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FLEXURAL TESTING MACHINE AS AN OFF-LINE CONTROL SYSTEM FOR QUALITY MONITORING IN THE PRODUCTION OF BENDED CERAMIC TILES

Abstract: *The capability to bend in a controlled manner Grès Porcelain stoneware tiles passing by a very exclusive process of pyroplastic deformation opens up entirely new opportunities in utilisation of this important family of ceramics. A bended tile can be exploited in innovative applications, such as stairs, shelves, benches and even radiators, turning this element from a simple piece of furnishing in a modern functional component. But this change in functionality also requires a different approach in the quality control, both at the product and process levels, that can no longer be limited to the use of tests specified in the regulations for traditional ceramics (e.g. colour, porosity, hygroscopic ...). This article describes the first device so far devised for the verification of resistance to bending of curved tiles, discussing the correct way of use. The adoption of this particular equipment as an off-line control device can represent a valid strategy for monitoring the product and process quality.*

Keywords: *Grés Porcelain, mechanical tests, equipment design, international standard, quality control*

1. Introduction

Far from representing the current popular opinion, Grès Porcelain stoneware can be rightly considered as an very advanced material: compact, durable and economical, especially suited to meet the needs of the world of construction and civil buildings (ISO 14411, 2012). The porcelain stoneware slabs are obtained by a sintering process of ceramic clays, feldspar, kaolin and sand (Dondi, 1999). These basic materials are first milled into "slips" and then finely atomised until a granulometrically homogeneous powder is obtained. At this point the mixture passes to the pressing phase where forces are applied by a mechanical compression of the order of 500 Kg per cm² before proceeding towards the oven for the thermal treatment. The firing takes place at a temperature of about 1150-1250°C in long kilns, up to 140 meters, where the raw material is gradually brought to the maximum temperature, maintained there for about 25-30 minutes. It follows a gradual cooling down to the ambient temperature. The cooking process determines the transformation of powder in ceramic ("vitrification"), attributing the typical characteristics of abrasion resistance, water resistance and longevity. Extremely

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popular, the grès porcelain stoneware offers a valid coating solutions for both indoor, and outdoor, ranging from public to the private. A deep analysis with relevant details regarding the global significance of grès porcelain tile manufacture, the scientific activity in grès porcelain tile’s performed during the last decades (including the progressive improvement of quality for processes and products) and the overall importance of the tile’s business are available in (Sanchez *et al.*, 2010). Thanks to several recent developments in ceramic technologies, producers are now available to present on the market tiles with sizes ranging from 5x5 to 100x300cm (“large format tiles”) and thickness from 3 to 20 mm. Nowadays, grès porcelain represents a perfect solution in a extremely large range of practical applications: from small tiles for bathrooms or swimming pools to huge slabs, perfect for coating large sized spaces, such as airports, squares and public buildings.

According to a rough estimation carried out by the author, starting from data provided by the most recent investigation available on tiles sales (Serri and Luberto, 2011) and considering, as analogy, the market trends of similar sectors, it is possible to declare that more than 750 millions square meters of grès porcelain stoneware are produced every year in the World. At the same time, all these elements have the same “intrinsic limitation” for application: they are entirely commercialized in flat slabs.

On the contrary, some interesting patents, related to an innovative process developed in Italy more than 10 years ago (Fabbroni, 2003), but only recently refined toward a complete troubleshooting of technical problems (Conti, 2014), allow to produce porcelain tiles shaped in the three dimensions, thus overcoming the limitations imposed by the planar form.

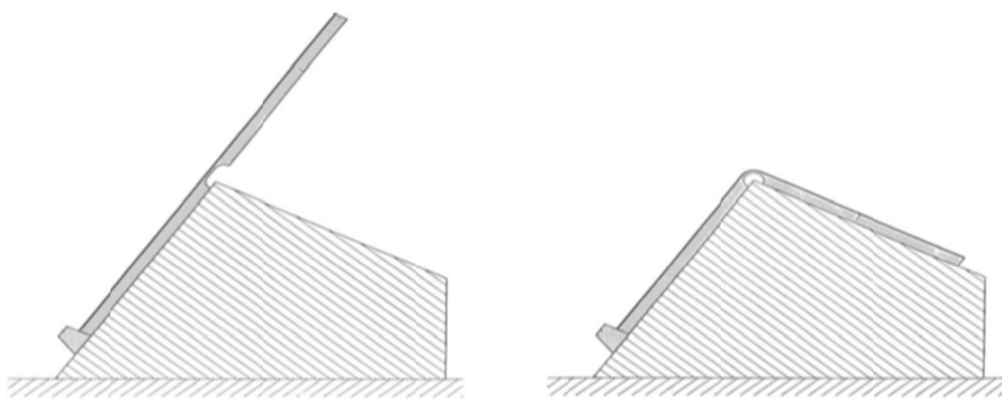


Figure 1. Bending process for a tile

This process is based on a proper combination of tool machining and secondary firing in an oven which allows to bend the porcelain stoneware tile (Figure 1). Everything starts from an ordinary flat tile. On the inner side of the tile several incisions are realized using a tool machine. These grooves have to be modelled with an extreme precision, since they will serve as a guide during the bending phase. The tile is then placed on special shaped supports, of refractory material, which slide inside a roller kiln (Figure 2). The oven, divided into temperature stages, is able to accurately calibrate the thermal profile to which the tile has to be subjected. There is a long, but controlled phase of slow heating. When the temperature of the tile reaches a certain threshold, viscoplasticity phenomena appears in the materials, better known as "pyroplasticity" (Bernardi, 2006): the ceramic becomes ductile, the mass of material is deformed by gravity and is modelled (by pyroplastic deformation) couching the shape which supports it. The process ends with a slow cooling and the final exit from the oven (Figure 3).

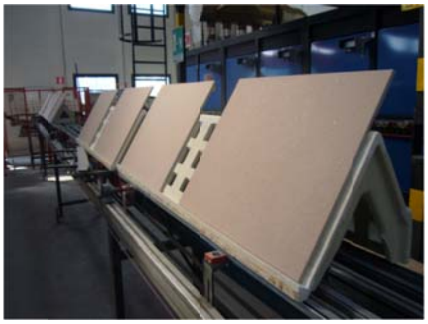


Figure 2. Tiles entering in oven

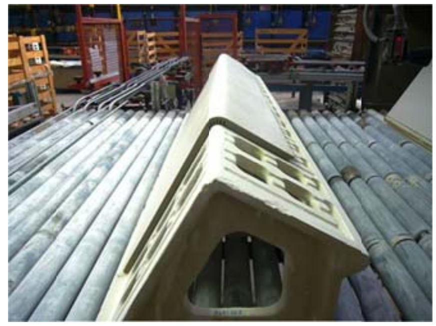


Figure 3. Tiles exiting from oven

The potential of bending technology is huge and bended ceramic tiles can cover a wide range of applications from the world of construction and architecture (Serri and Luberto, 2011). A bended ceramic tile may be used, for example, to make a complete step, a skirting board connected to the floor, a shelf, a corner of the house, and much more (Figure 4).

But this change in functionality, to be correctly implemented, also requires a new and very different approach to the methodology adopted in quality control. International standards, largely used for the quality classification of traditional ceramic tiles, are too limited in the case of bended tiles. In fact, these standards do not take into account how a tile folded tent to resemble more to a mechanical component that one element of furniture. On the contrary, both the ISO 13006 and 10545 that the more general EN 14411 appear to refer, in their entirety, to ceramics for architectural, or decorative coating. A detailed analysis of the limits of applicability of the existing rules to the case of curved tiles is presented in (Fragassa, 2015).

Figure 4. Advanced solutions in architecture permitted by bended tiles as steps & stairs or exterior edges in villas

The necessitate to pay a particular attention both to the control of products and processes, combined with the almost total lack of specific standards which could be used as a valuable reference for testing, has been the central motivation for this study.

The need of implementing specific and accurate tests for the quality control of bended tiles and bending processes is particularly relevant also considering that, currently, neither theoretical, nor numerical studies specifically investigate the transformations occurred in tiles during the bending phase focusing the attention of their mechanical functionality. A preliminary analysis is represented by a very recent publication of the author (Fragassa, 2016) where a methodological approach is proposed aiming at modelling the viscoelastic response of grés porcelain during bending process by the use of commercial Finite Elements codes. In this research it is showed how apparently marginal changes in inputs or even assumption in models, particularly regarding the material behaviour and its response in terms of time- and temperature- depending viscoelasticity (e.g. shifting functions of relaxation modulus), lead to a large unpredictability in tiles' final proprieties. This variability reduces the range of applications where bended tiles can be used, especially limiting their adoption when an accurate estimation of dimensional and mechanical proprieties is mandatory. Without a different approach toward the TQM, involving a deeper comprehension of quality aspects, as described, for instance, in (Fragassa *et al*., 2014) and referred to different market sectors, it is hard to transform the bended tiles in large-mass products.

2. Quality in ceramic industry

In the ceramic industry in general, even if the implementation of methods and tools for a multistage quality control has advanced in the last decades, it is still behind the traditional industry (as chemical or mechanical) where very refined solutions are already developed even involving artificial neural network-fuzzy algorithms of simulation (Azadeh *et al*., 2010). Adding several studies also investigated the interesting aspects of the transmission of variations along the different stages of a manufacturing process (as reported in Heredia and Gras, 2010; Heredia and Gras, 2011).

This methodological backwardness in ceramic sector is partly related to the fact that it works with draft materials and technologies characterized by a level of knowledge in unit operations that has progressed far less than in other industrial applications (as highlighted in Edgar, 1996) where a detailed state of arts of solutions for controlling unconventional process is proposed). An additional aspect that makes quality control difficult stems from the structural and chemical nature of the ceramic product, making the required end characteristics to be multiple and complex, since the complexity of chemical transformations occurred during processing (de Noni *et al*., 2010). In the case of traditional ceramic tiles, the end product must meet a number of requirements that range from purely technical characteristics (low porosity and wear resistance) to aesthetic qualities (gloss and design), often restricting the implementation of quality control systems. An implementation of techniques of control in the ceramic tile industry would be justified for high value products. In general, according to the International Standards, a porcelain tile has to be characterized by water absorption, mechanical strength, frost resistance, hardness, chemical resistance, stain resistance and aesthetics (e.g. colour, polishing, glazing, etc.). Even if these aspects are clearly not homogeneous, all of them contribute to the overall quality of the final product. At the same time, a strict tolerance of specific properties, particularly regarding the geometrical dimensions, are traditionally used as a frontline control for monitoring the quality of process. In (Santos-Barbosa, 2013), for instance, empirical relationships used to obtain a model for predicting the final dimensions of tiles (diameter and thickness) in lab scale, taking into account the dimensional changes experienced along the manufacturing steps was developed. In the same work, several aspects regarding the difficulty in implementing automating controls inside this type of industry is also discussed and related to the large variety of products.

One of the main quality concerns is related to the dimensional uniformity of the tile (size and form). The challenge of dimensional control is to produce the highest amount of tiles within a standardized specification. The dimensional changes of ceramic tiles have been broadly studied in the last decades, using different approaches. The final size of fired bodies has been related to the composition of raw materials and/or processing parameters, including preparation, forming, and firing steps. Some of these works could be associated with tentative approaches to provide data for future-automated control of unit operations in the ceramic tile industry. Particularly, pressing and firing steps have been studied more deeply. For instance, the characteristics of an industrial powder and the influence of its particle size distribution on the wet and fired densities were studied by (Amoros *et al.*, 1984). This large investigation also proposes corrective solutions related to excessive deviations from required dimensions of the final products adjusting the density distribution of basic elements in moisture, the compacting pressure, the firing shrinkage, etc.. It is stated that dimensional variations of only 0.1% can be enough to cause significant deformations on large tiles and loss of functionality. Considering the importance to keep the process parameters under a strict and stable control, several similar researches also propose new methods/systems for the effective monitoring of powder moisture, compaction pressure, temperature of fire, even with on line measures. Even if the positive effect of the application of a TQM approach in the traditional ceramic manufacturing is easy to be verified, as in (de Noni *et al.*, 2006), nevertheless, the influence of the main process variables on the final and intermediate characteristics of the tiles (mass, size and thickness) has not yet accomplished in the literature considering the tile manufacturing process as a whole. Further efforts are necessary in this direction.

Outside several concepts here detailed and generically referable to the application of TQ methods and tools in the traditional ceramic industry, additional considerations have to be expressed regarding the use of TQM for monitoring bending processes. In fact, to be efficient and functional, a quality monitoring on processes and products in ceramics industry has to take in count of several specificities. The conventional industrial processing of grés porcelain tiles covers three main stages: milling/mixing and spray drying of the raw materials; pressing, drying and decorating of the green body; firing and classifying of the finished product. In the case of bended tiles, another stage, the forth, is also added: as previously detailed, it consists in a further tile firing in kiln, leading to bend the flat shape by “pyrodeformation” and gravity. This additional process is totally independent by the previous ones: it is commonly realized in a different process plant and can be almost applied to the whole gamma of flat tiles available on the market. As a consequence, wherever the concept of TQM for bended tiles is mentioned, it specifically refers to the necessity of monitoring the quality parameters along this forth stage of treatment (used for tile bending) without considering the previous ones (used for tile production). In other terms, in the following sections of the present article, the quality of flat tile is a constant basis for every further TQM consideration.

3. International standards applicability

This investigation starts from a preliminary analysis of common methods and equipments used in ceramics tiles for the evaluation of mechanical proprieties of resistance. In this field, as first step, ISO 10545 has to be recognized as the essential standard ruling the test methods provided for the qualifying characteristics ceramic tiles in function of their use. This large standard consists of 17 different sections, one for each test method. Anyway, only the *Part 4*, on *Determination of modulus of rupture and breaking strength* refers to mechanical tests and proprieties. For instance, it reports that grès porcelain stoneware has to demonstrate (to be commercialized) a breaking strength ≥1300N and a bending strength ≥35N/mmq as lower limits.

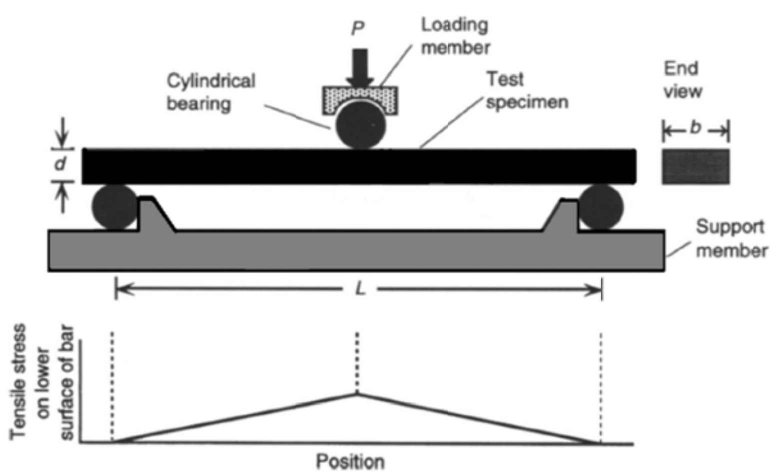
These value can be measured by experimental tests using, for instance, a servohydraulic testing frame fatigue machine, equipped by a load cell. Specimens can be loaded in control of displacements and stresses measured. Data have to be acquired with an appropriate acquisition rate, able to correctly monitor the failure phenomena. Grips and fixtures have to be selected/realized and positioned according to the standards. Even the number of specimen is strictly defined by standard with the aim at reducing experimental variability.

For each specimen, tests and calculations permit to determinate:

- the force-displacement diagram
- the breaking loads and displacements
- the breaking strength and deformation
- the stress-strain diagram

In the case of determination of flexural breaking strength, a flexural test has to be used. It permits the determination of the breaking load, breaking strength and modulus of rupture of a tile by applying a bending force at a specified rate to the centre of the tile, the point of application being in contact with the proper surface of the tile.

There are different methods for measuring strength, such as the most common three-point and four-point flexural tests (Figure 5), but also equibiaxial disk flexure test, ring-on-ring and ball-on-ring are sometimes used. As reported in *ASTM C1161*, in general the three-point test configuration exposes only a very small portion of the specimen to the maximum stress. Therefore, three-point flexural strengths are likely to be much greater than four-point flexural strengths. Three-point flexure has some advantages. It uses simpler test fixtures, it is easier to adapt to high temperature and fracture toughness testing, and it is sometimes helpful in Weibull statistical studies. However, four-point flexure is preferred and recommended for most characterization purposes.



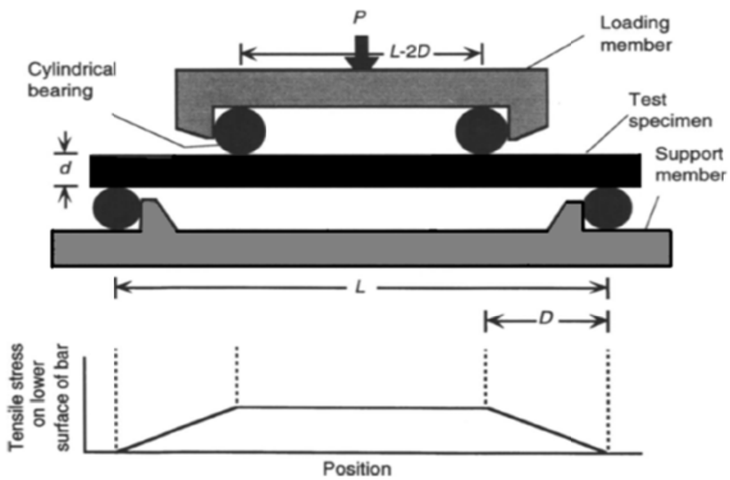


Figure 5. Application of loads with 3-point and 4-point flexural test

According to the previous investigations (Fragassa, 2015), it is possible to confirm that ISO 10545/4 and, in particular, a three-point flexural test represents an appropriate method for measuring the mechanical flexural behaviour of Grès Porcelain stoneware even in the case of bended tiles. This test has also been appropriately used for monitoring the process of bending of tiles (as reported in Fragassa *et al.*, 2014b)

Using the three-point experimental configuration:

- breaking load is the force necessary to cause the test specimen to break as read from the pressure gauge
- breaking strength is the force obtained by multiplying the breaking load by the ratio (span between support rods)/(width of the test specimen)
- bending strength or modulus of rupture is the quantity obtained by dividing the breaking strength by the square of the minimum thickness along the broken edge (on the base of a rectangular cross-section).

4. Experimental equipment

This investigation aims, as main objective, at providing a precise and detailed description of an experimental apparatus the first so far devised for the quality control of curved tiles. This validation test, performed by the use of this specific equipment, passes by the measurement of the flexural strength in the most stressed point for the tile. It is meant to represent an innovative operational mode, useful not only for the quality control of the production lot, but also to optimize the process parameters and to enable their continuous monitoring.

The analysis was initiated by a careful modelling of mechanism and movements, with special regards to the proper evaluation of conditions adopted in application of loads and constraints. From this preliminary analysis, a list of design parameters emerged, including their effect of stress levels.

It appears immediately clear the opportunity to focus this investigation on the strength of the curved part of the tile. This area, one side is weakened by the incisions made on the tile to allow the folding, the other is almost always the point of greatest stress concentration in exercise. The same conclusion is evident by examining actual cases of broken tiles curves (Figure 6). It can also recognize how this area, in the normal conditions of use, is subject predominantly to a bending stress. Consequently, the new test equipment was imagined to provide a pure bending moment in the fold, with the additional requirement, especially linked to the environment of intended use for the device, to be robust, reliable and of practical use.

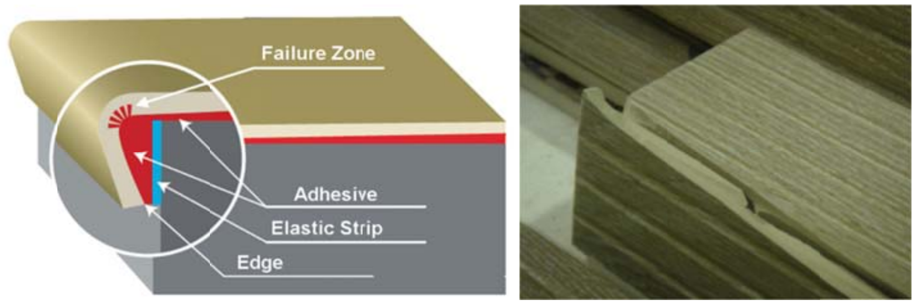


Figure 6. Tile failure

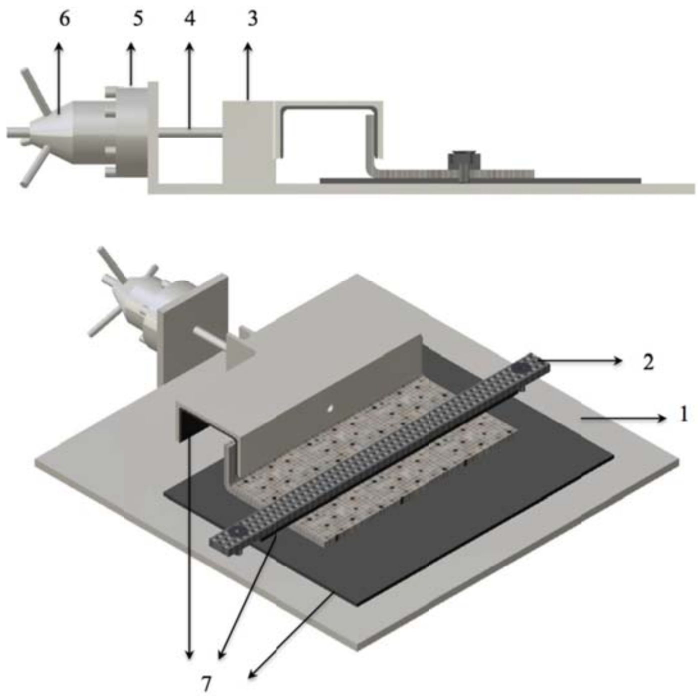


Figure 7. Drawing of testing machine

The result is a very simple equipment, manually activated, highly functional, which will complement what is already required by ISO 10545.4 on how to commission testing of ceramics by calculating the flexural modulus of rupture and the effort of bending failure.

In Figure 7 this device is shown, together with its main parts including:

1) supporting table
2) fixing lever for arresting the bended tile
3) gripping system for loading the bended tile

4) endless screw for motion transmission
5) ball joint for a correct directional alignment of forces
6) load cell for evaluation of forces
7) handlebar for a manual application of loads
8) rubber support inserts for a correct surface contact
9) bended tile under testing

The tile is lying on the supporting table where it is blocked by the pressure exerted by the fixing lever. This bar is close to the tile through the use of two screws which are binding to the supporting table. By a manual action of loading on the handlebar, moved by the endless screw, the operator imposes a translational adjusting the gripping system. When this movable part of the equipment comes in contact with the curved section of the tile, the movement is no longer free: any additional load on the handlebar by the operator turns into a pressure field on the tile.

The load cell has precisely the task of reading the intensity of this force. A ball joint, positioned between the endless screw and the gripping system, reduces the effect of any misalignment of the tile with respect to the contact surface.

All the structural parts of the equipment are made in construction steel (35CrMn5). Some inserts in rubber (a PTFE with density=2170kg/m^3; G=500GPa; ν=0.48) allow to limit the incidence of local effects of contact. In particular, rubber pads are present between:

1) tile and supporting table
2) tile and gripping system
3) tile and fixing lever

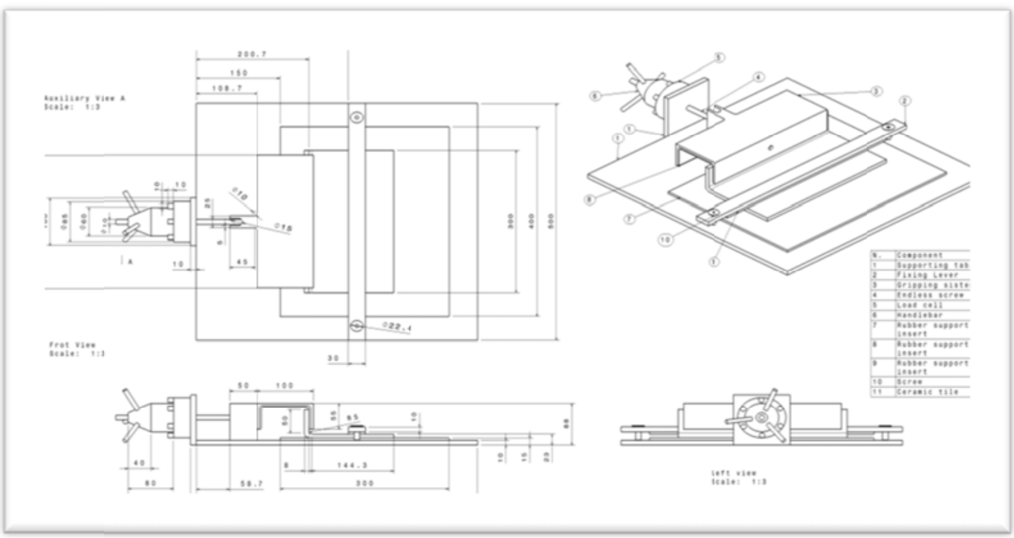


Figure 8. Device technical design

A drafting listed device is available in Figure 8.

5. Test methods

With the aim at modelling force/constrains faces several simplifications are possible.

As first step, it is worthy of attention that this mechanism can be considered in a two-dimensional prospective without relevant changes. In this case, the tile, now reduced to a bi-dimensional bar, presents 3 degrees of freedom (instead of 6): it can be translated along the x axis, translated along the y axis, and rotated, as rigid body, about one rotating point. Specifically, the tile is locked on the support table by the pressure exerted by the screwed bar: this loading system can be easily schematized by a planar revolute pair *(R-pair)* and a planar prismatic pair *(P-pair)* as reported in Figure 9. No movement is permitted with the tile in a isostatic boundary conditions.

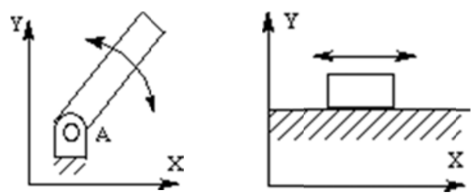


Figure 9. Planar revolute and planar prismatic pairs

Referring to the device's functionality, by the handlebar the operator imposes a rotation to the endless screw, which, thanks also to a rigid flat abutment, is transferred to the gripping system in terms of horizontal translation. When the gripping system comes in contact with the bended tiles, the macroscopic displacements are prevented and induce a stress / strain state in the ceramics

In practice, the torsional moment acting on the handlebar is directly transferred to the tile by the gripping system as a contact pressure on the vertical surface and, as a consequence of this, in terms of flexural stresses in the bending zone.

The simplified system of constraints and forces is represented in Figure 10.

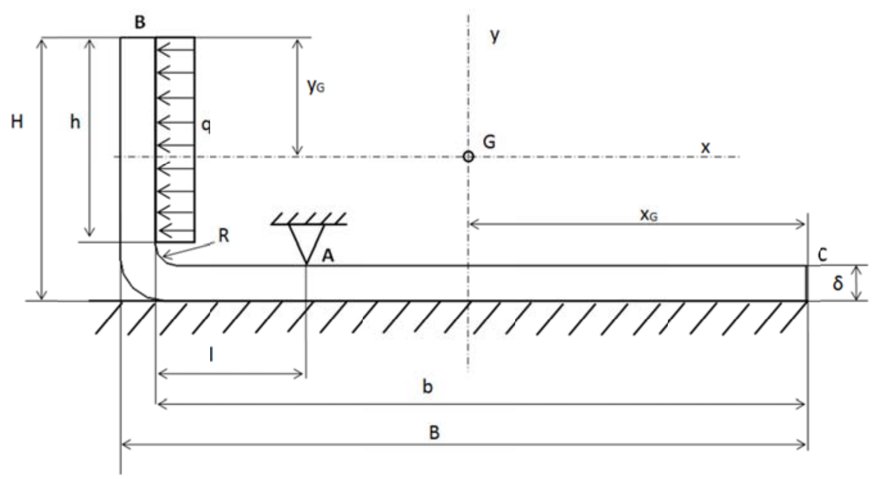


Figure 10. Modelling loads and constrains

where it is defined

- H tile (external) height
- h tile internal height
- B tile (external) length
- b tile internal length
- A tile width
- **δ** tile thickness
- l distance of fulcrum of the lever
- R radius of curvature
- q distributed load on surface
- h_q height of loading area

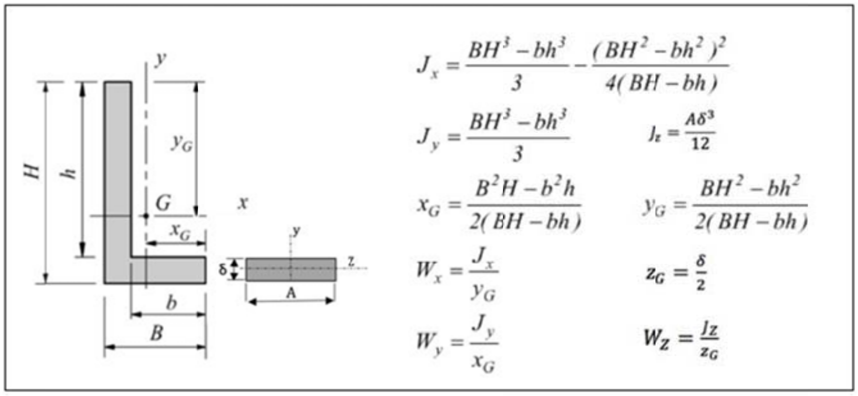


Figure 11. Standard formula for an "L" shaped beam

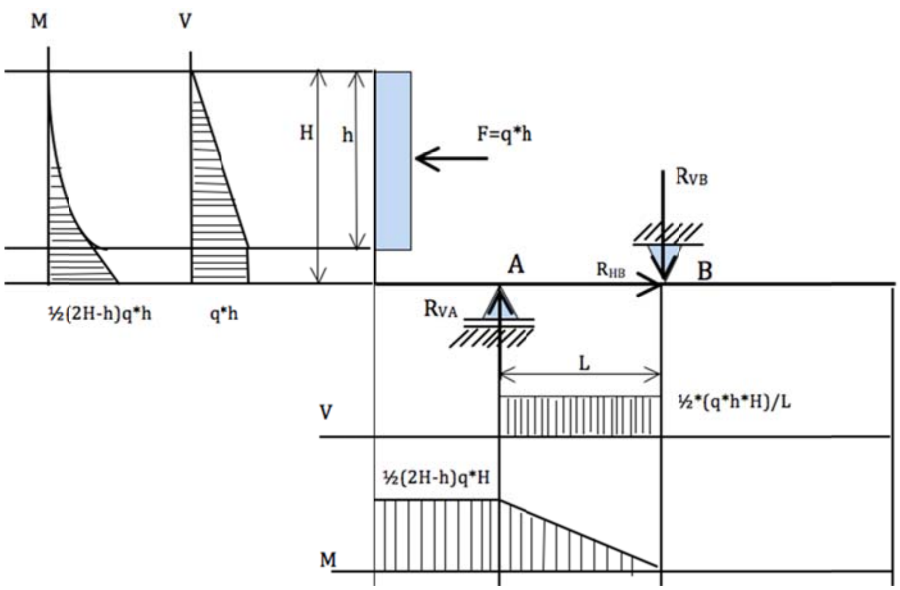


Figure 12. Evaluation scheme of loads (F), reaction forces (R), shears (V) and bending moments (M)

With reference to the diagram of calculation of Figure 11 and without considering the presence of a bending radius, it is possible to estimate (as reported by Cesari *et al.*, 2013; Paolacci, 2010):

$J_Z \sim 128\ 000\ mm^4$ (1)

$W_Z \sim 3\ 200\ mm^3$ (2)

The evaluation of reaction forces, sheers and bending moments can be obtained in accordance with the simplification represented in Figure 12 and, as a consequence:

$$M_f = \frac{F_q \times (2H - h)}{2} \quad (4)$$

For instance, in the case of

$$F_q = 4.0\ kN \quad (5)$$

then,

$$M_f = 140\ Nm \quad (6)$$

$$\sigma = \frac{M_f}{W_Z} \sim 44\ MPa \quad (7)$$

6. Quality control

The equipment is finally assembled and use for a direct measures of flexural resistances of bended tiles (Figure 13). This preliminary test aims at validating the adoption of the new equipment as testing device for the quality monitoring of bending processes instead of investigating specific lots of production. Between other useful proprieties, the measures have to be, first of all, constant and repetitive when referred to analogous tests and samples. According to the general simplicity of functional principles and of operating mechanisms, a high repeatability for the measurements is supposed.

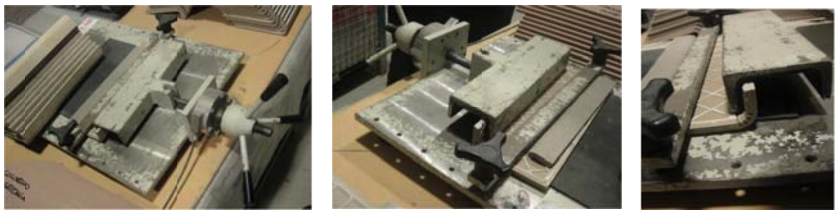


Figure 13. Equipment used for testing bended tiles

This check on measure sensibility was implemented testing ceramic specimens manufactured in stable conditions of materials and process, in accordance with general theory on statistical quality control (Montgomery, 2007) and on design and analysis of experiments (Montogeomery, 2001).

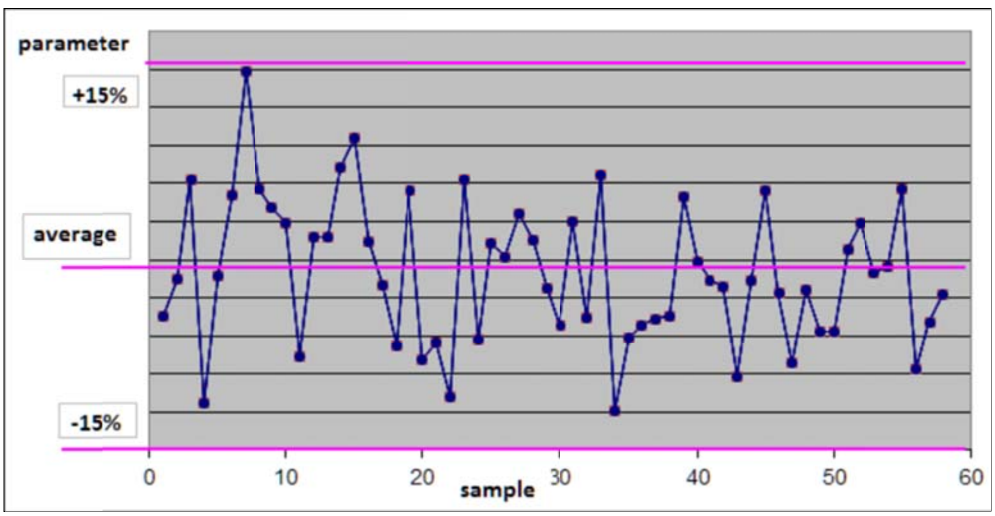


Figure 14. Control chart regarding the flexural resistance of bended tiles

Specifically, n. 60 tiles were bended taking care of having the same:

- basic material (a commercial fine porcelain stoneware)
- production plant (a specific tunnel kiln)
- time-depending profile of temperature.

These samples were firstly verified in dimensions and, then, tested using the new flexural testing devices. For each specimen the maximal loading force (leading to tile's rupture) was recorded and compared. The ultimate flexural stress was also calculated and compared.

Generally, a slight variability in experimental data is acceptable dealing with ceramics, which, due to a combination of several factors (relative to compositions, processes...), tends to be a material from a quite unpredictable mechanical behaviour. According to (Palmonari and Carani, 2005; Fragassa *et al.*, 2014c) or similar investigations, mechanical proprieties in ceramics can unsurprisingly vary of 15-18%. A similar inaccuracy is waited from instrumental outputs. In the current case, the range of variability was higher than 25% (Figure 14).

The problem of uncertainty on experimental measurements, compared with the inherent variability of the material, is a recurrent matter to be considered whenever natural materials or unconventional processes are present. In this case, both of these aspects of unpredictability surely coexist, and are able to justify the amplitude of control chart. With the aim at assuring that the accuracy of measurement is sufficient to ensure the validity of experimental results, a specific FEM investigation is also implemented and presented in (Pavlovic, 2016) toward the complete qualification of the testing equipment.

7. Conclusions

In the case of bended tiles, designers are facing an entirely new class of functional elements, perfect for providing several convincing architectural solutions in a large range of applications where traditional porcelain stoneware fails. The situation renders obsolete the traditional rules for the determination of the mechanical characteristics of the planar tiles. In particular, this limit refers to the applicability of ISO 10545.4 that describes the mode for testing the mechanical proprieties of ceramics by calculating the modulus of rupture in bending and breaking strain in bending. In the case of bended tiles, this standard even fails to address the area of concentration of tensions. In fact, it is evident how the test conditions are totally different respect to the working conditions: therefore, the need of new experimental methods emerged.

As a direct consequence, a new testing device was designed and realized. It was specifically intended to test the flexural strength of bended tiles in their most critical area, as a fundamental parameter for monitoring the quality of process and products. The present article described the apparatus, the specimen requirements, the test procedure and all the calculations permitting to obtain the maximal value of flexural strength starting from the experimental measures. The procedure can be indifferently applicable to monolithic or particulate- or whisker-reinforced ceramics tiles, when bended. Furthermore, this experimental equipment is very simply in its utilisation and can be used at ambient temperature or environmental conditions without particular limitations. Since all these aspects, the new method of testing is ready to assume a role of standard in the case of quality certification of bended tiles.

The paper also proposed an initial use of the equipment for the quality monitoring of bending process by a direct measures of flexural resistances on some lots of tiles. This preliminary test manly aims at validating the adoption of the device as testing tool inside a larger approach of TQM. Regrettably, experimental measures showed an unforeseen uncertainty in predictions. During the design of the equipment, the apparent simplicity in operating principle invited to the suppose a high repeatability of measurements. The practical use of this device highlighted a strong variability in experimental data. If this variability is related to the act of measuring, several improvements in design of the equipment or in the procedure for testing can be easily implemented. On the contrary, if the detected variability is related to a real unpredictability of physical proprieties of bended tiles, it could reduce their spread perspective throughout the potential applications, especially limiting their use in those cases where a quality "assurance" on mechanical and dimensional proprieties is requested for absolving specific functions.

The problem of uncertainty on experimental measurements, compared with the inherent variability of materials and processes is a relevant matter of investigation when ceramics are involved. It should be verified that the accuracy of measurement in itself, intended both as precision of the instrumentation used that as correctness of the procedure adopted, is sufficient to ensure reliable results for the parameters investigated, at least compared to the error of the typical size of the ceramic. In this case, the adoption of this particular device is a valid strategy for monitoring of product quality and process.

In any case, it is far away from transforming these bended tiles in large-mass products without implementing an approach toward TQM in which the use of this devise represents a single step of control.

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