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STUDY THE STRUCTURAL PROBLEM IN THE BRAKE SYSTEM APPLYING A DIFFERENT PRESSURE FUNCTIONS

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Abstract: *During every braking process, the wear in the contacting surfaces of brake disc and brake pads will be occurred. Therefore, it's very important to investigate the effective parameters on the wear mechanism of the contacting surfaces, this is necessary because of the lifetime of the elements of brake is proportional directly with the rate of wear.*

In this research paper, the influence of the applied pressure function by which brake pads act on the brake disc is investigated using finite element method. Three different functions of pressure were applied which are: constant, linear and exponential. 3D model has been developed in order to analyze the penetration in the contacting surfaces of the elements of brake system. The results presented the variation of penetration with braking time. Furthermore, the results illustrated the distributions of the contact pressure in the friction pair (inner and outer sides) at any instant during the braking process.

Also, it was found that the values of stress at the end of the braking process (regardless of the contact area) were the same for all functions of the applied pressure. The differences in the stresses occurred when applied different function of pressure function during the braking process.

Keywords: *brake system, wear problem, finite element method, penetration effect, stress analysis.*

1. INTRODUCTION

In order to improve the understanding of the tribological characteristics of the braking system, it is necessary to compute the pressure distribution in the contacting surfaces (between the braking disc and braking pads). In order to observe what is happening in every moment during the braking process with minimum cost and time, therefore numerical analysis is the optimal way to find the solution of such complex problem.

The analysis of the thermo-elastic interaction that occur in the interface between the disc and pads is very complex, because of there are many parameters affect the barking process such as surface structure, material properties, degree of cooling, sliding speed etc. [1].

This differences that exist in elements of brake system, are making an obstacle for consistency and repeatability of results. The microscopic tests are necessary to investigate the contact geometry, surface composition and mechanical characteristics in contact zone.

The most effective factors on the wear ratio are the properties of the selected material for the braking disc, besides that it should take into the consideration the price of the materials [2].

The distribution of the contact pressure in the contacting surfaces is considered the significant factor that specify the magnitude and distribution thermal stresses that generated during the sliding process [3].

It is necessary that the pressure distribution in the contact area is uniform as much as possible, in order of braking system life prolonging.

Abu Bakar и Ouyang [4] has a goal to obtain the uniform pressure distribution on the contact surface, as well as the lowest possible values of the pressures in the contact. Four different models have been tested, and for each model are obtained different values for the contact pressure, as well as for the pressure distribution. The dynamic contact pressure distribution in the disc brake system remains impossible to measure through experimental methods. This makes numerical analysis using finite element method an indispensable alternative tool to predict the contact pressure during the braking process [5]. By developing technology and current commercial software packages that are capable of predicting more realistic results of contact pressure distributions.

In the research of Sarip et al. [6], it was presented that the friction material compressibility is important in pressure distribution analysis of brake, where the high value of Young's modulus has a negative effect on the distribution of contact pressure. In addition to these literatures, there are other studies which investigated the effect of the brake pad surface topography on the the contact pressure distribution [7]. Also, there is a little difference in the contact pressure for pads with and without damping shims. The test results also proved that the change in brake-line pressure results in different contact pressure distributions, when the brake-line pressure increases the maximum contact pressure increases too, and vice-versa. The worn pads will be produced more concentrated contact pressure than the new sets of pads, where highest contact pressure appeared at the outer border region of brake pads. Earlier research's Stojanovic et al. showed that highest values for the penetration occurred on the outer side of the disc, which is directly related with the pressure that occurred in the contact area [8].

The results of Belhocine and Bouchetara were showed that temperature field and stress field in the process of braking phase was fully coupled. The temperature, Von Mises stress, total deformations of the disc and contact pressures of the pads are higher than disc, because the thermal stresses are added to mechanical stress which caused the crack propagation and fracture of the bowl and wears in the disc and pads [9].

The aim of the research paper is to investigate deeply the influence of the function of applied pressure on the contact pressure distribution during the braking process. Where, it was applied different functions of the applied pressure. The results presented the distribution of the penetration and stresses at any time of braking. The thermal stresses are not disused in this research paper.

2. STATE OF THE PROBLEM

In this section will be introduced the initial and boundary conditions. The values of applied pressure, angular velocity and friction coefficient are obtained experimentally [10]. The conditions of test of a vehicle were in ambient temperature of 22 $^{\circ}$C. The vehicle is moving at a speed of 80 km/h then should be barked to stop. This means that the initial angular velocity is equal to 71.12 rad/s. Figure 1 shows the model of the brake system with all parts. The applied pressure affects both pads with the same intensity.

Friction in most mechanical element is undesirable phenomenon; however in the brake system is considered useful to achieve the task of brake, therefore without friction the vehicle could not be stopped. The contact pair, between disc and the brake pads is realized friction. The value of the coefficient of friction is 0.288.

Figure 1. Disc brake components [11]

In this paper, three different analyses have been performed, when the pressure for each analysis has been applied based on different function as shown in Figure 2.

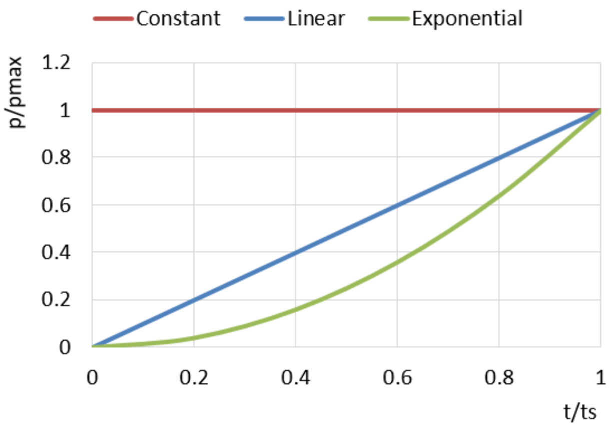


Figure 2. The functions of applied pressures

The maximum value of the pressure is the equal for all three cases. Equation 1 represents the function of the linear applied pressure, while Equation 2 represents the function of the exponential applied pressure. Where, the third case, the applied pressure is constant during the braking process. Values of the speed and the friction coefficient are the same for all three cases, as well and other boundaries. Also, the characteristics of materials for the braking disc and pads are the same for all cases; Table 1 lists the properties of materials of the brake system.

$$p = t \cdot 0.254 + 3 \cdot 10^{-16} \quad (1)$$

$$p = t^2 \cdot 0.0508 + t \cdot 4 \cdot 10^{-16} + 2 \cdot 10^{-15} \quad (2)$$

The mesh type which used to build the finite element model is hexahedra. In the contact of pads and the disc the mesh size is very fine, and will be coarser when go away from the contact area. Number of elements and nodes are listed in Table 3.

Table 1. Material properties of the brake disc and brake pads [10]

	Density (kgm^{-3})	Young's modulus (GPa)	Poison ratio (-)
Disc	7100	118	0.32
Pads	2300	20	0.3

Using tetrahedral mesh it does not take much time for mesh defining, while its needs more time when used the hexahedra mesh type. It's necessary to select the suitable element size, when used the hexahedra mesh type. The advantage for hexahedra is to obtain accurate results of stress, without using very fine mesh [12].

As the nonlinearity present in frictional contact, an extra attention is necessary to be paid about the contact algorithms and their input parameters. For surface-to-surface contact elements, the program offers several different contact algorithms [13]:

- Penalty method uses a contact "spring" to establish a relationship between the two contact surfaces. The spring stiffness is called the contact stiffness;

$$F_n = k_n x_p \tag{3}$$

where F_n is contact force, k_n is contact stiffness and x_p is the distance between two existing nodes or separate contact bodies (penetration or gap), as shown in Figure 3.

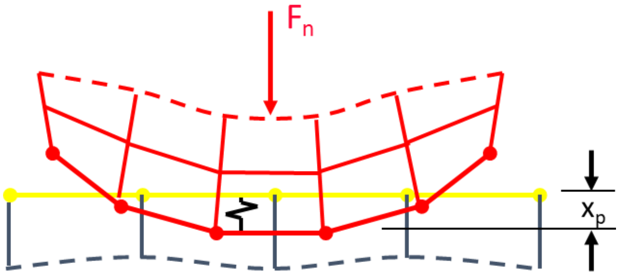


Figure 3. Contact between two parts [14]

- Augmented Lagrangian method is an iterative series of penalty methods. The contact tractions (pressure and frictional stresses) are augmented during equilibrium iterations so that the final penetration is smaller than the allowable tolerance. Compared to the penalty method, the augmented Lagrangian method usually leads to better conditioning and is less sensitive to the magnitude of the contact stiffness;

$$F_n = k_n x_p + \lambda \tag{4}$$

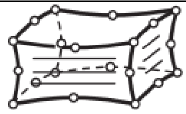
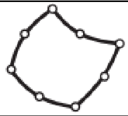
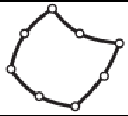
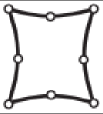
where is λ Lagrange multiplier component.

- Lagrange multiplier on contact normal and penalty on tangent - enforces zero penetration when contact is closed and "zero slip" when sticking contact occurs. This method adds contact traction to the model as additional degrees of freedom and requires additional iterations to stabilize contact condition It often increases the computational cost compared to the augmented Lagrangian method;
- Pure Lagrange multiplier on contact normal and tangent - enforces zero penetration when contact is closed and “zero slip” when sticking contact occurs. This algorithm does not require contact stiffness. Instead it requires chattering control parameters. This method adds contact traction to the model as additional degrees of freedom and requires additional iterations to the stabilized contact conditions. It often increases the computational cost compared to the augmented Lagrangian method, and
- Internal multipoint constraint (MPC) is used in conjunction with bonded contact and no separation contact to model several types of contact assemblies and kinematic constraints.

In defining the coefficient of friction, it was used Augmented Lagrange algorithm. Figure 4 shows the finite element model of the brake system using the element hexahedra. It was selected a fine mesh in the contact area between the brake disc and brake pads where supposed the highest stresses will be occurred, the mesh size is very fine at the contacting surfaces and then will be more coarse when moving away from the contact area through the thickness of disc surface.

The advantage to select the hexahedra is to obtain the accurate results (stresses) with not very fine mesh [15]. The elements are used for contact elastic model in this analysis are listed in Table 2. The primary mesh is hexahedra, but due to the complexity of the model, the tetrahedral mesh has appeared in some places, in doing so, the accuracy of the results will be not reduced. For the contact surfaces, the mesh type is hexahedra. The DOFs from Table 2 that are used in this analysis, these elements can have other DOFs but they aren’t used in this analysis. The contact surfaces are surfaces of the brake pads and the target surfaces are surfaces of the brake disc. The finite element model which used to achieve the numerical analyses is the same for all three cases, as listed in Table 3.

Table 2. The type of elements and description [16]

Title	Description	Degrees of freedom	Illustration
SOLID186	3-D 20-Node Structural Solid 20 nodes 3-D space	Displacement in *x*, *y* and *z* axis	
SOLID187	3-D 10-Node Tetrahedral Structural Solid 10 nodes 3-D space	Displacement in *x*, *y* and *z* axis	
CONTA174	3-D 8-Node Surface-to-Surface Contact 8 nodes 3-D space	Displacement in *x*, *y* and *z* axis	
TARGE170	Contact 3-D Target Segment 8 nodes 3-D space	Displacement in *x*, *y* and *z* axis	
SURF154	3-D Structural Surface Effect 4 to 8 nodes 3-D space	Displacement in *x*, *y* and *z* axis	
COBIN14	Combination Spring-Damper 2 nodes 3-D space	Displacement and rotation in *x*, *y* and *z* axis	

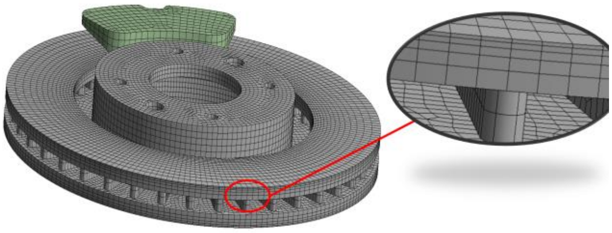


Figure 4. The finite element model of the brake system

Table 3. Number of finite elements and number of nodes

		Number of nodes	Number of elements
Disc		206956	59781
Pad			
Initial case	Inside	2640	434
	Outside	2673	440

3. RESULTS AND DISCUSIONS

3.1 Linear Applied pressure

This section presents the results of the contact pressure when applied a linear function of the pressure. Figure 5 illustrates the variation of the highest of contact pressure on the inner and outer sides of the pads. It can be noticed that the contact pressure appeared only on the inner side at the initial period, later on the contact pressure starts rising after 0.75 s of the braking process. It can be seen that the values of the contact pressure on the inner side grown approximated linearly with time until reach the maximum value at the end of the braking process. While, the contact pressure on the outer side increased directly to the peak value at t = 1.3 s, and after that the contact pressure decreased to the final value at the end of the braking process. It can be observed that the values of the contact pressure on the outer side are higher than those occurred on the inner side the reason of these is the umbrella effect. It can be seen from the results that the values of contact pressure at the outer location are higher than the applied pressure except at the beginning period. Also, the values of contact pressure at the inner location are higher than the applied pressure during all the period of braking process, where the contact pressure at the inner location is approximately double of the applied pressure at end of the braking process, while the contact pressure at the outer location is approximately 3.5 times of the applied pressure. Efficiency of such braking system is very good, because vehicle with such braking system will have a small stopping distance. From Figure 5 it can be seen that on the outer side of the disc, impact loads spear, which further can cause system failure.

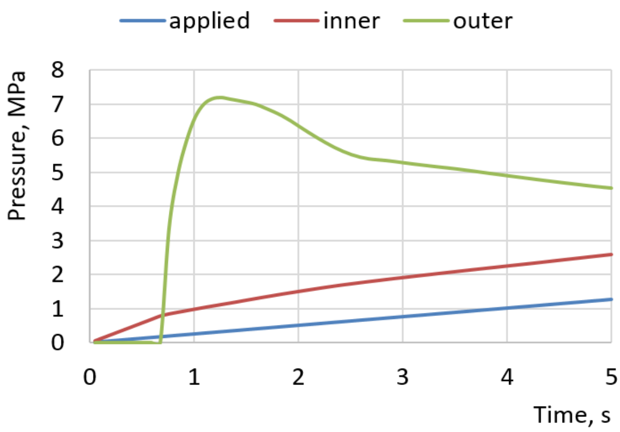


Figure 5. The variation the contact pressure at different locations when applied linear pressure

Figures 6 and 7 show the distribution of penetration on the inner and outer sides of the friction pair during the braking period. It was found that the highest values of the penetration occurred on the outer side, because, the penetration is proportional directly to contact pressure. The maximum values of the penetration on the inner side occurred at the end of braking period (t=5 s). However, penetration on the inner side of the friction pair, increased approximately linear with time. While on the outer side, the maximum value of penetration occurred after 1.3 s, and then decreased to the final value at the end of period. It can be seen, that the penetration zone in the inner side was dominant, while on the outer side the penetration area was limited. The reason behind the existing difference in the contact pressure between the inner and outer sides is this is the consequence of the umbrella effect.

3.2 Constant Pressure

When applied a constant pressure on the braking disc, the contact pressure on the contact surfaces will not change with time as shown in Figure 8. The results showed that the contact pressure on the outer side is higher than those occurred in the inner side. In each case, the values of obtained contact pressures

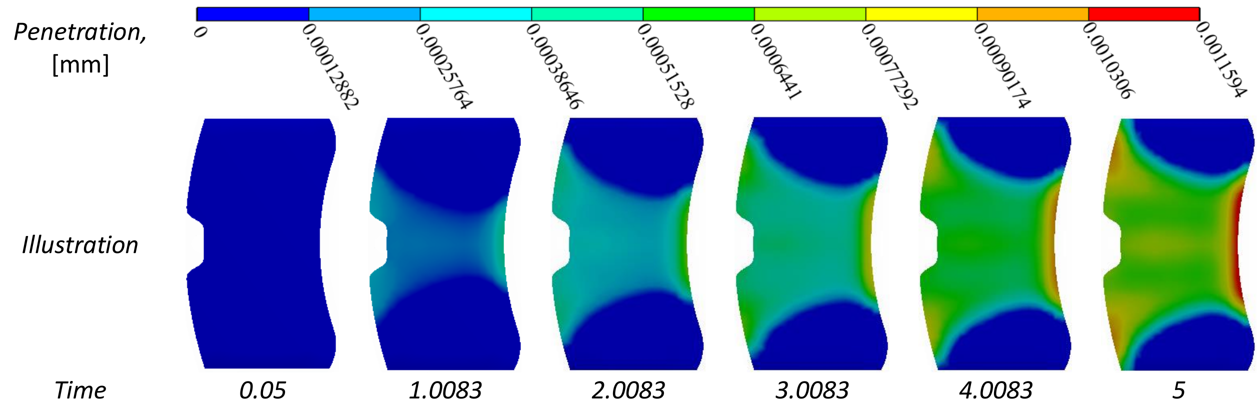


Figure 6. Penetration over the time on the inner side of the friction pair

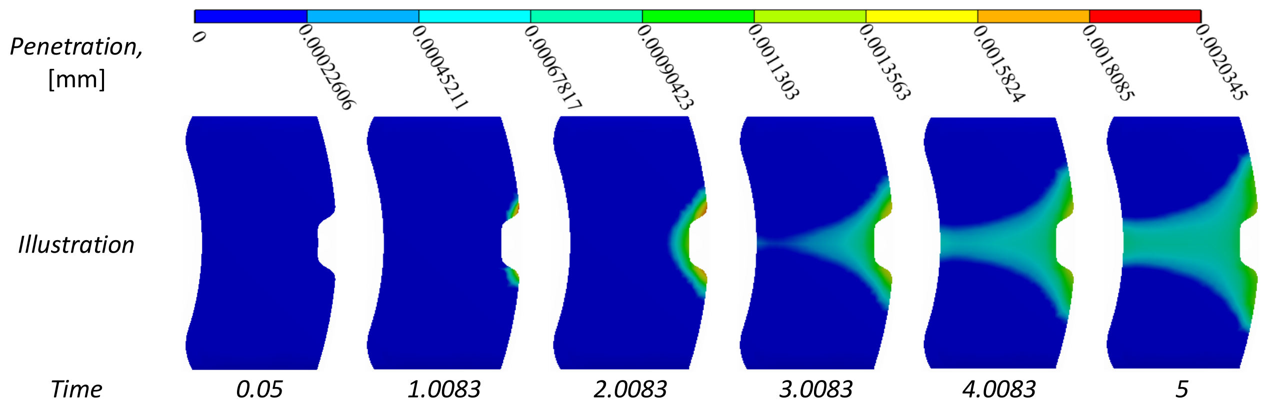


Figure 7. Penetration over the time on the outer side of the friction pair

are higher than applied pressure, and which it's directly depends on the coefficient of friction and size of contact surfaces. It was found at any instant during the braking process that the contact pressure at the inner location is approximately double of the applied pressure, while the contact pressure at the outer location is approximately 3.2 times of the applied pressure.

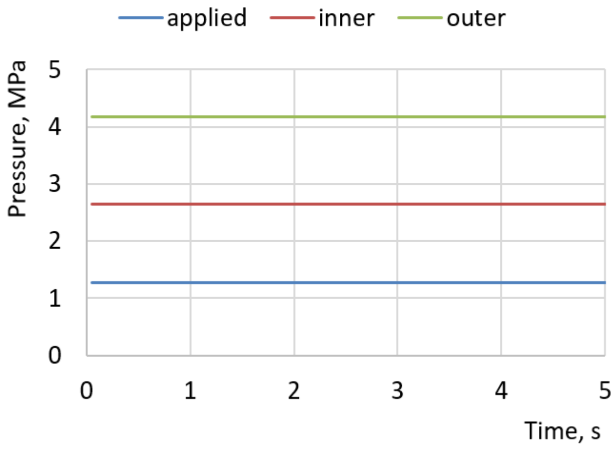


Figure 8. Obtained pressures for constant pressure

It was observed that the values of penetration on the outer side are higher those in the inner side as shown in Figures 9 and 10. However, it is interested results which obtained, where the maximum value of the penetration is approximately the same on the both sides but the distribution is different. The penetration focused in the outer side on area that is smaller than those in the inner side.

3.3 Exponential pressure

In this case the pressure was applied as exponential function during the braking time. Figure 11 exhibits the contact pressures when applied pressure as exponential function. The maximum contact pressure appeared in outer side and the minimum one on the inner side. It can be seen the big different in the behaviour of contact pressure between the inner and outer sides. Where at the inner side, the contact stresses increases gradually from low value at the beginning of the braking period to the high value at the end of period. While, at the outer side, the contact stresses started with huge increasing after 1.8 s of the beginning of the braking period to the high value (maximum) and then decreased to the low value at the end of period. It's clear that the behaviours of the contact pressure relative to the applied pressure are similar to the case when applied a linear function of pressure.

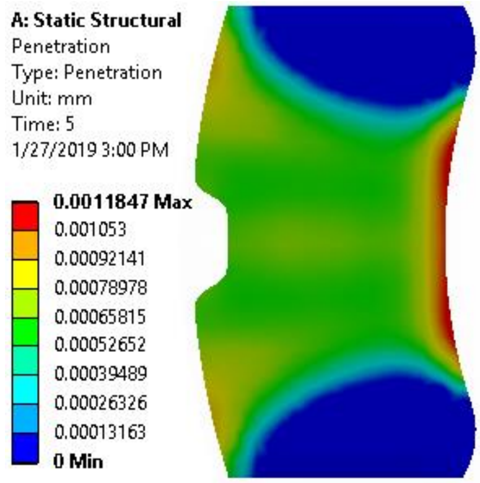


Figure 9. Penetration on the inner contact of the friction pair

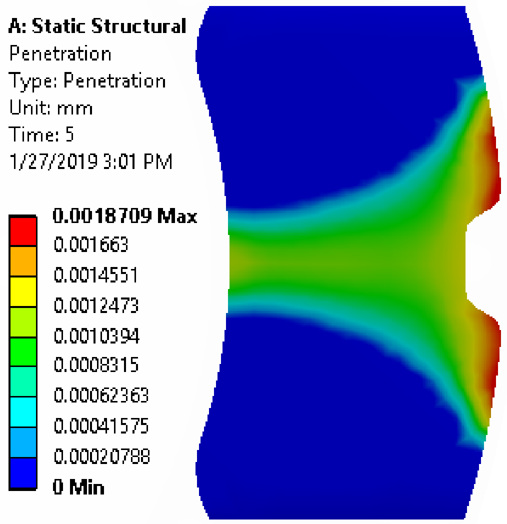


Figure 10. Penetration on the outer contact of the friction pair

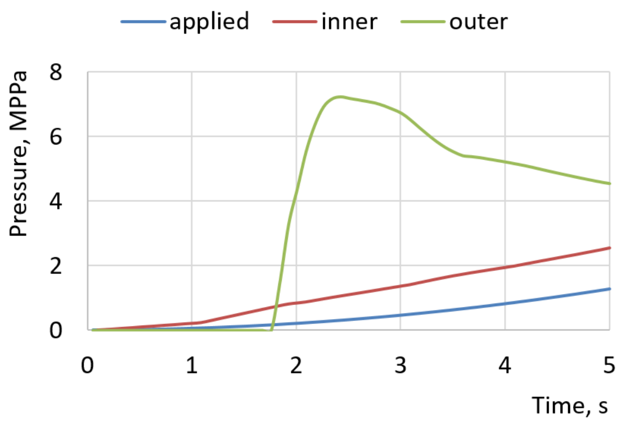


Figure 11. The contact pressures when applied pressure as exponential function

In the first two seconds, the penetration doesn't appeared on the outer contact, but after the time passed (3 s) the maximum value of penetration appeared as shown in Figures 12 and 13. After that the penetration decreased to the finial value at the end of the braking process. It can be noticed that the maximum value in mentioned cases occurred on the outer contact. The values of the penetration and contact pressure that occurred on the inner contact of the friction pair were very small. Figure 14 illustrates the distribution of penetration on the brake pads acting on the disc at the beginning and at t = 1.0083 s.

3.4 Stresses Analysis

Also, in this numerical analysis, it was computed the stresses that generated during the sliding period. Figure 15 shows the variation of Stresses during the braking process at different locations of brake system. It can be seen during the complete period of braking at the inner side (disc and pad), that the maximum stresses generated when applied a constant pressure. While at the outer side, the maximum stresses generated when applied the linear and exponential function for pressure.

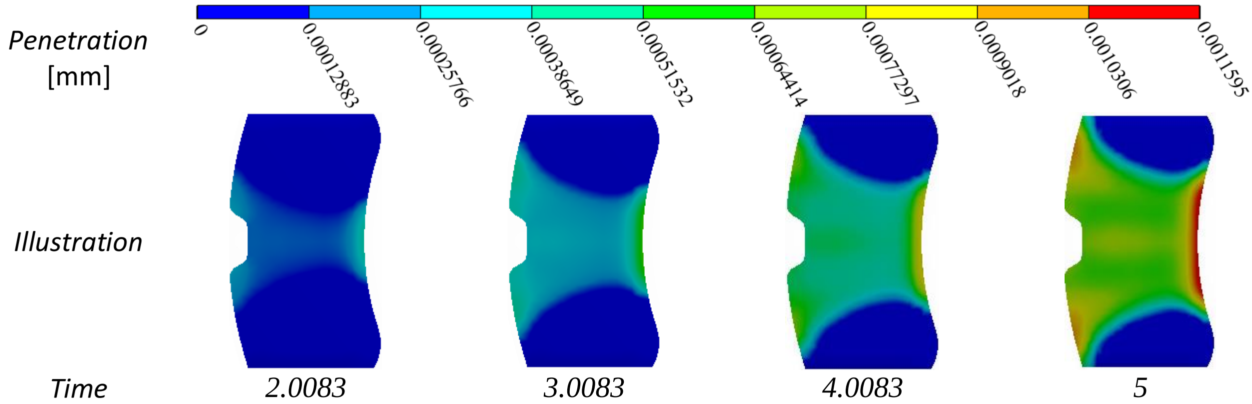


Figure 12. Penetration on the inner contact of friction pair during time

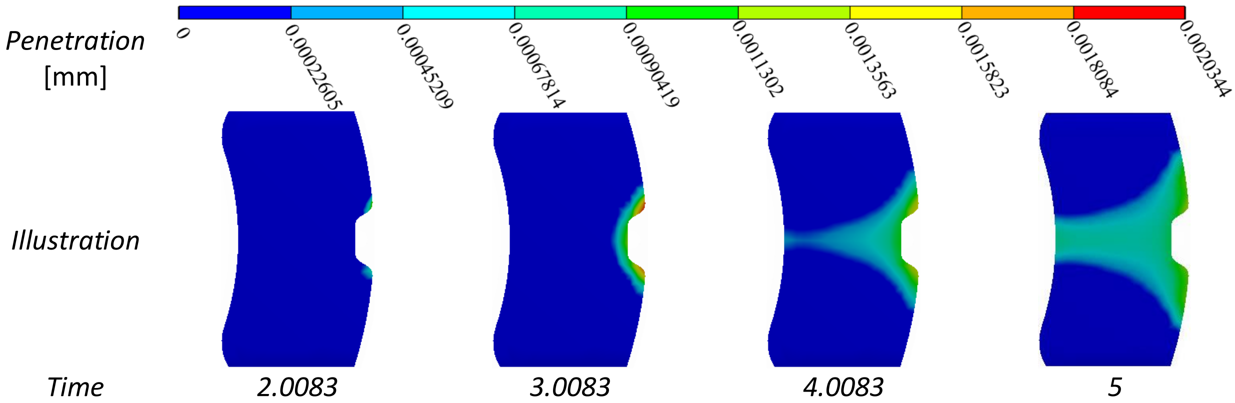


Figure 13. Penetration on the outer contact of friction pair during time

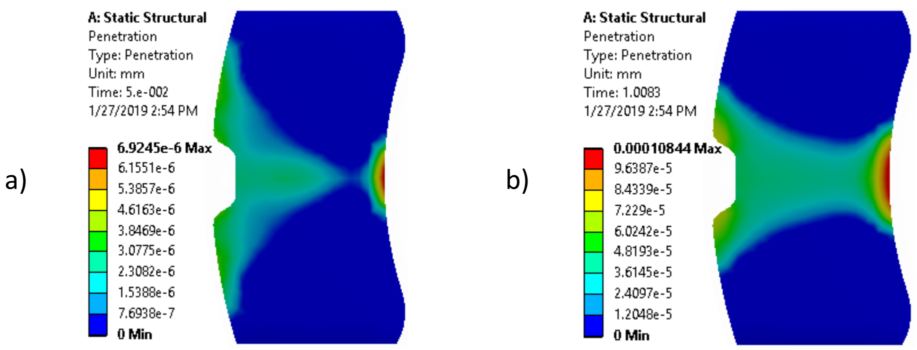


Figure 14. Penetration on a) the inner and b) outer contact pair at the beginning of applied pressure

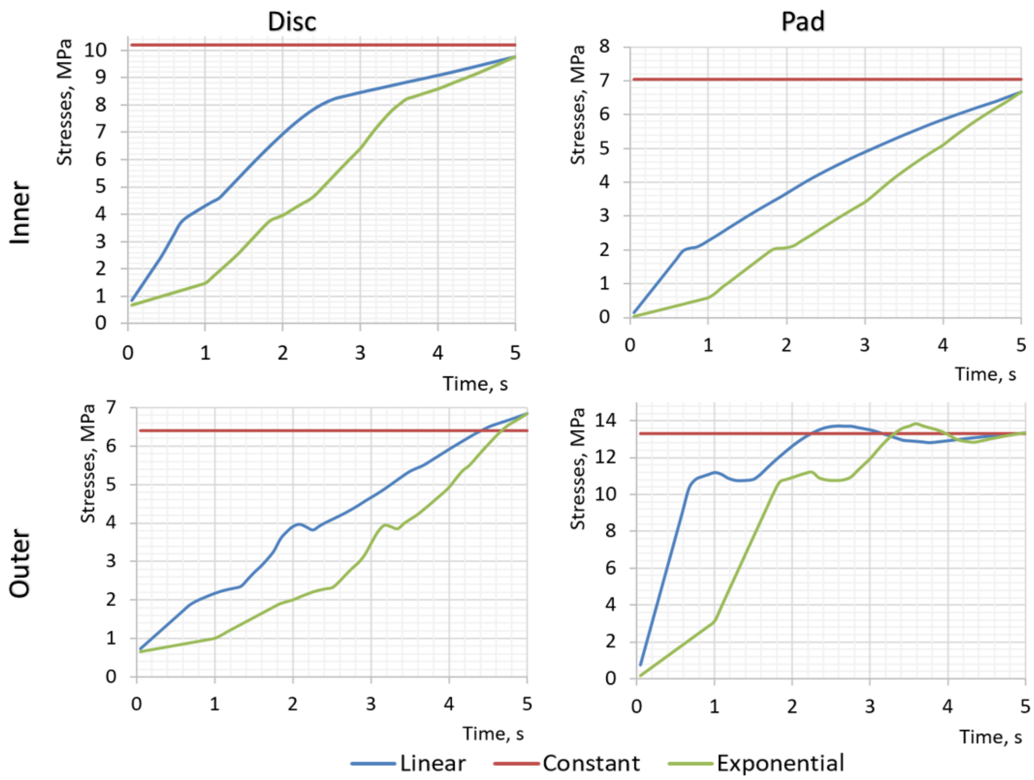


Figure 15. Variation of von-Misses Stresses during the braking process at different locations of brake system

In general when we compare the two cases of the applied pressure (linear and exponential), it can be noticed that the values of stresses when applied the linear function of pressure are higher than those generated when applied the exponential function.

By observing Figure 15, it can be noticed, that the outer pad was exposed to fluctuating stresses over the time, when applied the pressure as linear or exponential function, and this is lead to appear the maximum penetration.

In the inner side, it can be seen that the stresses when applied the linear and exponential functions are lower than those when applied the constant pressure. While at the outer side, the stresses when applied the linear and exponential functions exceeded the stresses of constant pressure function at some period during the braking process.

Besides all of that, the highest values of Von-misses stresses occurred at the outer side of the braking disc, which is the consequence of the umbrella effect [17].

During the process of the brake design, it should be paid more attention about the level of stresses that expected, where it must be lower than the allowable stresses of the selected materials.

4. CONCLUSIONS AND REMARKS

In this research paper, it was developed a numerical approach to investigate the effect of the applied pressure function on the magnitude and distribution of the contact pressure and penetration of the contacting surface of the brake system. It was applied three different functions which are contact, linear increasing with time and exponential.

It was found that the highest values of contact pressures and penetration appeared on the outer contact side when applied the pressure as exponential and linear functions. While, the lowest values of penetration appeared on the contact surfaces when applied a constant pressure.

The highest pressure values in the contact surfaces appeared in case of linear function almost at the beginning within the period from 0.75 to 1.3 s. While, for the exponential function occurred within the period from 1.8 to 2.4 s. In the third case study, when applied a constant pressure, it was found that the contact pressures were constant at any instant during the braking process.

Also, it was found that the maximum stresses appeared in the outer pad because of the pad is from one side pressed by pistons, and from the outer by the disc, which is consequence of the umbrella effect. While, in the inner side the maximum stresses occurred in the disc. The reason of this result is constructive nature of the disc brake.

The values of contact pressure between pads and the disc of any case are much higher than those of applied pressure of any functions. This is very good point, because the vehicle that has such braking system and that is manufactured from materials such as in this paper, will have very short stopping time (shortest stopping distance). As result of this, the safety of traffic participants will not be disturbed.

This research is preliminary research that will be followed by further research that will study deeply all the effective factors on the behaviour and performance of the brake system in order to find the optimum design.

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