CONCERNS REGARDING TEMPERATURE DISTRIBUTION OBTAINED BY EXPERIMENTS AND FINITE ELEMENT ANALYSES FOR TWO TYPES OF BRAKE DISCS

Ştefan VOLOACĂ[1], Gheorghe FRĂȚILĂ[2]

Lucrarea analizează cauzele solicitărilor termice ce apar în două tipuri de discuri de frână. A fost efectuat un studiu de caz pentru o frânare intensivă de la 100 km/h, în urma căruia a fost studiată, comparată şi explicată repartiția de temperaturi obținută experimental şi cu ajutorul analizei cu element finit. Studiul a mai cuprins analiza repartiției temperaturilor la interiorul discurilor studiate cu ajutorul analizei cu elemente finite, subliniindu-se câțiva factori ce influențează solicitările termice. S-a constatat neuniformitatea repartiției radiație şi conducției termice pe suprafața şi în masa discurilor, datorată caracteristicilor materialelor, de prelucrare cât şi de severitatea regimului de frânare.

The paper analyses causes of thermal stress which appears in two different brake discs, with different geometries. A case study was made for an intensive braking from 100 km/h. It was possible to study, to compare and to explain the temperature distribution obtained by experiments and finite element analyses (FEA). Further the study encompasses temperature distribution inside the studied brake discs obtained by finite element analyses, highlighting some thermal stress influence factors. It was observed the non-uniform repartition of radiation and conduction over the surfaces and inside the brake discs, due to characteristics of material, their processing and the braking severity.

Keywords: brake disc, thermal stress, finite element analyse, FEA, experiment, thermography.

1. Introduction

Based on the first law of Thermodynamics, during braking, kinetic energy is converted to thermal energy. Due to friction between the main components of disc brake (pads and disc) the conversion of energy takes place.

Initially the generated thermal energy is transferred by conduction to the components in contact and next by convection and radiation to environment (Fig. 1) as explained in [1] [2], [3].

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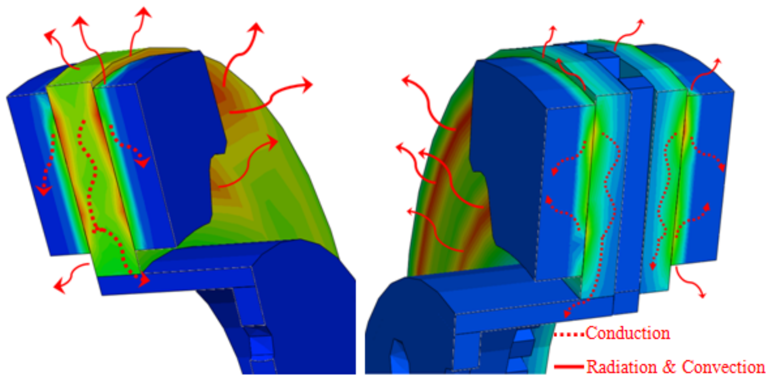


Fig. 1. Heat dissipation inside and outside the discs due to conduction, convection and radiation

An optimal disc brake must assure a short time and distance to stop in good and safety conditions in case of an intensive braking.

The brake disc and the pads are exposed to high thermal stresses due to high quantity of energy transformed from mechanical to thermal.

Thermal stress σ is defined by the thermal strain generated by temperature variation ΔT inside an object and due to exterior condition of having no possibility to contract or expand [4]. Those stresses can be written as [1]:

$$\sigma = -\frac{E}{1-\nu} \cdot \alpha \cdot \Delta T \qquad (1)$$

where α - brake disc thermal expansion coefficient, $\Delta T = T - T_a$, T – local disc temperature (real), T_a – environment temperature, E – Young's modulus, ν – Poisson coefficient. The values of α depends on temperature, but in most cases is considered constant. From relation (1), it the dependence of thermal stress with temperature and α coefficient can be observed.

2. The work methodology

For temperature distribution, which influences thermal stress of brake disc, a case study was made for an intensive braking from 100 km/h to 0 km/h. It was made a finite element analyses and some experiments outside the laboratory, for two types of brake discs.

The finite element analyses were made for a complex geometry of discs and pads, which were the same as the real one from Dacia Logan. The aim of these analyses was to reproduce the exact complex shapes and sizes of discs and a pads, thing rarely met in specialty literature [5].

Brake pads have a friction material thickness of 12 mm and a contact width, with the brake disc friction surface, of 41 mm.

Friction surfaces of disc have an outer radius of 234 mm and inner radius of 152 mm. For the simple disc, the thickness is 11 mm. For the vented one the thickness of inner wall differs to the outer one, first is 7 mm and the second 8 mm. The vanes between the walls have a thickness of 6 mm, and are radially positioned. Based on these dimensions, the geometrical elements (discs and pads) were meshed. After meshing, the assembly of disc and pads was completed by specifying the position constrains. The whole assembly was finally transformed to an oprah-mesh element (Fig. 2).

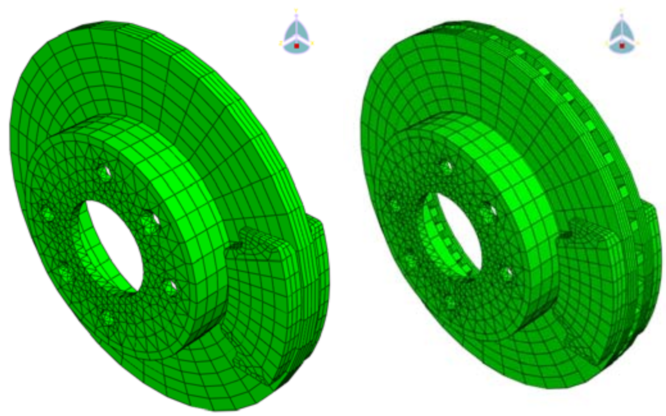


Fig. 2. Oprah mesh element of disc-pads modelled in ABAQUS

Table 1 presents the number and type of elements and nodes from oprah-mesh elements.

Table 1

Meshing characteristics of oprah-mesh elements

	Simple disc	Vented disc
Number of nodes	3502	5179
Number of elements	3929	4468
Number of hexahedral elements C3D8RT	1680	2513
Number of tetrahedral elements C3D4	2249	1955

Brake pads are made of a mixture of elements glued by a binding component and the discs were made of cast iron. Thermal and mechanical properties were taken from [6]. Some parameters vary with temperature (Young's modulus, friction coefficient, expansion coefficient).

After declaring these properties the friction surfaces were declared. The simulation was divided in two steps. First was for the pressure of pads over the disc and thus the contact between them. This step propagates to the second one in which the angular speed of brake disc starts to decrease to zero. The angular speed of 89 rad/s is equivalent to 100 km/h of motor vehicle speed. Total time of this step was 4 seconds as the time of experimental braking tests.

Initially, the pad has no degree of freedom. Over the exterior sides of the pad, a pressure of 3.6 MPa was applied. The pressure was computed for the total time of braking, and the dimensions of brake components [7]. In the centre of the disc a reference point to the disc, was declared for which the angular speed of brake disc was introduced. The second step is declared as a "smooth step", as to reduce the centrifugal forces effect over the model, at the beginning and the end of this step.

With this input data, the analyses started and were run in ABAQUS/Explicit.

Experimental tests were carried out, outside the laboratory, on two Dacia Logan motor vehicles to validate the finite element model (Fig. 3). They were equipped with thermal cameras to record temperature variation and distribution over brake disc – simple and vented brake disc.

Fig. 3. Position of thermal camera on test motor vehicles
Left – unvented brake disc; right – vented brake disc

The used thermal camera took gray scale images of heat radiated from discs. These images were processed with specialized software to make possible the estimation of temperature repartition and forward to analyse thermal stress of brake disc.

To process the data, it was necessary to know the total time of braking, initial temperatures of discs and environment and the weather conditions (humidity, wind speed).

The tests were made at short time period between them on the same testing field making the state of the road having no influence over the results.

3. Results and interpretation

Fig. 4 presents a comparison between testing and finite element analyses which results at the end of the intensive braking for two types of brake discs (unvented and vented brake discs). In this figure as a result of testing are presented pseudocoloured images, of brake discs taken by the thermal camera and images obtained with a finite element analysis, in ABAQUS.

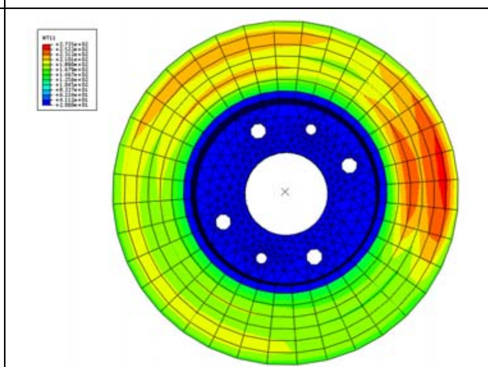
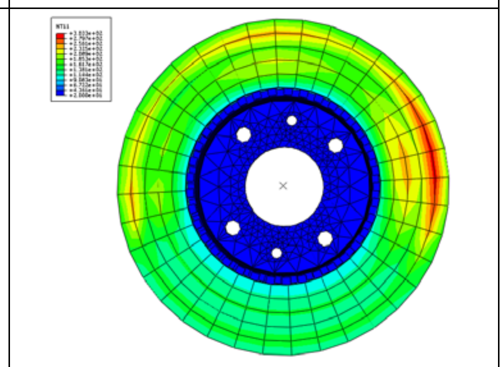
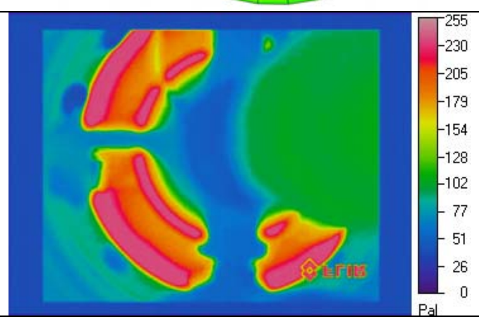
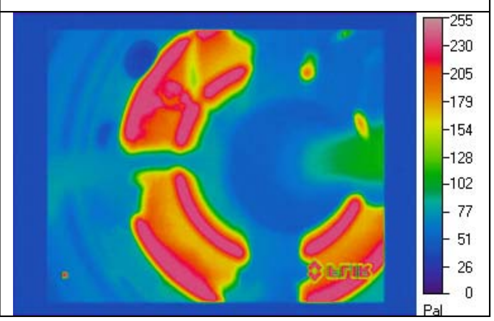
	Unvented brake disc	Vented brake disc
theoretical images		
thermal images		

Fig. 4. Comparison between theoretical images (obtained by FEA) and thermal images (results of tests) at the end of intensive braking

The repartitions of temperature are almost identical for both types of discs in real images and modelled ones. This fact is argued by:

- Both motor vehicles have almost the same weight;
- The material of disc and the one of the pads are the same in both cases;
- Pads geometry is approximately identically.

Figs. 5 and 6 present comparison regarding radial temperature distribution over friction surfaces for two interest areas. First area *1* is identical positioned in images for both modelled and tested one. Based on this repartition the accuracy of experiments and simulation is established. The second area *2* analyses the area under the pads from the image obtained by finite element analyses. Those analyses are made to highlight one of the thermal stress causes.

The histograms of temperature repartition were made by processing the images with ImageJ software. Thermal images were analysed as they were taken (gray level scale). To have fast results interpretation of thermograms the radiance was taken as a reference element, expressed by the color index (intensity of gray). This fact was demonstrated by the authors in a previous paper [8].

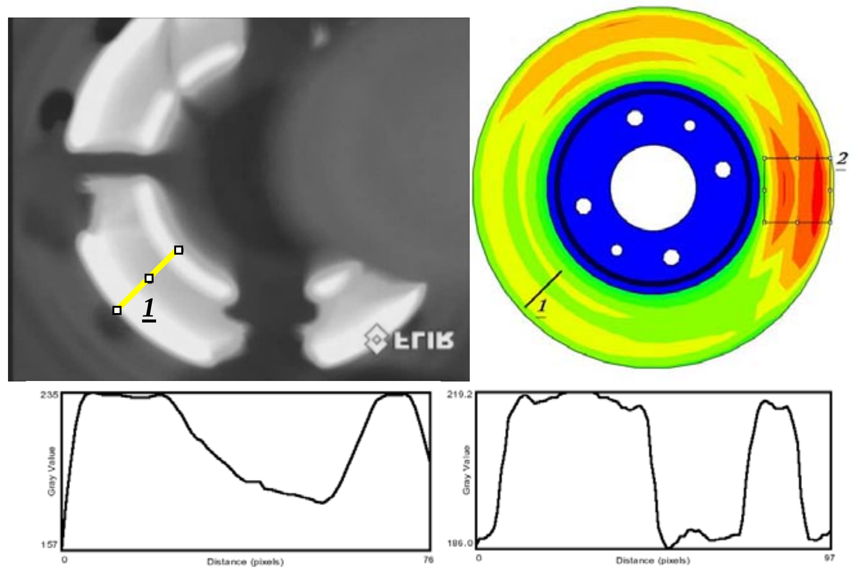


Fig. 5. Radial temperature distribution (over line ***1***) for the simple brake disc (left - real distribution; right – modelled distribution)

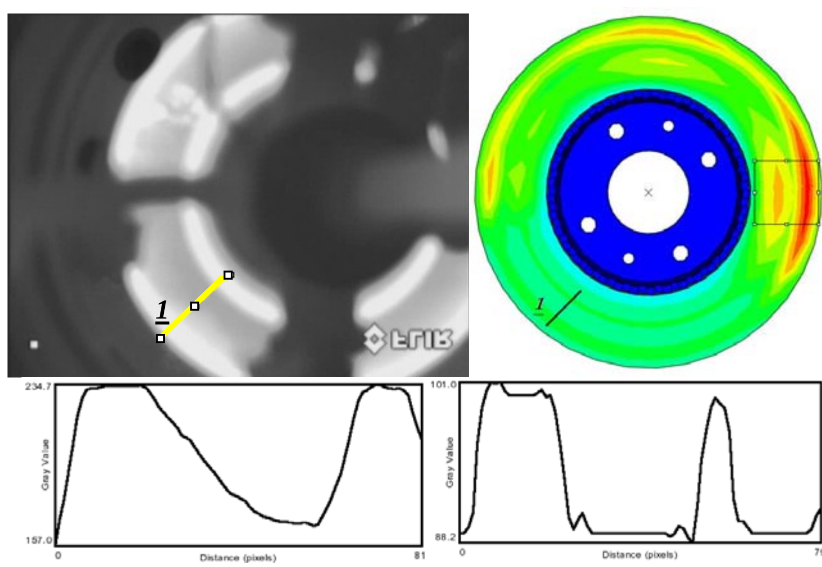
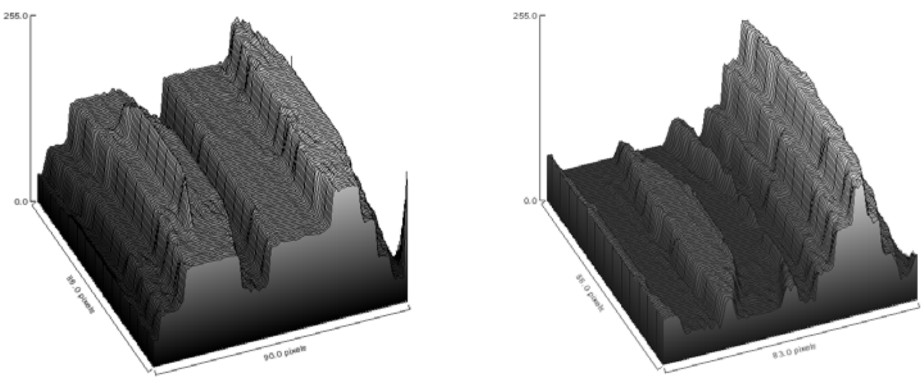


Fig. 6. Radial temperature distribution (over line ***1***) for the vented brake disc (left - real distribution; right – modelled distribution)

Regarding radial temperature distribution for both experimental and modelled part, at the middle of analysed line ***1***, temperature has lower values than the extremities.

Fig. 7 presents the spatial repartition of temperatures over disc friction surface under the pads for the results of analyses (equivalent to second area *2* from figures 5 and 6). The same repartition of temperature was found - higher to extremities and lower to the middle of selected area.



For simple brake disc For vented brake disc

Fig. 7. Spatial temperature distribution over the brake disc surface under the pads (over the surface ***2*** from figure 5 and 6)

The shape of temperature profile on radial direction can be generated due to geometry of pads and the fact that the pad wear was not considered in finite element analyses. This thing is sustained by the fact that the tested motor vehicles were almost new and had run few kilometres.

Hao Xing [9] obtained a close radial shape of temperature distribution over brake disc as the one resulted from the FEA. Also he specifies the fact that the pad wear was not taken into account.

Using thermocouple, introduced inside the pads, Kwangjin Lee [10] analysed the repartition and variation of temperature at the disc surface. He specifies that in his experiments the tested discs and pads were new.

The non-uniform repartition of temperature is caused by thermo-elastic behaviour of disc and the pads. The temperature rises at the upper part of the pads due to high slip speed between disc and the pads. This fact makes the temperature to rise in that area. This way the material will distend, while the pressure remains constant over the pads back, the contact will rise at the inner radius part so the temperature will rise too. For long braking, the temperature shape will reverse [10]. This process is the effect of thermo-elastic instability (TEI) phenomenon which causes the pressure and temperature variation [11].

This temperature variation causes material structure changes, generating heat spots that can be amplified. Thus noises and vibrations result [11].

Thermal stresses are amplified at the end of the braking if the car driver holds the brake pedal pressed so the pads press the disc. This thing can't be controlled because it is a problem of traffic safety.

A section was made through the disc to analyse the heat transfer inside and outside the disc. In this way it is possible to analyse temperature in two points for the simple disc and three points for the vented disc (Fig. 8).

Temperature values measured in these points were studied in two sections – first one through the pads zone and the second diagonally opposite to the first one.

For both discs, point number **1,** is placed at their exterior. Point number **2** is placed in the middle of the simple disc. For the vented disc, points **2** and **2'** are placed at its interior in the vanes zone (Fig. 8).

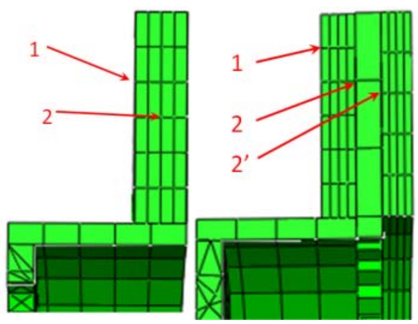


Fig. 8. Position of studied points inside and outside the discs (left – simple brake disc, right – vented brake disc)

The pads of the assembly cover 9% of the brake disc friction surfaces. For a simple disc 26% of the heat is released by radiation at the opposite zone of the pads and temperature inside the disc rises with 3%.

At vented disc the heat will be released in the first phase from the friction surface. Due to conduction, in the second phase the heat will be released inside the disc between vanes. The total surface of heat release is more than 60% bigger than the simple disc. For a high value of conductivity, the heat will be released in a short period of time and in a high quantity.

Due to the difference between the thickness of the left and the right part of the vented brake disc (Fig. 9), the heat flux will reach faster, through the left part (which has a smaller thickness), the interior of the brake disc.

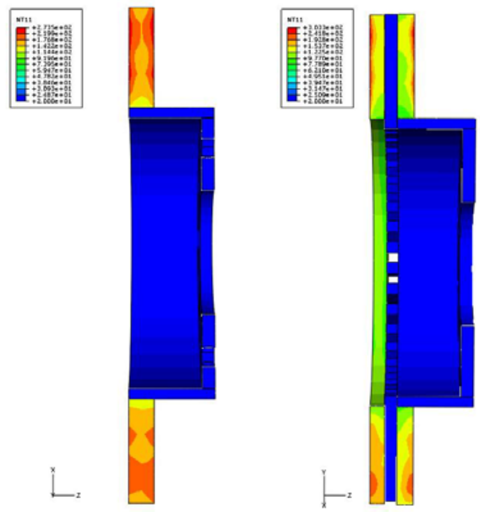


Fig. 9. Temperature distribution at the end of intensive braking inside the studied discs (left – simple brake disc; right – vented brake disc)

At the interior of vented disc surface, the surface has a bigger emissivity due to its states (it is not polished). The heat will be released easily through the interior surfaces, of vented brake disc, than the exterior surfaces, which are polished and have a smaller emissivity.

3. Conclusions

Regarding radial temperature distribution, over the brake disc friction surfaces, for both experimental and finite element analyses results, temperature is higher at the extremities than the middle of those surfaces, due to thermo-elastic instability.

Considering input conditions and the temperature distribution over the brake disc, which influence the thermal stress, the results of the finite element analyse and the tests are in good agreement.

For a half disc rotation (at the opposite part of the pads), the heat is dissipated, by radiation, about 26% over the friction surfaces. In case of vented disc, which has a dissipating area about 60% bigger than the simple one the heat will be dissipated also at the interior of the disc. Thus, the disc is less thermally stressed.

Analysing the vented model, thickness plays an important part in heat transfer. Combined with interior surface state, the heat will be dissipated faster at a smaller thickness.

Once with the validation of finite element model it is possible to make further studies as to reduce thermal stresses by optimising and designing disc brakes.

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