# STRAIN CYLINDERS FOR COMPRESSION TESTING MACHINES

Philippe Averlant

Head of Force and Torque Laboratory
Laboratoire National d'Essais, France

**ABSTRACT**

Measurement results of the compressive strength of concrete specimens depend on the manner of force transfer by the testing machine. This performance is verified according to a standard using strain cylinders. However, the qualification or calibration of strain cylinders is not defined in the standard. This paper presents a new procedure for cylinder calibration. The measurand is defined. The standard quantity is modelised depending on the specific manner of loading during calibration. Uncertainties are computed using theoretical equations. The results of a first cylinder calibration are given.

## 1. INTRODUCTION

Safety concerns about concrete constructions have initiated a series of European standards dedicated to the study and assessment of the characteristics of concrete. The main safety characteristic of concrete is its capacity to resist compressive loads. This characteristic depends on many factors, including the nature of its components. In order to study and qualify concrete, concrete specimens are tested in compression on specific machines. To ensure the quality of these tests, testing machines are subject to standard specifications. The calibration of testing machines designed for measuring the compressive strength of concrete is currently under the scope of the European standard EN 12390-4 [1]. This standard specifies in particular the procedure for assessing the accuracy of force indication. Classes of testing machines are currently recognized, corresponding to scale accuracies. A uniform force distribution within a section of the specimen is at least as much important with regard to the effect upon measured compressive strength. As a result, the European standard includes requirements for the manner of force transfer. It defines strain gauged columns, hereafter "strain cylinders", and the proving procedures to be implemented. Strain cylinders are used to assess the uniform distribution of the forces generated by the machine within a section of the specimen. However, the procedure for cylinder qualification and calibration is not specified. So far, at the European level at least, there is no standard or recognized procedure showing the traceability to national standards. **So far, there is no calibration of strain cylinders**.

Strain cylinders, which are used to measure force distribution, shall be interchangeable so that the calibration results of the machine do not depend on the cylinder. Moreover, in order not to influence assessment results, they shall disclose a force distribution close to the one applied to them. These requirements show the need to establish a procedure for cylinder calibration, set maximum accuracy errors, and verify that after calibration the accuracy errors of every cylinder used in machine calibration are below the maximum values.

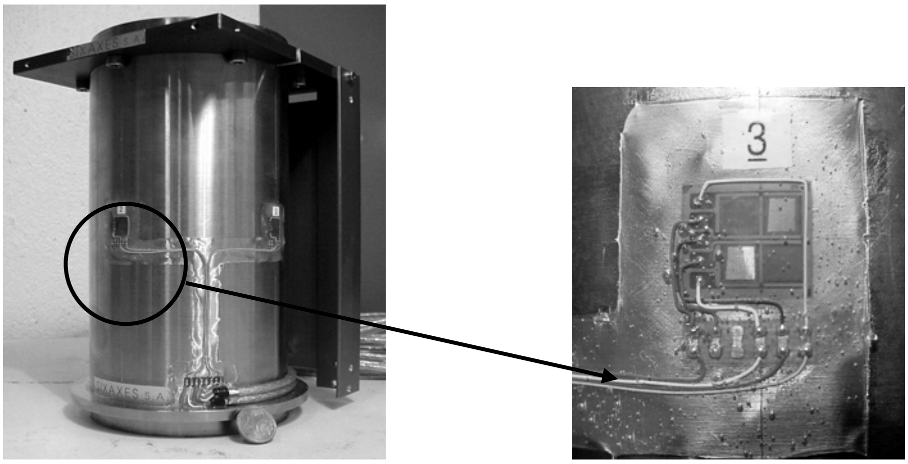
After reminding strain cylinder characteristics, this paper proposes a procedure for cylinder calibration. The measurand is defined. The standard quantity is modelised depending on the specific manner of loading during calibration. Uncertainties are computed using theoretical equations. The results of a first cylinder calibration are given.

## 2. CHARACTERISTICS AND OPERATION OF CYLINDERS

Calibration shall be performed for qualification purposes to assess the ability of cylinders to meet the requirements related to their use. **Before defining the calibration procedure, it is necessary to understand the design and use of cylinders**. We present hereafter the main characteristics of strain cylinders and we give an overview of the operating process.

### 2.1. Characteristics of strain cylinders

The European standard defines a set of characteristics concerning the dimensions of strain cylinders: diameter of 100 mm and height of 200 mm, and concerning shape and geometric tolerances: flatness, parallelism, squareness and cylindricity. The choice for materials is limited: nickel-chrome steel. The strain-gauge equipment is specified: sixteen strain gauges are assembled to form four complete Wheatstone bridges [2], each centred at one of the ends of a pair of orthogonal diameters half-way up the cylinder.




The standard specifies that the response of the cylinder is measured by the strain ratio of the gauge bridges. The mean $e_m$ of the four bridge outputs ($e_1$, $e_2$, $e_3$ and $e_4$) is used to calculate the strain ratio $(e_n - e_m) / e_m$ for each bridge, where $e_n$ is the strain at the bridge position under consideration.

### 2.2. Operating process

The European standard presents the procedure for operating cylinders during machine calibration. It includes three steps.

**Verifying the self-alignment of the upper platen**. The cylinder is placed centrally in the machine. The upper ball platen is tilted towards one of the four bridges and a force of 200 kN is applied on the cylinder. The responses $r_1$ to $r_4$ are measured. The test is repeated by tilting the platen towards the other three bridges successively. The differences in strain ratios shall not exceed 0.1. The purpose is to verify that the stress on one of the four generatrices does not depend on the initial platen tilt.

**Verifying the alignment of the component parts of the machine**. The mean strain ratios are measured for each of the four bridges. They shall be equal to zero $\pm 0.1$. The purpose is to verify that the stresses generated on the four generatrices are equal when the cylinder is centred on the axis of the machine.

**Verifying restraint on movement of the upper platen**. The cylinder is displaced by 6 mm towards each of the four bridge directions. The mean strain ratio along one displacement axis shall be lower than 0.36 for a force of 200 kN and 0.24 for a maximum force of 2000 kN. The purpose is to verify that stress inequality is limited if the cylinder is eccentric.

**Cylinder calibration**. The European standard specifies that the cylinder with its dedicated strain measuring equipment shall be calibrated to national standards at least every two years. But no method is indicated. Moreover, in case of doubt on the equivalence of bridges, it is specified to repeat the self-alignment test by rotating the cylinder a quarter turn about its loading axis. This increases test duration by four. **Calibration, by showing the equivalence of bridges, will allow the user to reduce significantly the process of operating cylinders and to decrease operating costs by four.**

## 3. CALIBRATION PROCEDURE

According to [3], calibration shall be used to establish the relation between the values of the quantity indicated by the cylinder and the corresponding values obtained with standards. The concept of calibration requires to define precisely the measured quantity: the measurand.

### 3.1. Definition of the measurand

On the basis of the characteristics (see previous chapter) and purpose of cylinders, and the formula for determining cylinder response, it appears that cylinders are force distribution measuring instruments. In other words, the **mesurand** can be defined by the ratio r, that is:
**"The relative stress distribution between two opposite generatrices half-way up a 100 mm diameter and 200 mm high cylinder subjected to compressive loads".**

This notion is essential for the rest of the study. Calibration design and related uncertainty measurements depend on it. In particular, by including the conventional values of 100 mm and 200 mm in the definition of the mesurand, the need to measure the height and diameter of the cylinder during calibration is avoided. The standard ratio will be calculated for these specific conventional values and without uncertainties. If the dimensions of the calibrated cylinder are different, the ratio given by the cylinder will be different. An accuracy error will be detected.

### 3.2. Calibration procedure

Having defined the quantities, the definition of **cylinder calibration** becomes:
**"Operation that consists in applying a standard ratio and recording the corresponding ratio indicated by the cylinder."**

Actually, as described in chapter 2, the cylinder indicates four strain ratios: one for each bridge. The calibration procedure will then have to be repeated four times. This has the advantage, as mentioned above, of establishing the equivalence of bridges and facilitating their use.
For the calibration of one bridge, the nominal values of the standard ratios applied to the cylinder are selected according to the range of ratios measured when using the cylinder. We propose to choose the values mentioned in the European standard. In addition to the ratio of zero, the European standard specifies a ratio of 0.36 at 200 kN and 0.24 at 2000 kN.

The calibration procedure takes shape:

- **For a force of 200 kN: apply standard ratios with nominal values of 0.0 and 0.36**
- **For a force of 2000 kN (depending on the cylinder maximum permitted force): apply standard ratios with nominal values of 0.0 and 0.24.**
- **For each standard ratio, record the ratio indicated by the cylinder.**

### 3.3. Verification procedure

**The term verification is used in the sense of confirmation that the specified requirements are met.** Calibration results will have to be analysed in relation to the criteria that set the minimum metrological quality of cylinders. Those criteria are defined according to the quality required when using cylinders, i.e. the quality of the machines verified by the cylinders.

For alignment verification (see § 2.2), the European standard specifies a maximum difference of 0.1 between the mean ratio generated by the machine and the expected ratio in central position, that is 0.0. This is an accuracy tolerance for the machine. We propose to divide it by three in order to obtain the accuracy tolerance for the cylinder. **The difference between standard ratios (0.00; 0.24 and 0.36) and the mean ratio indicated by the cylinder during calibration shall be within 0.03**. This is the first verification criterion.

A common and relatively optimum approach in metrology consists in selecting a factor of three between the metrological quality of the calibrated or verified instrument (compression testing machine) and the metrological quality of the standard (strain cylinder). This can be explained in terms of uncertainty, i.e. quantification of the quality of a measuring instrument. If we want a final uncertainty equal to U, selecting U/3 as the uncertainty component due to the standard makes the influence of the standard in the final uncertainty negligible. Indeed, uncertainties can normally be added quadratically [4], and the square root of $U^2 + (U/3)^2$ remains close to U: the uncertainty in the standard is low enough and does not increase the instrument uncertainty.
For the self-alignment verification (see § 2.2.), the compression testing machine shall not generate ratios with a dispersion exceeding 0.1. And the cylinder itself must not show major dispersions. The calibration process described previously is repeated in order to determine the reproducibility characteristics of the cylinder. Again, a factor of three is selected. **The difference between indicated ratios and mean value shall be lower than 0.03**.

### 3.4. Quality of the standard

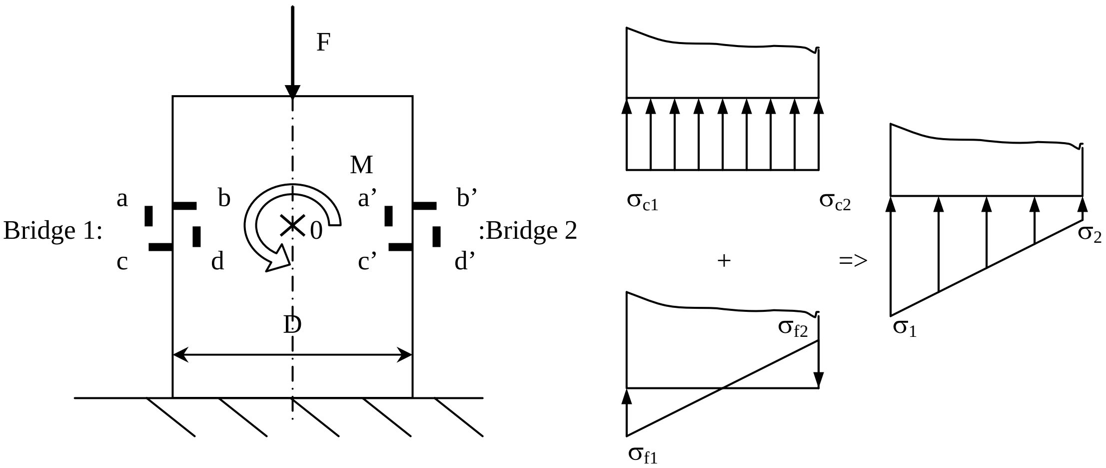
Cylinder accuracy and reproducibility tolerances require an appropriate knowledge of standard ratios. From the same factor of three, a maximum reproducibility and accuracy of 0.03 implies an **expanded uncertainty in the ratio generated by the cylinder calibration bench lower than 0.01**. This is a performance criterion related to the calibration bench and independent from the cylinder.

At this stage, the calibration and verification procedure is really taking shape. The values of standard ratios, as well as cylinder accuracy and reproducibility criteria have been defined. As for many calibration methods, a repeatability criterion may be added. Moreover, the metrological quality of the calibration bench has been quantified. Now the question is how to generate a standard ratio of 0.00, 0.24 or 0.36 with an uncertainty of 0.01.

## 4. DETERMINATION OF STANDARD RATIOS

### 4.1. Principle

We propose to generate standard ratios by applying on the cylinder of diameter D **a centred standard axial force F associated with a standard bending moment M** applied about the axis perpendicular to the plane of two opposite bridges and going through point 0.




The theoretical ratio that is created can be calculated from the laws used in the study of the strength of materials [5].

### 4.2. General theoretical relation

When studying stress distribution in the section half-way up the cylinder, we find:

**Compressive stresses**: $\sigma_c$

The compressive stresses due to the compressive force are constant along the section of the cylinder: (1) $\sigma_{c1} = \sigma_{c2} = \sigma_c = F / S$ with S: Section surface = $\pi D^2 / 4$

**Normal bending stresses**: $\sigma_f$

The normal bending stresses due to the bending moment are proportional to the distance to the centre of the cylinder. $\sigma_f = M\, v / I$ ; with v: distance to neutral axis, that is D/2 for bridge 1 and –D/2 for bridge 2. Hence:

(2) $\sigma_{f1} = - \sigma_{f2} = M D / (2 I)$ with I: Moment of inertia = $\pi D^4 / 64$

**Resultant normal stresses**: $\sigma$

Sum of the previous stresses $\sigma = \sigma_c + \sigma_f$

By expressing $\sigma_c$ and $\sigma_f$ using the formulae (1) and (2), we find the stress at bridge 1 :

(3) $\sigma_1 = \frac{4}{\pi D^2}\left(F + \frac{8\,M}{D}\right)$ ; Similarly, the stress at bridge 2 is :

(4) $\sigma_2 = \frac{4}{\pi D^2}\left(F - \frac{8\,M}{D}\right)$

**Gauge bridge outputs**: e

Each bridge is made of four gauges (a, b, c and d) used in a Wheatstone bridge. The relation between the output e of a gauge bridge and the relative elongation $\varepsilon$ of one gauge is [2]:

(5) $e_1 = (\varepsilon_a + \varepsilon_d - \varepsilon_b - \varepsilon_c)\, k/4$ and (6) $e_2 = (\varepsilon_{a'} + \varepsilon_{d'} - \varepsilon_{b'} - \varepsilon_{c'})\, k/4$ for bridge 2.

Hooke's law, which gives the relation between stress and elastic strain, is used to establish, for homogeneous materials with Young's modulus E, Poisson's ratio $\nu$, and well-positioned gauges of same factor k:

$\varepsilon_a = \varepsilon_d = \sigma_1 / E$ and $\varepsilon_b = \varepsilon_c = - \nu\, \varepsilon_a$ Similarly, for bridge 2:

$\varepsilon_{a'} = \varepsilon_{d'} = \sigma_2 / E$ and $\varepsilon_{b'} = \varepsilon_{c'} = - \nu\, \varepsilon_{a'}$

By replacing those new formulae for elongation in expressions (5) and (6), we find:

(7) $e_1 = (1 + \nu)\, \sigma_1\, k / (2 E)$ and $e_2 = (1 + \nu)\, \sigma_2\, k / (2 E)$

From expressions (3) and (4), we find:

(8) $e_1 = \frac{2k(1+\nu)}{\pi D^2 E}\left(F + \frac{8\,M}{D}\right)$ and $e_2 = \frac{2k(1+\nu)}{\pi D^2 E}\left(F - \frac{8\,M}{D}\right)$

**Cylinder ratio**: r

According to the European standard [1], the ratio of the cylinder is defined by the output ratio of gauge bridges (9) $r_1 = (e_1 - e_m) / e_m$ and $r_2 = (e_2 - e_m) / e_m$

with $e_m$ = mean output of gauge bridges. By using the formula (8) of $e_1$ and $e_2$ we find:

(10) $e_m = \frac{2\,k\,(1+\nu)\,F}{\pi D^2\, E}$

From relations (8) and (10) of bridge outputs, the formulae (9) become:

$$(11) \quad r_1 = \frac{8\,M}{D\,F} \quad \text{and} \quad r_2 = - r_1$$

**Therefore, the ratio generated on a cylinder of diameter D can be determined from the applied force and moment.**

**Note**: From relations (7) and (10) of bridge outputs, the formulae (9) become:

$r_1 = (\sigma_1 - \sigma_m) / \sigma_m$ and $r_2 = - r_1$

The ratio of the cylinder is representative of the relative stress distribution between two opposite generatrices. **A ratio of 0.33 implies that stresses are twice higher on one generatrix than on**

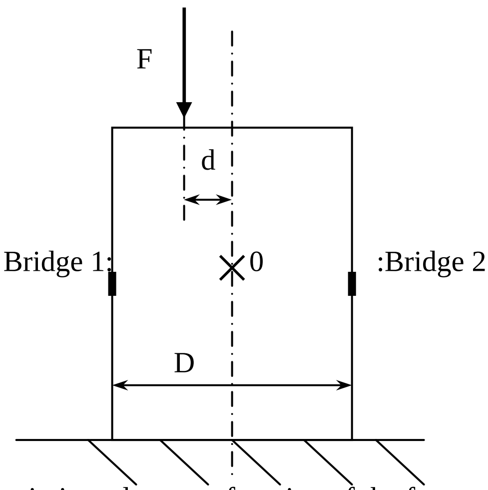
**the other one**. We can imagine the consequences on compression strength measurement.

### 4.3. Application of force and moment

How to apply the specific combination of force and moment? Multi-component calibration benches, which are able to generate the three forces and three moments of loading, are still rare and have relatively low ranges. Remind that the applied force shall be about the force generated by a mass of 200 tons. Standard machines in force and torque metrology are single-component machines: They generate either a force or a torque. From the single standard force of a standard machine, we propose to position the cylinder so that the force creates also a known torque on the median section of the cylinder.

Two methods are considered: eccentring the cylinder from the axis of the force bench, or tilting the cylinder from the direction of the force. The theoretical relations between the generated ratio and the applied force are established hereafter.

### 4.4. Relation for eccentric axial force



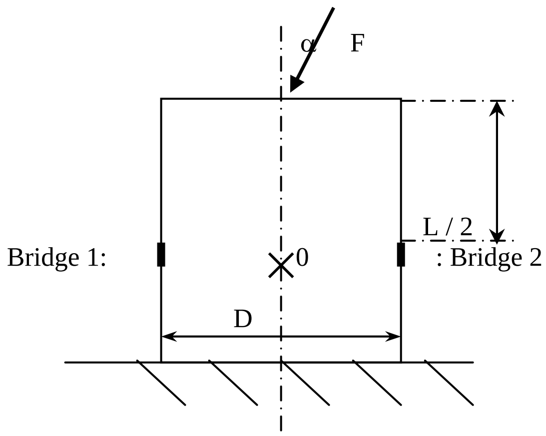

The loading conditions of the force standard machine correspond to a compressive force parallel to the axis of the cylinder and eccentred by a distance d. The eccentric direction coincides with the direction of the radius passing through both gauge bridges.

The bending moment due to the eccentric force F is M = F d. The theoretical relation (11) becomes:

$$(12) \quad r = \frac{8\,d}{D}$$

The ratio is no longer a function of the force and moment but of the distance between the axis of the cylinder and the axis of the force. Could cylinders be measuring instruments of the eccentricity or the position of the centre of pressure? We will have the opportunity to give answers in this paper. In all cases, **the ratio generated on a cylinder of diameter D can be determined from the eccentricity of the applied axial force.**

### 4.5. Relation for tilted centred force




The loading conditions of the force standard machine correspond to a compressive force centred on the cylinder and tilted by an angle α from its axis.

The compressive vertical force is equal to F cos(α). The bending moment M due to the horizontal component of the force F is equal to M = F sin(α) L / 2. The theoretical relation (11) becomes:

$$(13) \quad r = \frac{4\,L}{D}\,\mathrm{tg}\,(\alpha)$$

This shows that **the ratio generated on the cylinder of diameter D and height L can be determined from the tilt of the applied centred force.** In comparison with the eccentricity method, the formula takes into account the height of the cylinder. This has the advantage of verifying that the gauge section is half-way up the calibrated cylinder. Indeed, the standard ratio will be calculated for the section at 100 mm. If the plane of the gauges is not at 100 mm, the ratio given by the cylinder will be different. An accuracy error will be detected. Note that for the eccentricity method, applying a force perfectly aligned with the axis of the cylinder is not feasible. Similarly, for the tilt method, it is not possible to apply a perfectly centred force. Some tilt and eccentricity always remain.

### 4.6. Overall relation

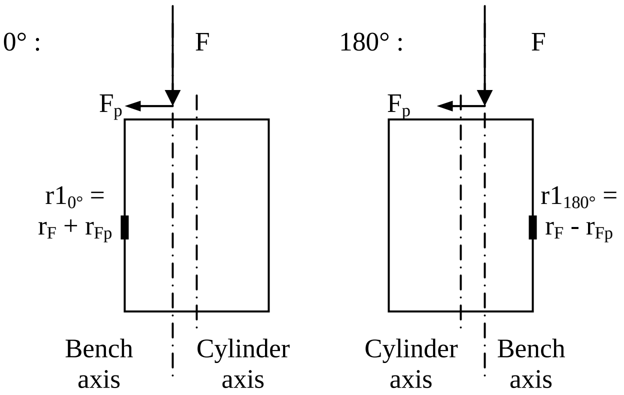
In loading conditions combining eccentricity d and tilt $\alpha$, the compressive vertical force is still equal to F cos($\alpha$). The bending moment M due to the horizontal component of the force F is M = F sin($\alpha$) L / 2, to which we add the eccentricity component d, equal to $F\cos(\alpha)\ d$ . The theoretical relation (11) becomes:

$$(14) \quad r = \frac{4}{D}\left[\ L\ tg(\alpha) + 2\ d\ \right]$$

This shows that **cylinders are not measuring instruments of the eccentricity of the applied force or of the centre of pressure**. The eccentricity-ratio relation is also a function of the tilt. The same ratio may be found via an eccentric force and then via a centred tilted force. For example, we may find a cylinder response of 0.1 from two completely different loading conditions: one with an axial force eccentred by 1.25 mm and the other one with a centred force tilted by 0.72°. The eccentricity-ratio relation is not bijective. Therefore, when using a cylinder, the obtained ratio cannot be used to quantify eccentricity and tilt effects. However, we notice that the effect of the bending moment due to the eccentricity $M_d$ = F cos($\alpha$) d is not dependent on the position of the section under consideration. For a section at one-third of the height of the cylinder, the ratio is the same. On the contrary, the effect of the bending moment due to the tilted force $M_\alpha$ = F sin($\alpha$) L / 2 depends on the position of the section. **Therefore, a solution for separating eccentricity and tilt effects would be to double the number of gauge bridges and to place them at different heights on the cylinder.** However, the priority is not to make the difference between tilt and eccentricity, but to determine if the stresses generated by the machine are uniform. If the machine does not meet the requirements, there is no need to determine the origin of an asymmetrical distribution. **We must give up the vocabulary of centre of pressure to define cylinder mesurand**. The relation between the ratio and the height of gauge bridges raises another comment: In some cases, the user must add spacing blocks in order to adjust the cylinder to the space available to test specimens in the calibrated machine. It is obvious now that **spacing blocks should be placed below the cylinder if we don’t want calibration results to depend on the distribution between inferior and superior blocks.** Therefore, with a good knowledge of the instrument’s physical laws we can avoid some traps related to its use, or explain some results that seem surprising at first sight. The previous theoretical relations correspond to optimum loading conditions that we could qualify of ‘textbook cases’. Now we need to specify which mechanical assembly can be used to set up either method. For simplification purposes, we focused on the first method: eccentric axial force.

## 5. MECHANICAL ASSEMBLY

Firstly, in order to maintain the metrological characteristics of force standard machines, we cannot eccentre the resultant of the forces of the bench operating axis. The resultant shall be in the axis of symmetry of the calibration bench. Therefore, if we mentioned an eccentricity between the load introduction system and the axis of the cylinder, it corresponds to a deviation of the axis of the cylinder. **The axis of the load introduction system will remain centred on the bench reference axis. Only the cylinder will be eccentric.** Moreover, on the basis of BNM-LNE’s experience in the field of force transfer on strain gauge sensors, we recommend that **the cylinder should rotate during calibration**. Repeating the tests on two diametrically opposite angular positions of the cylinder relative to the bench aims at averaging the effect of parasitical forces $F_p$ due to the calibration bench or the load introduction system. For an eccentricity towards the bridge no. i, the response of the bridge is $r_i$, written $ri_{0°}$. Then the cylinder is rotated by 180° relative to the calibration bench. During the rotation, the eccentricity continues to be towards the bridge no. i. The eccentricity rotates with the cylinder. Again the response $r_i$ is recorded, written $ri_{180°}$. The response selected for the determination of accuracy errors is the mean of both responses.

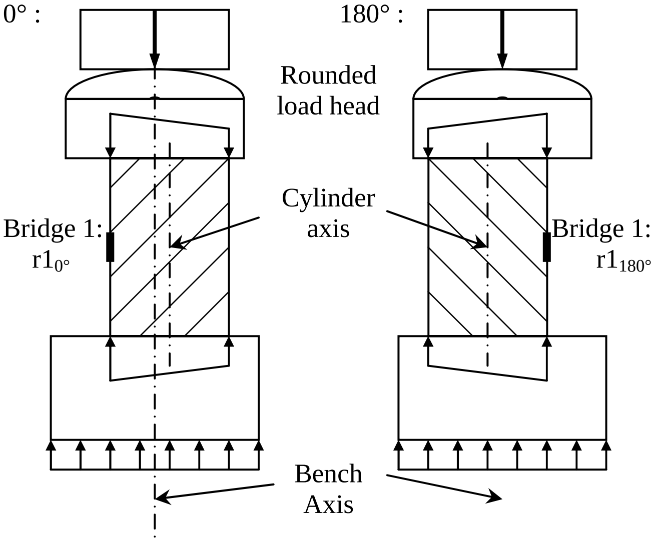



The mean value is less dependent on the calibration bench. With only one test at 0°, the ratios account for the eccentricity effect and bench parasitical forces. If parasitical forces have a positive effect on the ratio, the effect will be negative and of the same absolute value in the opposite position. The rotation and the determination of the mean nearly allow us to consider that we have the equivalent of a vertical loading. We notice that the effects of the parasitical forces that 'rotate' with the cylinder do not cancel each other out when the mean is calculated. Consequently, it is important to ensure that the bench is not sensitive to the rotation of the cylinder:

**<u>For the upper part</u> : A sphere-on-plane load introduction system is recommended**. With this method, stresses concentrate in a small area and then propagate towards the upper part of the bench in a repeatable way. The response of the upper part of the bench does not depend on the position of the cylinder, which is placed below this re-location. A mean can be calculated from the repeated parasitical forces.

**<u>For the lower part</u>: A loading pad with the appropriate thickness shall be prepared.** As for the upper load introduction system, the axis of the loading pad **shall coincide with the axis of the bench**, in order to have a uniform distribution centred on the lower bearing surface of the calibration bench.

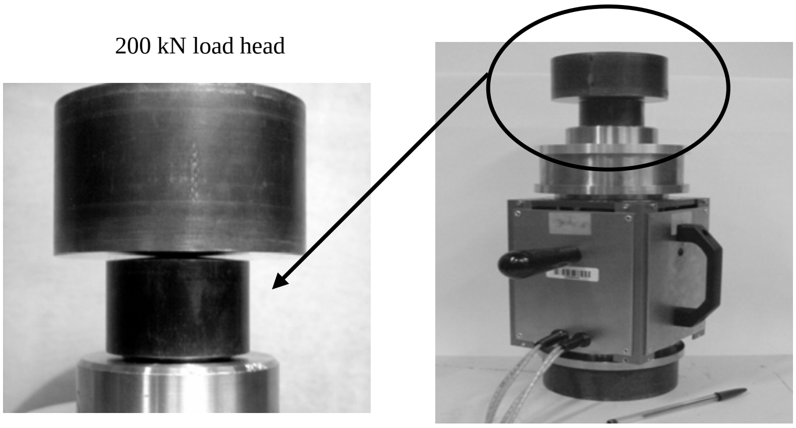
Recommended assembly:




This mechanical assembly shall be able to apply standard ratios and to control the propagation of forces. The mechanical quality of the parts is essential to propagate stresses in a manner close to theory. Shape characteristics in particular shall be closely respected.This can be achieved by rectifying surfaces.

200 kN load head

2000 kN load head:

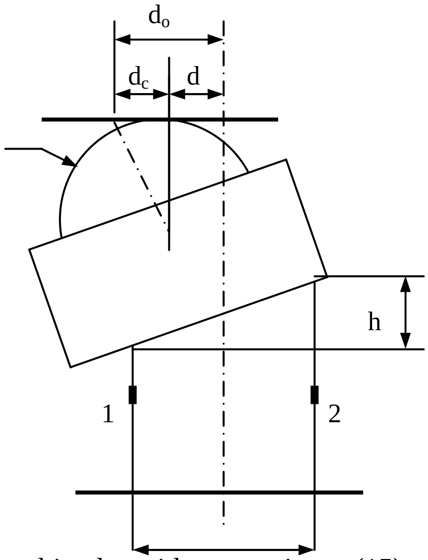


After defining the mechanical assembly for applying loads, we have to include it in the modelisation.

## 6. MODELISATION OF THE RATIO – SELF-COMPENSATION OF ECCENTRICITY

Using a rounded load head gives a degree of freedom of movement to contact parts, which shall be taken into account in the ratio-eccentricity relation. Based on the definition of the ratio, for a non-zero ratio, the stresses on two opposite generatrices are different. With strains proportional to stresses, the generatrices have different reduced lengths. The upper face of the cylinder tilts. Consequently, the load head, supported by the upper face, tilts also. The tilt of the rounded face of the load head makes the point of contact roll between the rounded face and the upper plane support. This causes a drift of the point of application of the resultant of the forces applied towards the axis of the cylinder, which re-balances stresses. **The mechanical assembly, by using a rounded load head, is a mechanically self-compensated system of eccentricity effects**. Strains being proportional to stresses, the tilt of the cylinder increases with the force, and the self-compensation effect amplifies with the calibration force. Moreover, for a given tilt, i.e. angle of rotation, the displacement is higher if the radius of the ‘wheel’ is large. Self-compensation is more important when the radius of the load head increases.

Exaggerated radii and strains:




The eccentricity d is defined by the initial eccentricity at force zero $d_o$ and a corrective term that is a function of the cylinder tilt: d = do – dc. Through obvious geometrical relation, we find: dc / R = h / D, that is: (15) d = do – (R h / D)
with h: strain difference in generatrices.
The relation between stresses and strains relates the strain difference h to the cylinder initial length L, Young’s modulus of the material E and the stress difference σ : (16) $h = L (\sigma_1 - \sigma_2) / E$
With the initial expressions of stresses (3) and (4) we find: $\sigma_1 - \sigma_2 = 64\ M / (\pi\ D^3)$, with M = F d. The strain difference (16) becomes: $h = 64\ L\ F\ d / (\pi\ E\ D^3)$

Combined with equation (15) we find:

$$d = d_o - \frac{64 L R F d}{\pi D^4 E}\text{, that is } d = \frac{d_o}{1 + \frac{64 L R F}{\pi D^4 E}} \qquad (17)$$

Depending on the initial off-load eccentricity, the ratio-eccentricity relation (12) becomes:

$$(18) \quad r = \frac{8 d_o}{D\left(1 + \frac{64 L R F}{\pi D^4 E}\right)}$$

In the case of a force of 2000 kN, the initial equation (12) requires an eccentricity of 3.0 mm to generate a ratio of 0.24. The new relation (18) establishes an initial eccentricity of 3.73 mm (using a rounded load head with a radius of 600 mm and Young's modulus of 200,000 N/mm²). The difference of 0.73 mm between both formulations accounts for 24%! Not taking into account the phenomenon of self-compensation results in an error of more than 0.04 in the determination of the standard ratio, which is four times the tolerance on the standard ratio uncertainty! **It is therefore necessary to include the corrective term in relation (18) to take into account the phenomenon of self-compensation of the eccentricity of the mechanical assembly used in cylinder calibration.** The self-compensation phenomenon could explain some characteristics of calibrated machines, which often work better at 2000 kN than at low loads. As a result, the tolerance given by the European standard is more severe at 2000 kN (0.24) than at 200 kN (0.36). The mechanical assembly has been defined. Its influence in the determination of the standard ratio has been modelised. Standard ratios have been defined. The calibration and assessment procedure proposed in chapter 3.2. is now complete enough to perform a cylinder calibration.

## 7. RESULTS OF A FIRST CALIBRATION

### 7.1. Calibration procedure

Standard ratios of 0.36 at 200 kN and 0.24 at 2000 kN are obtained with eccentric cylinders at respectively 4.56 mm and 3.73 mm from the rounded load head centred on the axis of the force standard machine. Eccentricities are determined by the formula (18) by selecting the respective radii of 300 mm and 600 mm of LNE's load heads. By using mechanical parts with different radii we can adjust swiveling and concentration functions to the load to be transferred. Initially, three loads are applied for at least 30 seconds without recording any indication.

**Repeatability (b') at 200 kN - ratio of 0.0** The sensor being centred on the load head, two successive loads of 200 kN are applied in similar conditions. The ratios of the four bridges are determined: $ri_{0°1}$ and $ri_{0°2}$ (i = 1 to 4). The repeatability criterion is selected at one third of the reproducibility criterion: $\mathbf{b' = |ri_{0°1} - ri_{0°2}| \leq 0.01}$

**Reproducibility (b) at 200 kN - ratio of 0.0** The mean of the two previous loadings is written $ri_{0°}$. The cylinder is rotated by 180°. A load of 200 kN is applied. The ratios are written $ri_{180°}$. The mean for each bridge is ri = ( $ri_{0°}$ + $ri_{180°}$ ) / 2. Dispersions shall be lower than one third of the dispersion tolerances on the testing machine: $\mathbf{b = |ri_{0°} - ri|}$ (or $|ri_{180°} - ri|$) $\leq$ **0.03**

**Accuracy (q) at 200 kN - ratio of 0.0** The mean ratio for each bridge, ri, shall be within 0.03 of the value of the generated standard ratio: $\mathbf{ri = 0.00 \pm 0.03}$ (or $|q| = |ri - 0.0| \leq$ 0.03)

Accuracy operations are repeated at 200 kN with a standard ratio of 0.36. As rotation is needed to determine accuracy, the reproducibility criterion can be examined each time without slowing the calibration process.

**Reproducibility and accuracy at 200 kN - ratio of 0.36** Two successive loads of 200 kN are applied with initial eccentricity of 4.56 mm towards the bridge no. i between the axis of the cylinder and the axis of the 300 mm radius rounded load head. Between each loading the cylinder is rotated by 180° about the axis of the bench. The ratios are written $ri_{0°ex1}$ and $ri_{180°ex1}$. The mean ratio is written $ri_{ex1}$. Reproducibility and accuracy shall be lower than

0.03. **b =** $|$ $\mathbf{ri_{0°ex1} - ri_{ex1}}$ $|$ **≤ 0.03** (or $|$ $ri_{180°ex1} - ri_{ex1}$ $|$ ≤ 0.03)
$\mathbf{ri_{ex1} = 0.36 \pm 0.03}$ (or $|q| = |ri - 0.36| \le 0.03$)
This part is repeated with eccentricity successively towards the other three bridges.

**<u>Repeatability, reproducibility and accuracy at 2000 kN - ratio of 0.0</u>** All initial operations at 200 kN (preload, repeatability, reproducibility and centred accuracy), are repeated at 2000 kN. The criteria are the same.
**b' =** $|$ $\mathbf{ri_{0°1} - ri_{0°2}}$ $|$ **≤ 0.01** **b =** $|$ $\mathbf{ri_{0°} - ri}$ $|$ **≤ 0.03** (or $|$ $ri_{180°} - ri$ $|$ ≤ 0.03)
**ri = 0.00 ± 0.03** (or $|q| = |ri - 0.0| \le 0.03$)
**<u>Reproducibility and accuracy at 2000 kN - ratio of 0.24</u>** Two successive loads of 2000 kN are applied with initial eccentricity of 3.73 mm towards the bridge no. i between the axis of the cylinder and the axis of the 600 mm radius rounded load head. Between each loading, the cylinder is rotated by 180° about the axis of the bench. The ratios are written $ri_{0°ex2}$ and $ri_{180°ex2}$. The mean ratio is written $ri_{ex2}$. Reproducibility and accuracy shall be lower than 0.03.
**b =** $|$ $\mathbf{ri_{0°ex2} - ri_{ex2}}$ $|$ **≤ 0.03** (or $|$ $ri_{180°ex2} - ri_{ex2}$ $|$ ≤ 0.03)
$\mathbf{ri_{ex2} = 0.24 \pm 0.03}$ (or $|q| = |ri - 0.24| \le 0.03$)
This part is repeated with eccentricity successively towards the other three bridges.

### 7.2. Results

This calibration method was applied using BNM-LNE force pyramids of 1000 and 3000 kN. The first cylinder calibrated according to this procedure is a strain cylinder from LNE's on-site calibration laboratory. The results are summarized in the tables below:

For a force of 200 kN:

| | | Bridge number | | | |
|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 |
| Standard = 0.0 | b' | 0.002 | 0.002 | 0.001 | 0.001 |
| | b | 0.016 | 0.016 | 0.012 | 0.012 |
| | q | -0.002 | 0.002 | -0.003 | 0.003 |
| Standard = 0.36 4.56 mm | b | 0.016 | 0.015 | 0.018 | 0.016 |
| | q | 0.000 | 0.007 | -0.006 | 0.005 |

We notice that all verification criteria are largely met. This result is quite satisfactory for both the user of the cylinder and the **validation of the method since obtained values, in particular accuracy values, correspond to expected modelised values**.

For a force of 2000 kN:

| | | Bridge number | | | |
|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 |
| Standard = 0.0 | b' | 0.000 | 0.000 | 0.000 | 0.000 |
| | b | 0.015 | 0.015 | 0.016 | 0.016 |
| | q | -0.003 | 0.006 | 0.004 | -0.007 |
| Standard = 0.24 3.73 mm | b | 0.009 | 0.006 | 0.012 | 0.009 |
| | q | 0.002 | 0.012 | -0.001 | 0.009 |

These results increase the confidence in the values of the generated standard ratios. Now this confidence, i.e. the uncertainty in standard ratios, has to be quantified. Standard ratio uncertainties will be used to quantify the uncertainty in cylinder calibration results.

Firstly, the uncertainty in the standard ratio generated by the calibration bench is estimated from the relation between ratio, eccentricity and tilt. Then this uncertainty is increased in order to find the uncertainty in cylinder accuracy errors. The purpose is to take into account the characteristics of the calibrated instrument in order to associate a calibration uncertainty to measured errors.

### 8.1. Standard ratio uncertainties

The standard ratio is determined from the eccentricity under loading and tilt:

(14 reminder) $r = \frac{4}{D}\left[\, L\ tg(\alpha) + 2\ d \,\right]$

Given u(y) the type-uncertainty related to the quantity y, the law of propagation of uncertainties [4] for independent variables gives:

$$u^2(r) = \left[\frac{\partial r}{\partial d}\right]^2 u^2(d) + \left[\frac{\partial r}{\partial \alpha}\right]^2 u^2(\alpha)$$

If we apply this relation to the formula (14) we find : (19) $u^2(r) = \left[\frac{8}{D}\right]^2 u^2(d) + \left[\frac{4\,L}{D}\right]^2 u^2(\alpha)$

The eccentricity under loading is related to the initial off-load eccentricity:

(17 reminder) $d = \dfrac{d_o}{1 + \dfrac{64\,L\,R\,F}{\pi\ D^4\ E}}$ Again, the law of propagation of uncertainties gives:

(20) $u^2(d) = \left(\dfrac{1}{1 + \dfrac{64LRF}{\pi D^4 E}}\right)^2 u^2(d_o) + (d_o - d)^2 \left(\dfrac{u^2(R)}{R^2} + \dfrac{u^2(F)}{F^2}\right)$

Equations (19) and (20) are used to determine standard ratio uncertainty. The numerical application in the context of the calibration under consideration gives ($d_o$ in mm, $\alpha$ in degrees):

$$u^2(r) < 0{,}08^2 u^2(d_o) + 0{,}14^2 u^2(\alpha) + 0{,}06^2 \left(\frac{u^2(R)}{R^2} + \frac{u^2(F)}{F^2}\right)$$

The sensitivity coefficients confirm that the sources of uncertainty that influence the knowledge of the ratio are the initial eccentricity and the parallelism of the force. **A ratio uncertainty of 0.01 requires an estimation of initial eccentricity of ± 0.1 mm and a maximum tilt of ± 0.05° (that is ≈ 0.1 mm for 10 cm)**. Therefore, the determination of the force and the radius of the load head within a few percents is sufficient. The geometrical properties of the LNE calibration bench ensure that tolerances are met. **The mechanical quality of the sphere-on-plane load introduction system and the stiffness of the whole calibration bench under loading are the main factors for success.**

the stability of the force during the gauge bridge output acquisition cycle can be an additional According to the characteristics of the electronic measuring system associated to the cylinder, factor of uncertainty. If the acquisition is sequential, the relations (8) show that the error in the determination of the ratio is close to the relative deviation between the force applied during the acquisition of one bridge and the force applied during the acquisition of the opposite bridge. That is, given the stability relative deviation ΔF/F: $r \approx \frac{8\,M}{D\,F} \pm \frac{\Delta F}{F}$ Hence, to obtain a ratio uncertainty of 0.01, a force stability of 1. $10^{-3}$ in relative value is acceptable.

### 8.2. Calibration uncertainties

The calibration result is given with an uncertainty that takes into account the standard and the specific characteristics of the calibrated item. We propose to increase standard ratio uncertainty depending on the dispersions observed during rotations in order to take into account the reproducibility of the calibrated cylinder. Considering a rectangular distribution law, and considering the mean [4], we find:

$U(q) = 2\sqrt{\frac{b^2}{2 \times 3} + u^2(r)}$ ; With: U(q): expanded uncertainty (k=2) in calibration accuracy errors;

b: maximum reproducibility observed (see § 7.1); u(r): standard ratio type uncertainty.

**For a cylinder that meets the dispersion criteria, with the required standard ratio uncertainties, the expanded uncertainty (k=2) in accuracy errors will be lower than 0.03**. This is enough to calibrate cylinders according to the tolerance requirements for concrete testing machines.

## 9. CONCLUSION

The characteristics assessed via strain cylinders have a major influence on the conclusions of tests on concrete specimens. It was essential to improve the qualification of these instruments. This paper presented the method developed and implemented in BNM-LNE laboratory of force metrology for strain cylinder calibration for compression testing machines. After an analysis of the needs and technologies, the calibration procedure was defined, including: mesurand, standard values, specifications to be met by cylinders and standards. The standard quantity was modelised depending on the specific manner of loading during calibration. Equations were revised in order to take into account the mechanical assembly and self-compensation effects on the accuracy of the modelisation. The results of a first calibration confirmed the possibilities provided by this method. Finally, the uncertainties, which quantify the quality of calibration, were determined. This paper fills a gap in the field of traceability and calibration of measuring instruments that have an influence on the characterisation of the quality of concrete constructions, and on the safety of their users.

## REFERENCES

[1] "Testing hardened concrete - Part 4 : compressive strength - Specification for testing machines.", Standard EN 12390-4, 2000.

[2] P. Averlant, "Chaîne de mesure de force avec capteur à jauges", Stage métrologie des forces, LNE – ME14, 1994.

[3] International vocabulary of basic and general terms in metrology, ISO, 1993.

[4] "Guide to the expression of uncertainly in measurement", Standard NF ENV 13005, 1999.

[5] A. Giet et L. Geminard, Résistance des matériaux, Paris : Dunod, 1968, tome 2, 5ème édition, 1994, ch. 14.3.3, pp. 48-49.

**Addresses of the Author:**

Philippe AVERLANT,
Head of force and torque laboratory,
LABORATOIRE NATIONAL D'ESSAIS (LNE),
1 rue Gaston Boissier 75724 Paris Cedex 15, France
Tel +33 1 40 43 38 71, Fax +33 1 40 43 37 37,
e-mail : philippe.averlant@lne.fr