6.5	1.304366	1.324433	1.344500	1.364567	1.384633
7.0	1.404699	1.424765	1.444831	1.464896	1.484961
7.5	1.505026	1.525091	1.545155	1.565219	1.585283
8.0	1.605346	1.625409	1.645471	1.665534	1.685596
8.5	1.705657	1.725718	1.745779	1.765840	1.785900
9.0	1.805959	1.826018	1.846077	1.866135	1.886193
9.5	1.906250	1.926307	1.946363	1.966419	1.986474
10.0	2.006529	2.026584	2.046638	2.066691	2.086744

Interpolation error can be calculated as below;

$$f_c = \frac{\bar{X}_r - X_a}{X_a} \times 100$$

F [kN]	$\bar{X}_r$ [mV/V]	$X_a$ [mV/V]	$f_c$ [%]
1.0	0.200630	0.200626	0.002
2.0	0.401282	0.401283	-0.001
3.0	0.601958	0.601960	0.000
4.0	0.802650	0.802650	0.000
5.0	1.003342	1.003342	0.000
6.0	1.204030	1.204028	0.000
7.0	1.404702	1.404699	0.000
8.0	1.605343	1.605346	0.000
9.0	1.805958	1.805959	0.000
10.0	2.006530	2.006529	0.000

### Calculation Of Relative Reversibility (Hysteresis) Error

$$v_1 = \left| \frac{X'_4 - X_3}{X_3} \right| \times 100$$

3. Serie			
F [kN]	X <sub>3</sub> [mV/V]	X' <sub>4</sub> [mV/V]	v <sub>1</sub> [%]
1.0	0.200630	0.200720	0.045
2.0	0.401280	0.401410	0.032
3.0	0.601955	0.602115	0.027
4.0	0.802650	0.802815	0.021
5.0	1.003340	1.003500	0.016
6.0	1.204025	1.204170	0.012
7.0	1.404695	1.404815	0.009
8.0	1.605340	1.605420	0.005
9.0	1.805955	1.805995	0.002

$$v_2 = \left| \frac{X'_6 - X_5}{X_5} \right| \times 100$$

4. Serie			
F [kN]	i <sub>4</sub> [mV/V]	i' <sub>4</sub> [mV/V]	v <sub>2</sub> [%]
1.0	0.200630	0.200720	0.045
2.0	0.401285	0.401420	0.032
3.0	0.601960	0.602120	0.027
4.0	0.802650	0.802820	0.021
5.0	1.003345	1.003510	0.017
6.0	1.204035	1.204175	0.011
7.0	1.404705	1.404815	0.008
8.0	1.605345	1.605440	0.006
9.0	1.805960	1.806000	0.002

Calculated reversibility error both 3. and 4. serie measurement data can be averaged using below equation;

$$v = \frac{v_1 - v_2}{2}$$

F [kN]	v <sub>1</sub> [%]	v <sub>2</sub> [%]	v [%]
1.0	0.045	0.045	0.045
2.0	0.032	0.032	0.032
3.0	0.027	0.027	0.027
4.0	0.021	0.021	0.021
5.0	0.016	0.017	0.016
6.0	0.012	0.012	0.012
7.0	0.009	0.008	0.008
8.0	0.005	0.006	0.005
9.0	0.002	0.002	0.002

### Calculation of Relative Creep Error . c

$$c = \left| \frac{i_{300} - i_{30}}{X_N} \right| \times 100$$

kN	i <sub>30</sub> [mV/V]	X <sub>N</sub> [mV/V]	i <sub>300</sub> [mV/V]	C %
0 kN	- 0.003955	2.002540	-0.005005	-0.001

### Calculation of Relative Resolution Error

$$e = \frac{r}{X_r} \times 100$$

F [kN]	r [mV/V]	$\bar{X}_r$ [mV/V]	e [%]
1.0	0.000005	0.200630	0.002
2.0		0.401282	0.001
3.0		0.601958	0.001
4.0		0.802650	0.001
5.0		1.003342	0.000
6.0		1.204030	0.000
7.0		1.404702	0.000
8.0		1.605343	0.000
9.0		1.805958	0.000
10.0		2.006530	0.000

## Classification of Force Proving Instruments

Table 2 — Characteristics of force-proving instruments

Class	Relative error of the force-proving instrument						Expanded uncertainty of applied calibration force (95 % level of confidence) %
	%						
	of reproducibility <i>b</i>	of repeatability <i>b'</i>	of interpolation <i>f<sub>c</sub></i>	of zero <i>f<sub>0</sub></i>	of reversibility <i>v</i>	of creep <i>c</i>	
00	0,05	0,025	±0,025	±0,012	0,07	0,025	±0,01
0,5	0,10	0,05	±0,05	±0,025	0,15	0,05	±0,02
1	0,20	0,10	±0,10	±0,050	0,30	0,10	±0,05
2	0,40	0,20	±0,20	±0,10	0,50	0,20	±0,10

Measuring range	Class for Case C (according to <i>b</i> , <i>b'</i> , <i>f<sub>0</sub></i> , <i>f<sub>c</sub></i> , <i>c</i> )	Class for Case D (according to <i>b</i> , <i>b'</i> , <i>f<sub>0</sub></i> , <i>f<sub>c</sub></i> , <i>v</i> )
1 kN - 10 kN	00	00
2 kN - 10 kN	00	00
3 kN - 10 kN	00	00
4 kN - 10 kN	00	00
5 kN - 10 kN	00	00

## Uncertainty Calculations of Force Proving Instruments

$w_1$  : uncertainty of applied force,  $2 \cdot 10^{-5}$

$$w_2 = \frac{1}{|\bar{X}_r|} \times \sqrt{\frac{1}{6} \times \sum_{i=1,3,5} (X_i - X_r)^2}$$

$$w_3 = \frac{b'}{100 \times \sqrt{3}}$$

$$w_4 = \frac{1'}{\sqrt{6}} \times \frac{r}{F}$$

$$w_5 = \frac{c}{100 \times \sqrt{3}}$$

$$w_6 = \frac{f_0}{100}$$

$$w_7 = K \times \frac{\Delta T}{2} \times \frac{1}{\sqrt{3}}$$

$$w_8 = \left| \frac{\bar{X}_r - X_a}{\bar{X}_r} \right|$$

$$W_c = \sqrt{W_1^2 + W_2^2 + W_3^2 + W_4^2 + W_5^2 + W_6^2 + W_7^2 + W_8^2}$$

<b>F [kN]</b>	<b>X<sub>r</sub></b> [mV/V]	<b>X<sub>wr</sub></b> [mV/V]	<b>X<sub>a</sub></b> [mV/V]	<b>b</b> [%]	<b>b'</b> [%]	<b>f<sub>c</sub></b> [%]	<b>v</b> [%]	<b>W</b> [%]
<b>1.0</b>	0.200630	0.200633	0.200626	<b>0.000</b>	<b>0.002</b>	<b>0.002</b>	<b>0.045</b>	<b>0.054</b>
<b>2.0</b>	0.401280	0.401280	0.401282	<b>0.000</b>	<b>0.000</b>	<b>-0.001</b>	<b>0.032</b>	<b>0.040</b>
<b>3.0</b>	0.601957	0.601958	0.601959	<b>0.001</b>	<b>0.001</b>	<b>0.000</b>	<b>0.027</b>	<b>0.034</b>
<b>4.0</b>	0.802650	0.802648	0.802648	<b>0.000</b>	<b>0.001</b>	<b>0.000</b>	<b>0.021</b>	<b>0.028</b>
<b>5.0</b>	1.003340	1.003340	1.003340	<b>0.000</b>	<b>0.000</b>	<b>0.000</b>	<b>0.016</b>	<b>0.024</b>
<b>6.0</b>	1.204027	1.204028	1.204026	<b>0.000</b>	<b>0.000</b>	<b>0.000</b>	<b>0.012</b>	<b>0.020</b>
<b>7.0</b>	1.404698	1.404700	1.404697	<b>0.001</b>	<b>0.001</b>	<b>0.000</b>	<b>0.009</b>	<b>0.018</b>
<b>8.0</b>	1.605342	1.605343	1.605343	<b>0.000</b>	<b>0.000</b>	<b>0.000</b>	<b>0.005</b>	<b>0.018</b>
<b>9.0</b>	1.805957	1.805945	1.805957	<b>0.000</b>	<b>0.002</b>	<b>0.000</b>	<b>0.002</b>	<b>0.018</b>
<b>10.0</b>	2.006528	2.006528	2.006528	<b>0.000</b>	<b>0.001</b>	<b>0.000</b>	<b>-.-</b>	<b>-.-</b>

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