NEW CONSIDERATIONS ON STRUCTURAL SAFETY OF MASONRY BUILDINGS IN BRAZIL

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ABSTRACT
Since 1970 nearly six thousands four-storey buildings were constructed in Recife, a northeast Brazilian city, on very poor quality horizontal hollow blocks load-bearing masonry. Neither Brazilian nor international standards were followed to design and build the buildings and, as a result, eleven collapses have happened during the last decades, leaving twelve fatal victims. In 2005 a simplified full-probabilistic tool was developed to estimate the reliability of those buildings, considering the dead, live and wind loads of every wall compared with its strength. The masonry compressive strength was considered taking both normal and log-normal distributions leading to numerically different results, some of them absolutely unacceptable. In this paper the differences between normal and log-normal distributions of masonry strength are exposed and the current use of the normal distribution is criticized due its physical incongruences. Moreover, the necessity of further studies on masonry strength properties is demonstrated, aiming to provide better confidence in the full-probabilistic approach to be used to save lives in Recife and around the world.

KEYWORDS: structural masonry, reliability, failure, collapse

INTRODUCTION
It is not uncommon in Brazilian engineering the lack of consideration of the technical standards in civil construction. In fact, many standards are not respected, mainly due to search of economy in construction.

Regarding to structural masonry, there are several examples of buildings designed and constructed without the consideration of the standardized calculation models. The definition of materials such as blocks and mortar is made empirically, without any scientific endorsement and with serious technical inadequacies. The most impressive cases are in the Recife's Metropolitan Region, where many buildings were built with horizontal hollow cladding clay blocks with inadequate structural function [1, 2]. The consequences, widely reported in the press, are cases of collapses that caused many deaths, possibly caused by incompetence, imprudence and / or negligence of the constructors.

Perhaps the most alarming report on the subject is on a government site [3]. The site reports six thousand buildings in the Recife's Metropolitan Region which have unsafe structure, according to data collected by the Pernambuco's Technological Institute (ITEP). This figure is confirmed by a technical work [2] which points to the existence of stability problems in some of these buildings. The large majority of these problems are probably related to inadequate practices of design or construction in structural masonry.

Extending the scope of the case for the rest of the country, it is possible to find the same problem of disrespect of standards and to detect buildings constructed with materials and procedures similar to these Recife's buildings. In fact, independent from the adopted structural system, the bad examples are commonplace. Often this attitude determines the reduced levels of structural safety, exposing the occupants to greater risks than those considered normal for house buildings.

Beyond the discussion about the pertinence or legality of building without strict compliance with the regulations, it remains the doubt about what to do with the large number of buildings with problems. Considering the collapses that have already occurred, many Brazilian engineers have given their opinion on the adequacy of the buildings in question. Such opinions, instead of a necessary convergence to solve the existing problem and to outline clear policies for future practices, created a big controversy. Part of the engineers emphatically state that the buildings are not safe to be used, while some say that the buildings are stable and can still be used.

While this question persists, thousands of families continue to reside in buildings whose reliability is unknown. Such families may, in an optimistic hypothesis, be living a kind of psychological torture, driven by socio-economic status to live in buildings popularly called 'coffins', whose structures are under suspicion. At worst, however, these families may actually be sentenced to death in collapses of buildings that would not have reliable conditions.

GENERAL AIM OF THE WORK

Considering the above and their implications, it is easy to conclude that there is a need for an objective assessment of the problem, aiming to solve it. One possibility would be to conduct load tests in buildings under suspicion, which is clearly unpractical due to the work and cost involved. Another possibility is the theoretical treatment of the case, what can be done at low cost, in short time and without significant interventions in buildings and in the routine of its inhabitants.

Assuming the theoretical approach, it is suggested to calculate the probabilities of ruin of buildings under suspicion and use it as criteria for acceptance of its structures. Although there is no law that determines an acceptable risk value, it can be inferred from the existing literature [4, 5] that this value would be close to 10^{-6} (one chance in a million), an amount that can be changed based in discussions that lead to consensus. Known the risk of each building, its failure probability would be confronted with the consensus, to establish if the building would be suitable or not for housing, to define the possible need for reinforcement and to determinate its evacuation or the maintenance of residents.

However, considering the monumental work necessary to estimate the structural reliability of a large number of buildings, it must be seek a solution that is easy to apply in order to minimize the time and resources spent, at least for a first analysis. Therefore a tool was developed to access the reliability analysis of these buildings. The tool had a clear development and a very simple use, and allows understanding and discussion of the methodology and its application to concrete cases.

GENERAL CONCEPT OF THE TOOL

Although there are several methods for calculating the probability of structures failure, the purpose of this work was to develop a simple tool. Thus, two spreadsheets were developed using the method of interference between the stress and strength, with analytical and numerical resolutions tested between themselves and also with a demo of the program Anthill for Windows [6].

The chosen method for the worksheets development is one of the oldest in structural reliability analysis. However, it is still popular due to its simplicity and easiness of use. The method's biggest disadvantage is the hypothesis that the strength and the load are statistically independent, which can be inappropriate especially when the load redistributing is a known effect.

The method allows examining each element, comparing their estimated strength with the acting stresses based on purely probabilistic parameters. Thus, the strength and stresses are compared, to estimate the probability of the latter to exceed the first. This leads to the collapse of a particular part of the structure, according to the equation 1 [7] and as demonstrated in Figure 1.

$$p_f = p(R < S) = \int_0^{\infty} F_R(x) f_Q(x) dx \tag{1}$$

where p_f is the probability of failure, and

$p(R<S)$ is the probability of the Resistance (strength) to be smaller than the acting Stress;

F_R is the cumulative distribution function (c.d.f.) in R; and

f_Q is the probability density function (p.d.f.) for Q.

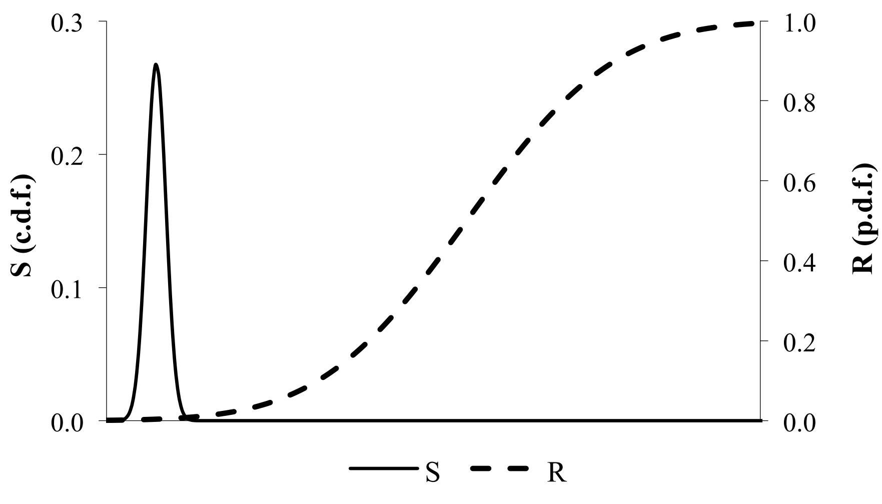

Figure 1: Stress-strength interference.

THE ASSUMED ASSUMPTIONS

The structures of buildings can be seen as a structural elements association. Thus, in a structural masonry building the structure could be divided basically into horizontal elements (slabs and existing beams) and vertical elements (walls). Slabs and beams, due to their ductile characteristics and reduced consequences from a possible collapse, were not considered. The walls, as already written, were the elements considered, restricted to the compressive loads, since lateral bending and shear stresses have not shown to be significant in the studied case.

Considering that each building can be made of multiple floors, each of them composed of several walls, the probability of the failure was estimated by the adoption of the hypothesis that the structure would behave according to a serial system demonstrated by equation 2 and in Figure 2.

$$P_f = 1 - \prod_{i=1}^{n} (1 - p_i) \tag{2}$$

where P_f is the global probability of failure, and
p_i is the probability of failure of each element.

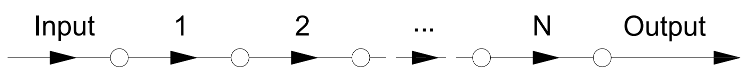

Figure 2: Representation of a serial system [8].

The authors alert that the real structures must behave as a system comprised of serial and parallel subsystems, but the choice of a serial system, even physically unrealistic, was made due to both the simplicity and the brittle structure behavior observed in the collapsed buildings in Brazil. Actually, it is recurring theme in the literature the need of caution with fragile structures when the load distribution is not advised.

It is important to point out that this is a simplification which defines an important change in the collapse mechanism of the building. In fact, some level of redistribution will occur before the wall rupture through the load spreading phenomenon and after breaking by the solidarity inherent to the structure. Convincing evidence of the load spreading phenomenon are the numerous types of changes in the investigated buildings without failure even with the elimination of structural walls. Even though, serial system was considered more appropriate because some buildings had complete failure without any previous sign of imminent crack.

The mechanical characteristics of the masonry walls such as the average compressive strength, coefficient of variation and distribution type had to be fixed for the subsequent calculations. Although the normal distribution is used for didactic explanations and even due to its ease domain, the distribution that best fits the strength of masonry seems to be the log-normal [5, 9, 10, 11]. Considering the lack of experimental data about the distribution for the buildings walls (in a global scale and particularly in the Brazilian out-of-standards masonry), these studies were carried out using both types of distribution, i.e., normal and log-normal. On the other hand, the coefficient of variation, which is strongly influenced by workmanship, was adopted based on results from literature review regarding researches on structural masonry in Brazil. The authors did not perform any experiment on the strength distribution of masonry or its coefficient of variation, and will make further considerations about this below.

As the compressive strength, the acting loads shall be known. In addition, the combinations of the different load types must be considered. A simplified load combination was made, considering all loads with normal distribution. This load combination S takes only the permanent loads (Q), the live loads (G) and wind loads (W). Any other source of load such as earthquakes or land settlement was not taken into account. The coefficients of variation used were 5% for the dead load, 100% for live loads and 38% for tensions due to the wind, which was the same coefficient of variation used to calculate the probability of ruin of buildings. Although other values of cv can be found in different sources, JCSS standard project guidelines were adopted [5, 12, 13].

EXAMPLES OF APPLICATION

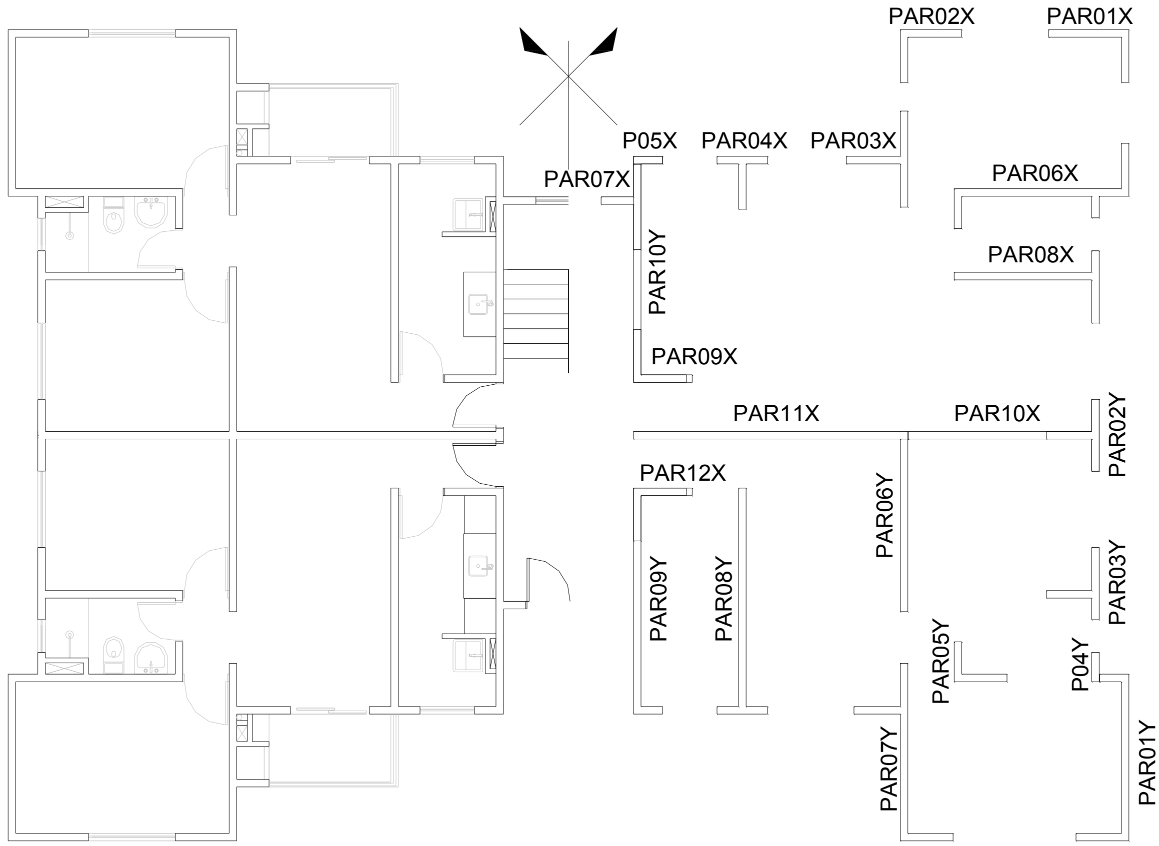

Figure 3: Floor plan of the building used to test the model and structural walls used.

Based on the developed theory and considerations, a four-storey high fictitious building was used to verify the result. First the test of reliability was made for a building designed and theoretically built entirely in accordance with the standards. It was considered the use of 14 cm thick concrete blocks. After that, it was calculated the failure probability of the same building designed not considering the standards procedures and with walls built with cladding clay blocks 9 cm thick. The plan of the building used in the examples is shown in Figure 3.

The failure probability of the building designed according to standards was calculated for each wall, taken into account that their strength may change at each floor according to the blocks resistance and the use or not of grout. Moreover, in a same floor each wall has a slightly different strength due to the β factor defined by BS 5628 [14]. It has to be pointed that the building is four storey high (and a basement) with 72 walls in each floor, i.e., there are 360 elements possible of collapse. The combination of all these probabilities gives the reliability of the building. After the calculation of the failure probability of each element, the overall probability of failure was determined according to the equation (2). For this case, assuming normal distribution for loads and strength, the global probability of collapse was 5.27×10^{-4}. Tables were prepared to show the failure probability for each wall and each floor. Table 1 shows the walls of the ground floor.

Table 1: Ground floor results for building designed in accordance with the Standards, assuming normal distribution for loads and strength.

Element	Repetitions	Loads (MPa)					Strength (MPa)				P_f individual
		G_k	Q_k	W_k	S	σ_S	R_k	β	R	σ_R	
PAR01X	4	0.41	0.05	0.06	0.43	0.03	4.12	0.91	5.61	1.12	1.98E-06
PAR02X	4	0.45	0.05	0.05	0.46	0.03	4.12	0.91	5.61	1.12	2.27E-06
PAR03X	4	0.60	0.08	0.05	0.61	0.04	4.12	0.89	5.45	1.09	4.65E-06
PAR04X	4	0.67	0.18	0.04	0.72	0.07	5.95	0.88	7.80	1.56	2.87E-06
PAR05X	4	0.40	0.04	0.07	0.43	0.03	4.12	0.93	5.70	1.14	1.92E-06
PAR06X	4	0.35	0.05	0.09	0.40	0.03	4.12	0.90	5.54	1.11	1.79E-06
PAR07X	2	0.81	0.22	0.05	0.86	0.09	5.95	0.94	8.33	1.67	3.78E-06
PAR08X	4	0.33	0.05	0.09	0.38	0.03	4.12	0.91	5.60	1.12	1.61E-06
PAR09X	2	0.35	0.06	0.05	0.38	0.03	4.12	0.90	5.52	1.10	1.60E-06
PAR10X	2	0.38	0.08	0.12	0.46	0.05	4.12	0.91	5.59	1.12	2.26E-06
PAR11X	2	0.40	0.12	0.13	0.50	0.06	4.12	0.92	5.62	1.12	2.67E-06
PAR12X	2	0.35	0.06	0.05	0.38	0.03	4.12	0.90	5.52	1.10	1.60E-06
PAR01Y	4	0.28	0.02	0.07	0.31	0.02	4.12	0.92	5.67	1.13	1.13E-06
PAR02Y	2	0.45	0.04	0.19	0.54	0.05	4.12	0.92	5.68	1.14	3.15E-06
PAR03Y	4	0.39	0.03	0.09	0.43	0.03	4.12	0.93	5.71	1.14	1.90E-06
PAR04Y	4	0.45	0.02	0.09	0.48	0.03	4.12	0.92	5.66	1.13	2.41E-06
PAR05Y	4	0.31	0.04	0.41	0.55	0.10	4.12	0.92	5.68	1.14	3.39E-06
PAR06Y	4	0.32	0.05	0.08	0.36	0.03	4.12	0.90	5.53	1.11	1.51E-06
PAR07Y	4	0.45	0.07	0.07	0.49	0.04	4.12	0.90	5.51	1.10	2.61E-06
PAR08Y	4	0.36	0.08	0.09	0.42	0.04	4.12	0.91	5.56	1.11	1.89E-06
PAR09Y	2	0.64	0.33	0.08	0.77	0.13	5.95	0.92	8.16	1.63	3.17E-06
PAR10Y	2	0.70	0.27	0.07	0.79	0.11	5.95	0.92	8.12	1.62	3.39E-06
Global probability of failure (ground floor)											**1.71E-04**

If the type of distribution of loads and strengths are assumed as log-normal for the building designed according to standards, the probability of failure would fall to only 4.5×10^{-14}. This seems to confirm that the best distribution to be used nowadays is the normal distribution. Besides to the fact that the standards have been based on it, there is not sufficient data to perfect characterize log-normal curves. It was found also that an overall probability of ruin of 10^{-6} would be achieved, adopting normal distributions for loads and materials strength and a coefficient of variation of 16%. This shows that, considering the building walls with a slightly better homogeneity than that used (20%), the building would achieve the theoretically required reliability.

The same building plan was designed considering the use of cladding clay blocks 9 cm thick walls and with 1.5 cm mortar rendering in each side. The same steps of the previous example were followed, changing only the walls dead load and its geometric and mechanical properties.

Although no standard allows considering the mortar rendering contribution on the compressive strength of the walls, some research works [15, 16] suggest the mortar rendering can increase the wall strength. Therefore, considering the aim of this work, it was decided to take the block thickness plus the mortar thickness as the effective width of the walls, i.e., 12 cm. The flanges were also considered. It is important to note that the authors understand that both the decision of taking the full width of the wall and the flanges shall be taken only after a careful investigation *in loco*. They depend on several factors, such as the integrity of the rendering, its regularity and adhesion to the blocks and the effective existence of connection between the walls.

From the imposed loads, the probability of failure was calculated, considering the average strength of masonry prisms of 3.25 MPa and a coefficient of variation of 20%. These data were obtained from test results of a building named Enseada de Serrambi, which collapsed [17]. The contribution of mortar was also considered. The coefficient of variation was chosen after observation of values from literature [15, 16, 18] which comprises a large number of tests. The compressive strength and the coefficient of variation used lead to a characteristic strength of 2.18 MPa, well below the one identified as necessary by the structural design, i.e., 9 MPa.

In this case, as the walls are equal for all floors, the difference was only the slenderness factor and the use of walls without rendering in the basement. For the basement the average compressive strength of the prisms was reduced from 3.25 to 2.57 MPa [17]. So, the calculated failure probability considering the normal distribution for the masonry strength was of 5.8%. For a sensitivity analysis the authors remember that 11 collapses occurred for 6,000 buildings along four decades, which leads to a failure probability of approximately 4.5×10^{-5} per year). Table 2 shows the individuals and global results for the ground floor.

Also in this case the log-normal distribution for stress and strength was tested. Unlike occurred in the previous example, for cladding block walls the results were closer to the 10^{-6} target. The global probability of failure is 4.38×10^{-3}, still considered extremely high, but that cannot be considered unreal. If further tests come to show that the material behavior has a log-normal distribution, this may better explain why there were not higher number of buildings collapse.

In another simulation the strength coefficient of variation was decreased to 15% with normal distribution. In this case the collapse probability would be around 2.8×10^{-3}, more acceptable than the nearly 6% observed in the original condition. If, in addition to this reduction, the average strength is increased 10%, the probability of failure would fall to around 9.1×10^{-4}, still high but already a reasonable limit.

Table 2: Ground floor results for building designed without compliance with the Standards, assuming normal distribution for loads and strength.

Element	Repetitions	Loads (MPa)					Strength (MPa)				P_f individual
		G_k	Q_k	W_k	S	σ_S	R_k	β	R	σ_R	
PAR01X	4	0.40	0.05	0.07	0.43	0.03	2.18	0.66	2.13	0.43	3.59E-05
PAR02X	4	0.44	0.06	0.06	0.47	0.03	2.18	0.66	2.13	0.43	4.91E-05
PAR03X	4	0.63	0.09	0.06	0.66	0.05	2.18	0.63	2.05	0.41	3.72E-04
PAR04X	4	0.68	0.20	0.05	0.74	0.08	2.18	0.62	2.02	0.40	9.42E-04
PAR05X	4	0.38	0.04	0.09	0.42	0.03	2.18	0.67	2.18	0.44	2.88E-05
PAR06X	4	0.35	0.06	0.11	0.42	0.04	2.18	0.64	2.09	0.42	3.39E-05
PAR07X	2	0.77	0.26	0.06	0.85	0.11	2.18	0.68	2.22	0.44	1.29E-03
PAR08X	4	0.33	0.06	0.11	0.39	0.04	2.18	0.65	2.12	0.42	2.43E-05
PAR09X	2	0.34	0.08	0.06	0.38	0.04	2.18	0.64	2.08	0.42	2.41E-05
PAR10X	2	0.40	0.10	0.14	0.49	0.05	2.18	0.65	2.13	0.43	6.76E-05
PAR11X	2	0.49	0.14	0.16	0.61	0.07	2.18	0.66	2.16	0.43	1.94E-04
PAR12X	2	0.34	0.08	0.06	0.38	0.04	2.18	0.64	2.08	0.42	2.41E-05
PAR01Y	4	0.26	0.03	0.08	0.31	0.02	2.18	0.67	2.16	0.43	9.01E-06
PAR02Y	2	0.43	0.04	0.23	0.55	0.06	2.18	0.67	2.17	0.43	1.10E-04
PAR03Y	4	0.37	0.03	0.11	0.42	0.03	2.18	0.67	2.18	0.44	2.89E-05
PAR04Y	4	0.45	0.02	0.11	0.49	0.03	2.18	0.66	2.16	0.43	5.60E-05
PAR05Y	4	0.29	0.04	0.50	0.60	0.12	2.18	0.67	2.17	0.43	2.39E-04
PAR06Y	4	0.32	0.06	0.10	0.38	0.04	2.18	0.64	2.08	0.42	2.25E-05
PAR07Y	4	0.47	0.08	0.09	0.51	0.04	2.18	0.64	2.08	0.42	9.06E-05
PAR08Y	4	0.36	0.09	0.11	0.43	0.05	2.18	0.65	2.10	0.42	4.05E-05
PAR09Y	2	0.63	0.38	0.10	0.79	0.15	2.18	0.66	2.16	0.43	1.33E-03
PAR10Y	2	0.71	0.31	0.09	0.83	0.13	2.18	0.66	2.14	0.43	1.62E-03
Global probability of failure (ground floor)											**1.71E-02**

THE NEED FOR FURTHER STUDIES

The results presented above make clear the need for further studies concerning the behavior of masonry, regarding both its distribution resistance and its coefficient of variation. Although this paper do not presents the state-of-the-art of the reliability evaluation, it alerts to a fundamental problem: any evaluation method will be inaccurate if the basic properties of the material are unknown.

One of the first researchers to make important contributions regarding to probabilistic criteria in the structural analysis was Alfred M. Freudenthal, between the 1940's and 1960's. He has stimulated the discussion on the topic through various papers [19, 20, 21], but never was concerned about the masonry behavior. After him an important contribution was made by Ellingwood *et all* [7] in 1980, but his work was not put into practice until today. In the last years, the Joint Committee on Structural Safety – JCSS, have developed a standard that deals with the subject [5, 12, 13, 22]. Its documents bring important considerations, alerting that there are many uncertainties concerning loads, materials and geometry and that in most engineering applications the statistical information about the variables are not completely available. In fact, although the normal distribution is the most widely used for didactic explanations and even for its easiness, the distribution that best fits the resistance of structures seems to be a log-normal, which is indicated for masonry by some technical works [5, 9, 10, 11].

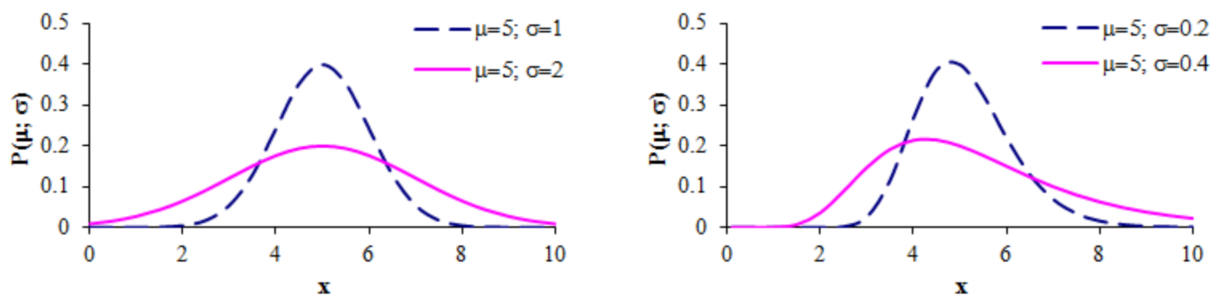

Figure 4: Differences between the normal (left) and log-normal (right) distributions.

As seen in the graphs of Figure 4, where the mean is relatively distant from zero and the variability is small (dashed lines), the distributions normal and log-normal are very similar. However, for cases where the average is near zero or if the variability is high, the distributions are quite different, which changes the calculation of structural reliability. Considering that it is physically impossible to have negative values to the resistance, there is a need to represent it with log-normal distribution. The problem is that the standards that adopt the partial safety factors, as the BS 5628 and Eurocodes, are still based on normal distribution of resistances [23, 24, 25].

So, it is highly necessary to conduct studies worldwide in order to understand the real compressive behavior of masonry, aiming a better confidence in the full-probabilistic approach to be used in the future. This need is most urgent in countries like Brazil, where there are thousands of buildings built with poor quality masonry and this approach seems to be the best way to ensure its structural safety.

In countries where standards are respected, the knowledge of the true behavior of masonry can lead to more economical designs. Indeed, if the log-normal distribution and a small variability of resistance will be confirmed, many financial and environmental resources can be saved, which will be beneficial to the entire planet.

We caution to the difficulty of estimating the coefficients of variation of the factors involved, balancing the theoretical values obtained from laboratory tests and practical experience with real data. In Brazil this will be an even more difficult task, since the variability of materials and workmanship is very high. It just shows the great difficulty that engineers will face if they accept the challenge that is proposed here.

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