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STUDY OF THE INFLUENCE OF STEEL STRIPS WIDTH IN THE BRAZILIAN TEST

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Abstract. *The Brazilian Test, or splitting test, is a method used to determine, in an indirect way, the tensile strength of materials such as concrete, asphalt mixtures, rocks, soils, among others. The test consists of applying a compressive load to cylindrical specimens. The compression load is applied along the length of the cylinder by auxiliary elements, that vary according to the standard and the material studied. Although the transfer mode of loading varies according to the studied material, the calculation of the maximum resistance is the same in all cases, because the theory that bases the method does not consider the influence of the material used in the application process of the loading. The main objective of this study is to evaluate the influence of steel strips width used as load transfer auxiliary elements. For this propose is used digital image correlation to analyze the crack pattern and, indirectly, the distribution of the resulting stresses in the specimens. It was possible to identify that the change in the width of the strips of steel directly influences the results, mainly due to shearing at the contact ends. It was also possible to conclude that the origin of the main crack does not coincide with the center of the cylinder in several tests, which indicates that the rupture did not occur as predicted by the theory underlying the method.*

Keywords: *Brazilian test, strips of steel, digital image correlation*

1. INTRODUCTION

Among the tests to determine the tensile strength, the most common is the Brazilian Test. The Brazilian test is a simple indirect testing method to obtain the tensile strength, which provides agility and easy execution, making possible through empirical formulations to determine the tensile strength of brittle material such as concrete, rock, and rock-like materials (Li and Wong, 2013).

This test is internationally recognized, being standardized for example by NBR 7222 (ABNT, 2011) and C496 (ASTM, 2011), manly for concrete Specimens, and consists of the axial compression of cylindrical specimens. The cylinders are compressed so that the contact between the load application surfaces occurs in two diametrically opposite generating lines along the length of the specimen, as shown by Fig. 1 (a), adapted of NBR 7222 (ABNT, 2011, p. 3), and Fig. 1 (b). For correct execution of the procedure, it is necessary to use components that ensure the best distribution of the load along the length of the sample that is in contact with the loading device, such as wood or metal and concave or flat format.

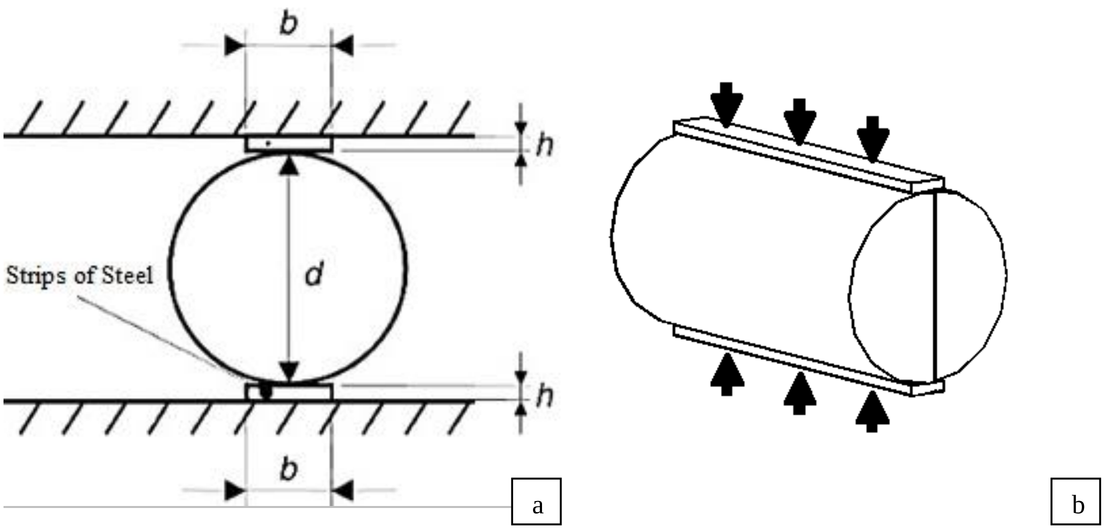

Figure 1. (a) Configuration of the Splitting Test; (b) Diametrical compression

According to Mehta and Monteiro (2008), the theoretical formulation predicts that the loading application process will produce a uniform transverse tensile stress along the vertical diameter, being maximum in the center of the specimen, thus forming the beginning of a crack that propagate continuously to the ends of the material. The maximum value of the rupture force of the test is then applied in equation Eq. (1), thus obtaining the value of the tensile strength of the material ($f_{ct,sp}$).

$$f_{ct,sp} = 2P/\pi dl \tag{1}$$

Where $f_{ct,sp}$ is the tensile strength of the material obtained indirectly through splitting test; P is the maximum breaking strength of the splitting test, d the diameter and l the length of the cylinder.

In order to investigate the way how occurs the distribution of tensile stresses, Hondros (1959) took into consideration a uniform load *"p"*, distributed in a finite arc, forming a central angle 2α, as shown in Fig. 2 (a), adapted of Fairhurst (1964, p. 535).

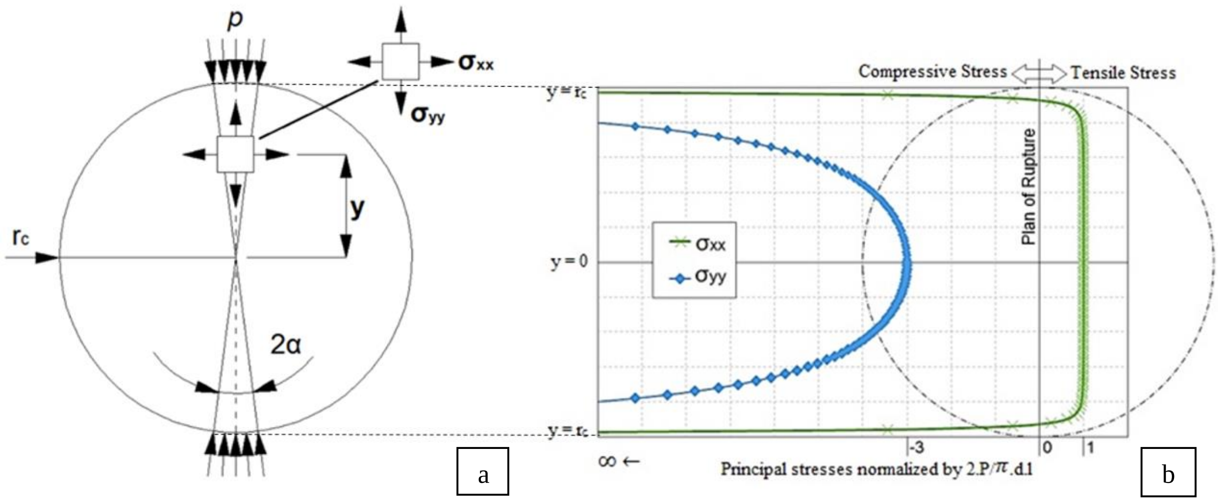

Figure 2. (a) Arc distributed load model; (b) Distributed arc load and resulting angle

From this different approach, the author described analytical expressions that represented the distribution of tensions found. Among them, Eq. 2 and Eq. 3, which express the value of the principal stress components along the plane formed by the compressed vertical axis.

$$\sigma_{xx(0,y)} = (2p/\pi)((1-(y^2/r_c^2))sen2\alpha/(1-2(y^2/r_c^2)cos2\alpha+(y^4/r_c^4)) - tan^{-1}((1+(y^2/r_c^2))/(1-(y^2/r_c^2))tan\alpha)) \tag{2}$$

$$\sigma_{yy(0,y)} = -(2p/\pi)((1-(y^2/r_c^2))sen2\alpha/(1-2(y^2/r_c^2)cos2\alpha+(y^4/r_c^4)) + tan^{-1}((1+(y^2/r_c^2))/(1-(y^2/r_c^2))tan\alpha)) \tag{3}$$

In equations, *"y"* refers to the distance from the center of the specimen and *"r_c"* refers to the radius of the disk. In Figure 2 (b), adapted from Fairhurst (1964, p. 536), shows an example of the distribution of principal stresses on the vertical axis (along the diameter of the cylinder) obtained through the formulation developed by Hondros (1959), at an angle α of 4.76°. The horizontal axis represents the normalized stresses, which vary from the compressive stress to the tensile strength. The green line refers to the normal stress to the vertical axis and the blue line to the stress parallel to the axis. Note that on the loading edge the normal stress corresponds to high values of compressive stress and in the central region the vertical plane is subjected to uniform tensile strength and it does not occur exactly in the center, as expected. While the stress component parallel to the vertical axis varies from one extremity to another with high values of compressive stress. In y = 0, center of the cylinder, the component reaches the lowest stress value, which in magnitude is three times higher than the maximum tensile strength.

In the case of the Brazilian Test, Eq. 2 is of special interest, especially when y = 0, because it is the center of the specimen, where theoretically the tensile strength must be maximum. When it is assumed that y = 0, whereas this equality is valid for small central angles (2α), the relation is deduced for Eq. 4.

$$\sigma_{xx} = (2p/\pi)(sen2\alpha-\alpha) \approx 2p\alpha/\pi \quad (4)$$

Considering that the uniform loading *"p"* used for disk analysis is equivalent to a point load P distributed along the length of the arc formed by the angle 2α and the height l of a cylinder, we obtain Eq. 5 below.

$$\sigma_{xx} = 2P/\pi dl \quad (5)$$

The analysis of the equations allowed the author to conclude that for small values of central angle 2α, formed by the arc of contact with the loading application, the stress calculated by Eq.1 is equivalent to the stress obtained by it, adequately describing the distribution representation of the stresses produced by the distributed load.

Similar to that of Hondros (1959), Tang (1994) made a study turning to the characterization of the parameter representative of the width in which distributed loading is applied. The results found by Tang (1994) showed that the effective width of the load application and the use of Eq. 1 do not represent the real tensile strength of the material. As with Hondros (1959), Tang (1994) proposed another formulation to describe the real tensile strength, taking into account the effective width of the load distribution, as his studies indicated it required. Then the Eq. 6 was formulated.

$$\sigma_{xx} = (2pt/\pi r_c)((1-(t/r_c)^2)^{3/2} \quad (6)$$

For this case, *"p"* is the uniform charge distributed along the effective width and *"t"* is half the effective contact width. Rocco et al. (1999) found the validity of Eq. 6, through numerical modeling of finite elements.

Riera et al. (2014) also investigated the Brazilian test under the influence of the application width of the arc loading, using numerical models of finite and discrete elements. The results applied in Eq. 1 had a change in the rupture loading value. The tensile strength increased according to the increase of the effective contact width, a non-coherent result, since it is a single material, the tension should remain close to the different contact widths.

Furthermore, Falcão and Soares (2002), when analyzing asphalt mixtures of soil-cement and concrete-cement through splitting test, varying the width of the strips of steel, realized that the origin of the crack, in the case of elastic materials, does not necessarily occur at the center of the specimen due to the combination of tensile and compressive stresses.

Li and Wong (2013) performed the numerical modeling of the test with the use of three-dimensional test specimens, consisting of a homogeneous material of elastic linear behavior, and analyzing the results concluded that both values of maximum tension and deformation were far apart of the center of the cylinder subjected to splitting test, at a distance of about 10% of the diameter of the loaded edge and the surface of the end of the specimen, so that the beginning of the crack may occur near the edge of the specimen when the deformation reaches the criterion of maximum deformation, rather than occurring in the center of the vertical axis.

Since the load distribution member, also known as strips, may exhibit different materials and shapes, the results to be obtained may vary according to the type of strips of steel adopted. Thus, it becomes questionable to state that Eq. (1) is applicable for all splitting test independent of the material and shape of the load distribution member.

Therefore, this study intends to verify the application of the diametrical compression test with concave-shaped strips of steel. Verifying the effective contact length and resulting center angle formed by the arc of contact with the load application, in order to compare with the information previously found and provide basis for this test. In addition, the study investigates the fracture mode for different widths of strips and if the test undergoes significant interference of other possible efforts, through the analysis of cracks propagation through the digital image correlation, which was shown through Liu's work (2010), an efficient technique to observe the distribution of stresses and deformations, useful for checking the origin and propagation of cracks.

2. MATERIALS AND PROCESSES

For the evaluation of the influence on the results of the use of strips of steel as distribution elements in splitting test, cylindrical concrete specimens 200 mm high and 100 mm in diameter were molded according to NBR 5738 (ABNT, 2015).

2.1 Splitting test

The procedure for the execution of the tests followed the current standard NBR 7222 (ABNT, 2011) and were carried out in the Static Hydraulic System of Universal Tests, model SATECTM 5590-HVL Series, brand of INSTRON ®, with maximum load cell of 1500 kN.

In relation to the size of the strips of steel used, in addition to the recommended in the standard (width b equal to 15 mm, with b/d ratio of 0.15), two more sizes were studied, being 10 mm and 20 mm wide with a b/d ratio of 0.10 and 0.20, respectively. As for the concavity of the strips of steel, the radius of curvature remained the same as the radius of curvature of the specimens used.

2.2 Digital image correlation

Before being subjected to the splitting test, the surfaces of the test specimens were prepared with a white background with PVA paint, and after drying, it was finished with the application of black aerosol paint, thus producing a stochastic pattern required for digital image correlation. In the Figure 3 (a) it is possible to visualize the configuration used to carry out the filming of the tensile test by splitting test. In the Fig. 3 (b) is the image the strips of steel used in the study.

For filming a high resolution digital camera (1920x1080 pixels) was used, with a capture rate of 30 frames per second. From the video were captured static images in jpeg format. The images were exported to the GOM Correlate software environment in order to obtain the two-dimensional analysis of the resulting displacements and deformations.

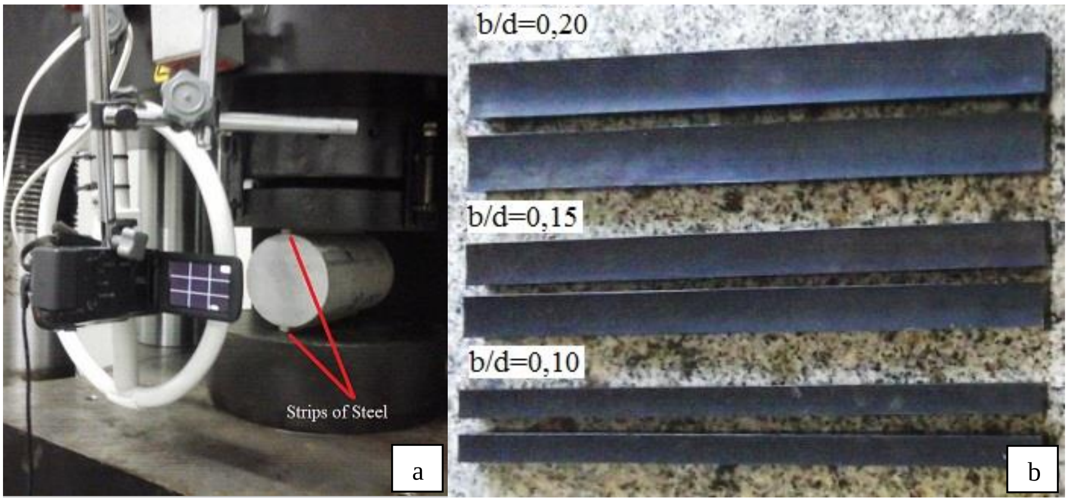

Figure 3. (a) Configuration of the Splitting Test and the camera used; (b) Strips of steel

3. RESULTS AND DISCUSSIONS

3.1 Results of the Splitting Test

In Figure 4 it is possible to verify the average values of the maximum tensile strength ($f_{ct, sp}$) determined from the breaking forces obtained by the splitting test, in four different specimens (S01, S02, S03 and S04) for each ratio b/d evaluated.

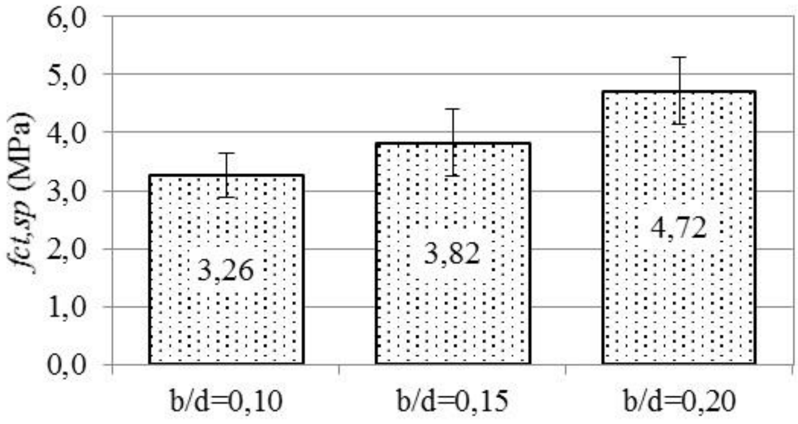

Figure 4. Results of tensile obtained in the Brazilian test

The values show a high variation in the calculated of the tensile strength, a fact that suggests a significant modification in the distribution of the tensions in the specimen. According to Fig. 5, the macroscopic observation of the specimens tested allows identification of cracks at the contact end between the strips of steel and concrete. This, failure is attributed to shear rather than to indirect tensile and this is the reason for the significant variation of the results.

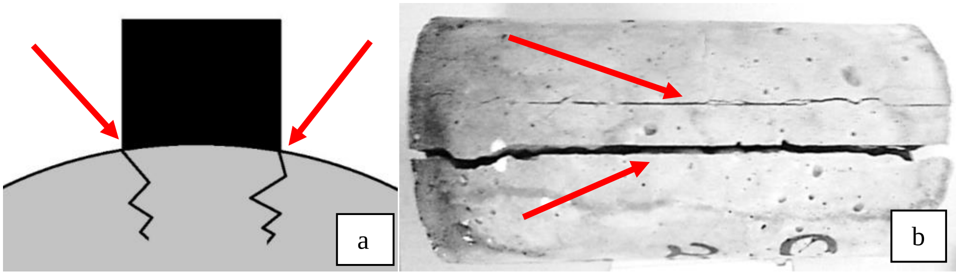

Figure 5. (a) Cracks in the edge; (b) Resulting premature rupture

From the results, the graph of Fig. 6 was constructed, which allows the comparison between the tensile strength curve obtained through NBR 6118 (ABNT, 2014) and the tensile strength values obtained through Splitting Test. With the curves it is possible to identify that the only tensile strength close to that recommended by NBR 6118 (ABNT, 2014) is found in the ratio b/d = 0.15. Assuming that Eq. 1 is valid, the results agree and justify the ratio recommended by NBR 7222 (ABNT, 2011).

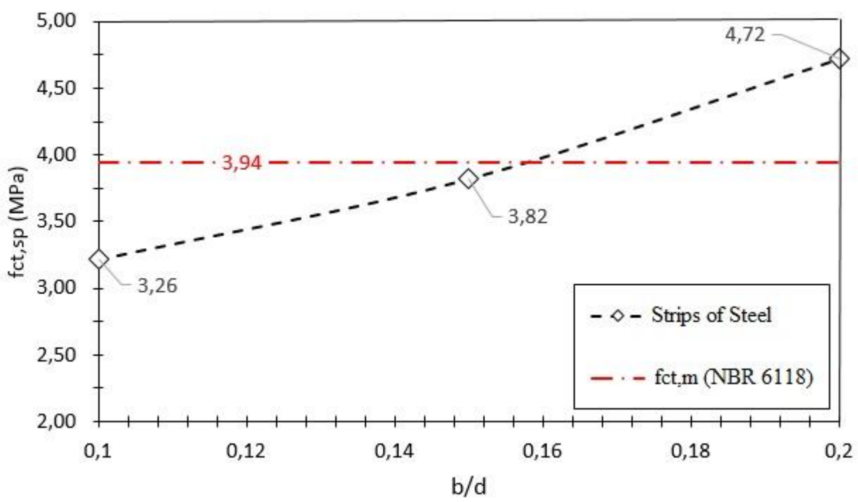

Figure 6. Results of the Splitting Test

For the concave strips of steel used in the work, the effective width of the load 2t corresponds practically to the value of the width considered. Being for b equal to 10 mm an effective width of 10.01 mm, with b equal to 15 mm has an effective width of 15.07 mm and for b equal to 20 mm the width found is 20.13 mm. The center angles for each width were: 5º44', 8°38'and 11°32' for the widths of 10 mm, 15 mm and 20 mm, respectively.

With the values of the angles it is possible to apply them in Eq. 2 and Eq. 6, formulations mentioned previously, which were developed by Hondros (1959) and Tang (1994), respectively, and obtain the maximum tensile strength values for the ratios used in this work, which are shown in Fig. 7. The red line indicates the value found according to NBR 6118 (ABNT, 2004). The results of the tensions obtained by the different formulations are very close. The greatest difference was found for the relation b/d = 0.20, being explained by the fact that this relation is the one with the greatest effective contact width, and angle although the variation was not significant, being 5.35% for Hondros (1959) and 5.94% for Tang (1994).

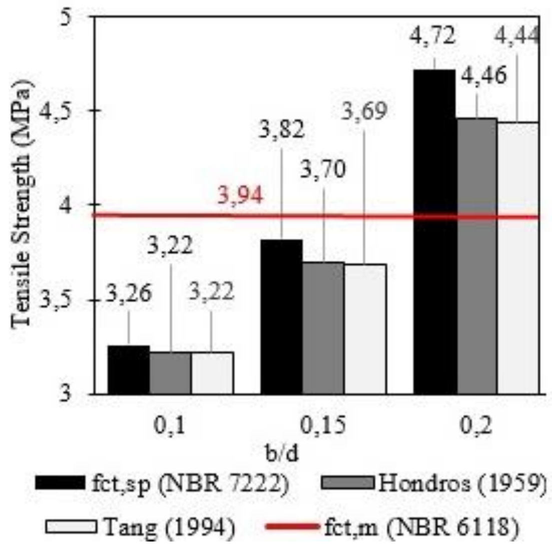

Figure 7. Results of the Splitting Test for different formulations

The behavior exhibited by the increase in the b/d ratio studied in this paper, in general, was a slight increase in the maximum load supported by the specimens, which incorrectly suggests an increase in the tensile strength of the evaluated material, with all formulations applied for the calculation of the stress showed the same.

3.2 Cracks, propagation and rupture

The image correlation analysis performed with the GOM Correlate software allowed following the propagation of cracks from the beginning of the test to the rupture of the specimens. It was possible to observe the place of beginning of these cracks and then to make the comparison of these results with the behavior predicted by the theory that gives base to the test.

In Figure 8 it is possible to visualize, for the ratio b/d = 0.10, the mapping of the deformations of S01 and S04, being those that presented the highest and lowest tensile strength, respectively. The analysis of the image allows to visualize the influence of the shear at the edge of the specimen, since the cracks begin near one end and propagate towards the opposite end, in which case it is impossible to assume that the rupture occurred by traction.

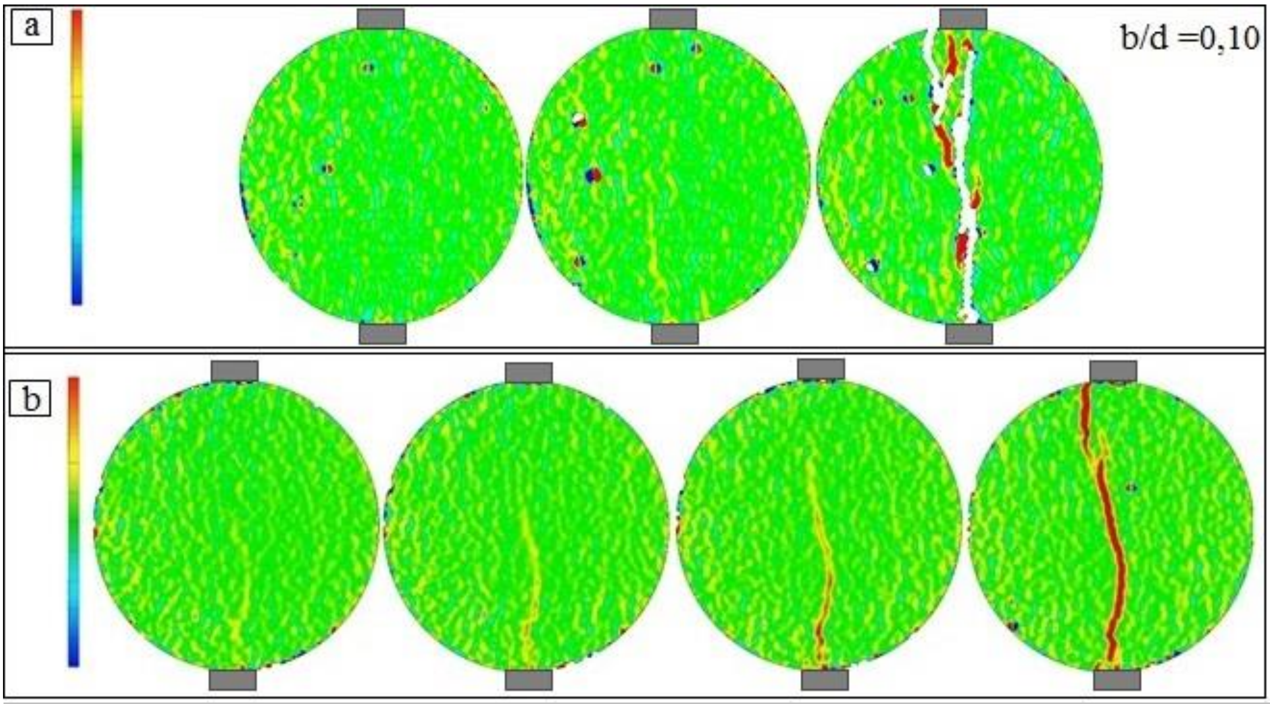

Figure 8. Mapping of the deformations: ratio b/d = 0.10. (a) S01; (b) S04

Figure 9 shows the S02 and S04 deformation mapping for the ratio b/d = 0.15, which presented the highest (S02) and the lowest (S04) tensile strength, among the specimens tested. It is possible to observe that the cracks are very different from each other, however, for both cases the origin of the cracks are influenced by shear forces, since they form at the edge of the specimen.

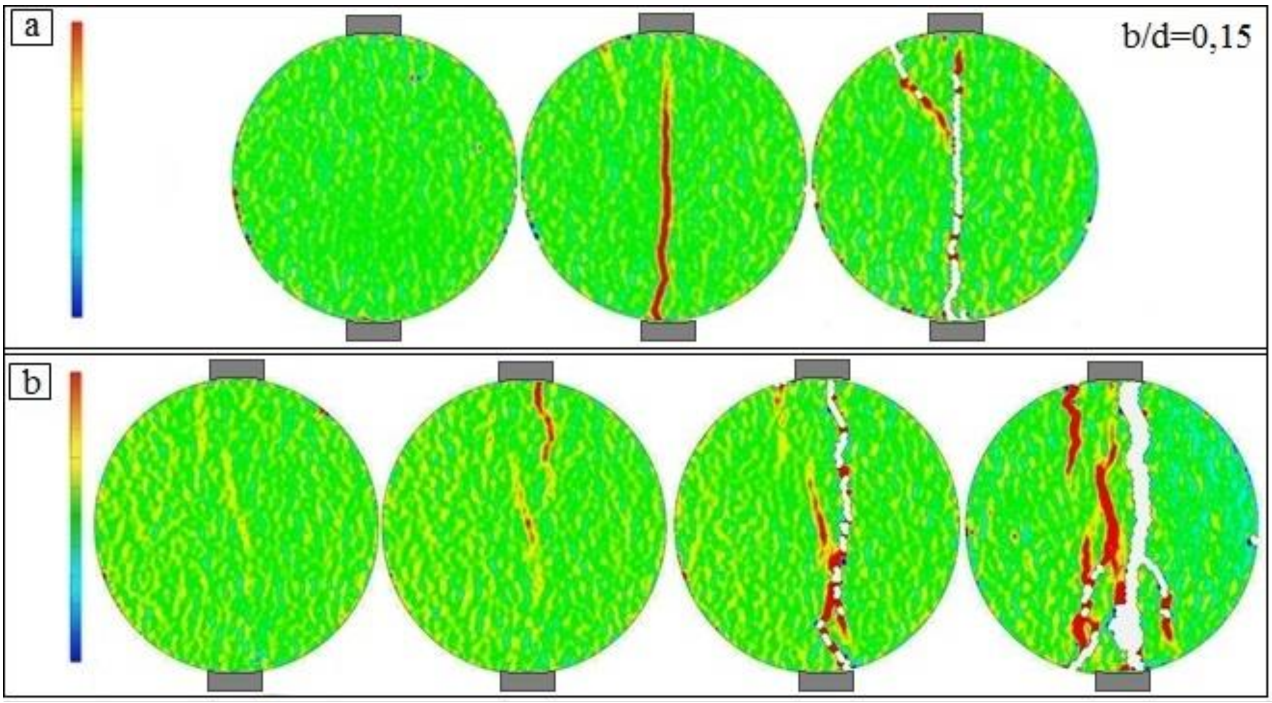

Figure 9. Mapping the deformations to the ratio b/d = 0.15. (a) S02; (b) S04

For the b/d = 0.20 ratio, the strain mapping shown in Fig. 10 is related to specimens S01 and S04, in which case the specimens presented the lowest and highest tensile strength, respectively. It is possible to observe that in the case of S01, the crack seems to propagate from the center to the ends of the specimen, while the S04, even with a well centered crack propagating towards the ends, also presents a crack close to the loading edge, probably due to the presence of shear forces.

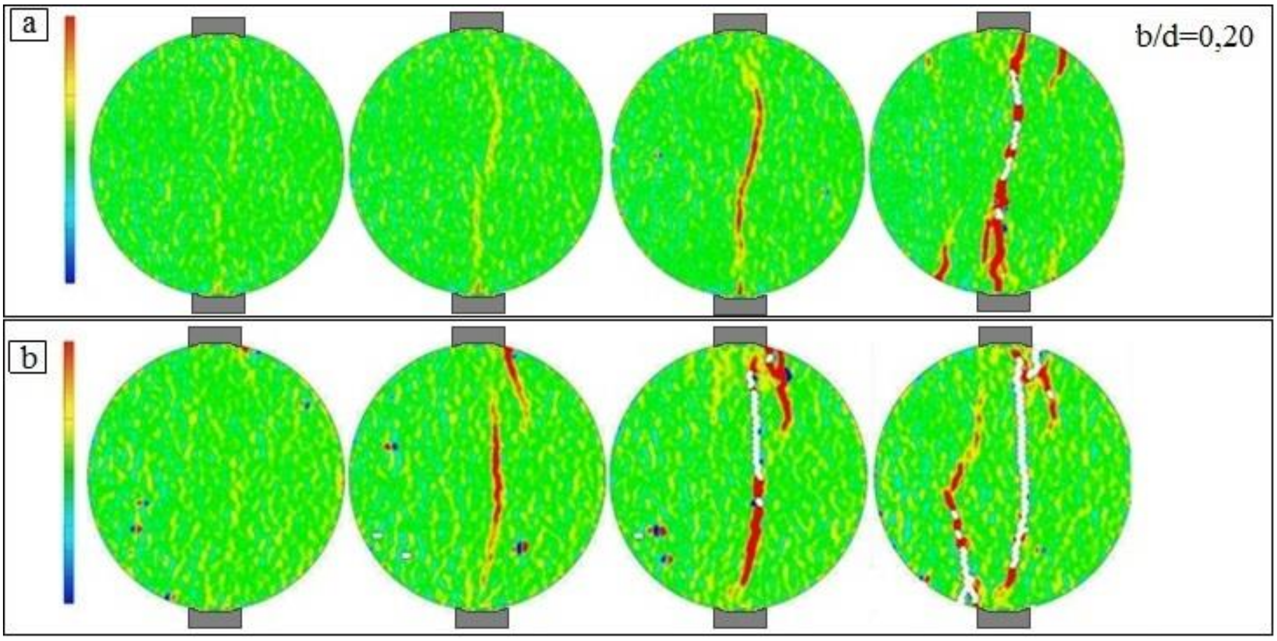

Figure 10. Mapping the deformations to the ratio b/d = 0.20. (a) S01; (b) S04

4. CONCLUSIONS

The variation of the width of the strips of steel affected directly in the final value of the tensile strength of the material, obtained through the splitting test, also the influence of shear stresses can be observed due to the cracks that appeared at the ends of the specimens tested. By means of the digital image correlation, it was possible to visualize that the place where the crack originates does not coincide with the exact center of the cylinders in numerous tests, being the appearance of more of a crack because of the rupture of the same in several cases, diverging with the theory that supports the method. Therefore, the formulations used for the calculation of the maximum tensile stress, which do not diverge significantly, can be considered only approximations of the real characteristic value of the tensile strength of the concrete.

Among the ratios used, it was verified that when b/d = 0.20, the influence of the shear is reduced, being for this work the most indicated for use in the test, diverging from that recommended by the norm (15 mm).

The technique of digital image correlation proved useful for identifying the propagation of cracks and shifts imperceptible to the naked eye, however due to the fragile behavior of the material not all the cracks that appear throughout the trial can be captured.

5. ACKNOWLEDGEMENTS

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