Review on the Study of Abnormal Braking in Trains

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ABSTRACT

This paper describes the working of braking system of trains, current status of non-uniform braking in trains and its causes. Non-uniform braking in locomotives and coaches or wagons in emergency conditions can lead to calamitous consequences such as wheel locking which lead to derailments and thermal cracking. Braking consists of evolution of thermal energy. After a period of usage, thermal cracks can be encountered on the friction surface of brake disc which can exhibit different initiation and propagation under different braking conditions. In this paper, there is a description of experimental testing done for the analysis of the effect of braking energy on fatigue crack evolution. This paper consists of two field trials done by Indian railway i) continuous rim temperature data for locomotive wheels ii) one time measurement of rim temperature of all wheels. The information obtained from the trials is used to find the causes of abnormal braking and to characterize the extent of non-uniformity. The paper aims to measure the existing state of non-uniformity in braking in passenger and freight trains and finding the underlying causes for the same.

Keywords: ***Braking system; Braking energy; Fatigue crack propagation; Brake cylinder pressure; Brake pipe pressure; wheel rim temperatures; Finite element analysis;***

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1. INTRODUCTION

A train in motion contains kinetic energy which is to be removed in order to retard it. This can be done by conversion of kinetic energy into heat energy by friction. This is usually executed by applying block or pad on rotating wheels or discs attached to the axles. Friction leads to energy conversion which causes wheels to slow down and eventually the train stops.

Braking system in trains is having a great importance as per as the safety of the passengers and goods is concerned and also it has restrictions on peak speed of train. Most commonly used braking system in trains is pneumatic and tread braking. Passenger trains use twin pipe system while freight trains use singe pipe system. There are many characters which influence the braking such as brake rigging, braking type, brake blocks, peak brake cylinder pressure. Abnormal braking can cause wheel slip, thermal cracking and excessive wear of brake block, generation of residual stresses etc. [1].

The high speeds trains (above 200 km/hr.) use brake discs and brake pads. Due to repeated braking thermal cracks and hot spot (overheat areas) are found on the friction surface of brake discs. The overheat areas are having different microstructure and mechanical properties and the thermal distortions near it can lead to cyclic tensile and compressive stresses. These stresses can cause radial, crackle and circumferential fatigue cracks. The rapid growth of thermal cracks represents a great threat to operational safety of trains which is nowadays increasing linearly with increasing speeds [2]. In order to analyse crack propagation and efficiency of braking, many tests and experiments where done by Indian railway and China railway and results were obtained.

Nomenclature

DBV	Drivers brake valve
MR	Main reservoir
AR	Auxiliary reservoir
DV	Distributor valve
IV	Isolating valve
BPP	Brake pipe pressure
BCP	Brake cylinder pressure

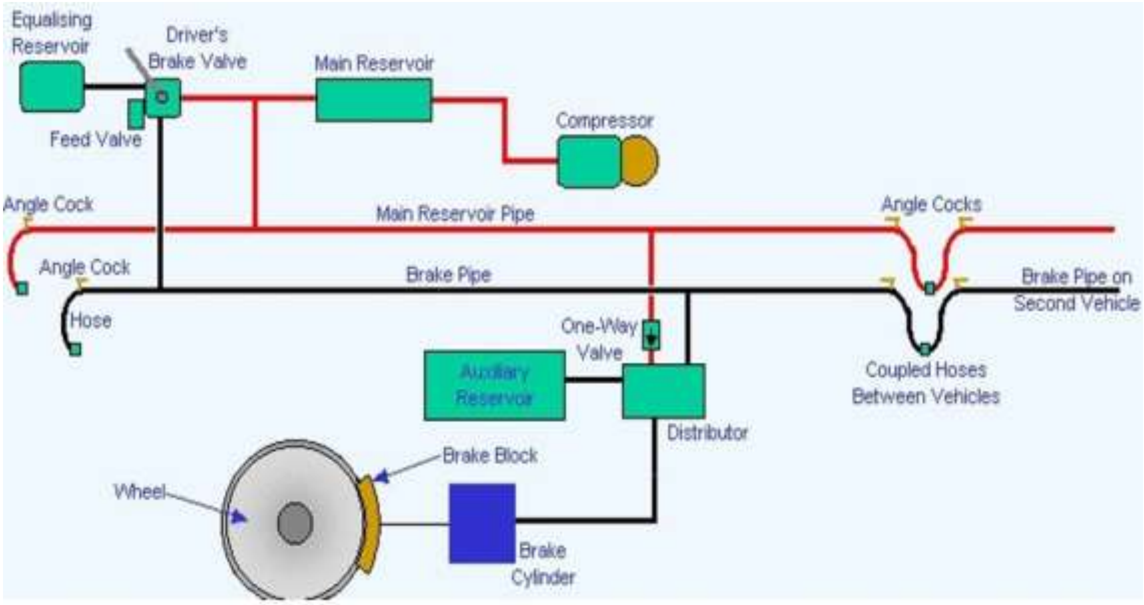


Fig-1: Schematic of twin pipe braking system

2. BRAKING SYSTEM

Fig 1. Shows a schematic of twin-pipe, air braking system used in passenger trains. The main components of braking system are Main reservoir(MR), Auxiliary reservoir(AR), Brake pipe, Feed pipe, Brake cylinder, Brake block, ,Brake rigging.

The compressed air is supplied to main reservoir from compressor. This compressed air from main reservoir supplied to auxiliary reservoir through feed pipe. The pressure value maintained in main reservoir as well as auxiliary reservoir is 8-10 bar and 6 bar respectively. Distributor valve connects auxiliary reservoir to brake cylinder. When the pressure in the brake pipe reduces by its nominal value 5 bar, it is detected by distributor valve and it results in the increment of brake cylinder pressure. This in turns causes the application of brakes. Rise of peak brake cylinder pressure is directly proportional to the reduction in the brake pipe pressure up-to 3 bar. Brake pipe pressure is maintained at the nominal value by connecting it main reservoir through drivers brake valve. Whenever the brake pipe pressure is to be reduced i.e. the brakes are to be applied, the loco pilot connects the brake pipe to the atmosphere by applying drivers brake valve. When the brakes are to be released, the loco pilot connects main reservoir to the brake pipe and brings back the brake pipe pressure.

There is one auxiliary reservoir and one distributor valve for each coach. Four cylinders on the two bogies in the coach are connected by distributor valve. In order to keep any bogie isolated from the system if required then isolated valve comes in operation which is located between distributor valve and each bogie. Brake rigging is the mechanism used to transfer force from brake cylinder to brake blocks. Brake rigging mainly consists of linkage mechanism with mechanical advantage transferring force from brake cylinder to brake blocks. Thickness of the brake blocks influences the braking effort on each wheel and hence while replacing the brake blocks all four blocks are replaced at a time [3] [4] [5].

3. EXPERIMENTS TO INVESTIGATE CRACK PROPGATION

The China railway investigated three types of braking conditions for finding out the effect of braking energy on crack propagation i.e. emergency braking at 300km/h, 200 km/h and routine braking. The braking tests were carried out on full scale dynamo testing machine. The brake discs used for 300km/h were having large amount of fatigue cracks on it and they were compared with virgin discs. Nearly 1000 times repetition of EB at 200km/h were performed on dynamo machine and the routine braking was monitored on railway car running under the normal condition of braking. The evolution of fatigue crack was compared using macroscopic photos of crack. The brake discs with fatigue crack were broken with hydraulic fatigue test machine. The portion having hot spot on the disc was cut for metallographic observations and polished and etched with a nital etchant. The microstructure of the specimen was observed and micro-hardness was measured. The chemical composition near the fatigue crack was also analysed. After microscopic evaluation, thermal and structural analysis was also done by using Finite Element model. Thus the effect of braking energy on fatigue crack propagation was analysed using microscopic and simulation analysis.

The simulation of braking process was done by means of the transient FE method. The braking energy while friction can be calculated by converting kinetic energy into heat. The heat flux applied on the contact area of the friction surface can be described by

$$q(r,t)= \eta\mu\omega(t)Pr\ldots1$$

Where η is the heat partitioning factor of frictional heat flux entering the disc, μ is coefficient of friction, P is braking pressure and ω (t) is the angular velocity of brake discs. The term q(r,t) is heat flux applied at radius r of brake disc at time *l* during braking. The braking pressure is the function of velocity which considerably low in routine braking chosen from series of data on a online railway motor car. Fig. 2 illustrates the variation of braking pressure with respect to the velocity. For the friction pair investigated in this work η was calculated to be 0.86 and μ was 0.265 [8] [9] [10] [11].

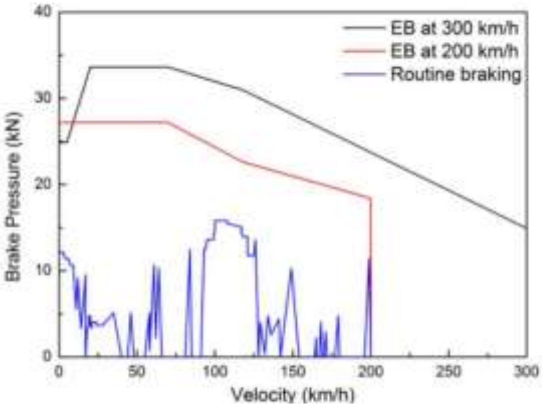


Fig-2: Variation of braking pressure along with velocity [2]

4. RESULTS OF EXPERIMENTS

4.1 Macroscopic observation of cracks:

When the braking is applied at 300 km/h, the energy dissipation is very high and hot spots are formed on the friction surface of disc. Thermal cracks occur around the hot spot due to repeated braking. Frequent emergency braking can cause the crack propagation and lead to premature failure of disc. The fatigue cracks are half elliptical in cross section and they propagate and join in longitudinal direction.

Crack propagation under emergency braking at 200 km/h is mainly dominated by the initiation of crack. Repetitive EB at 200 km/h leads to slight increase width of the crack instead of increment in the length. The presence of large amount of crackles reflects thermal damage of the braking disc and it leads to growth in length of main cracks. Crack evaluation under routine braking was observed on the brake disc used on online railway vehicle having speed of 200 km/h. The initial cracks were observed at speed 300 km/h. With these initial cracks the state of the cracks on the surface was compared at speed of 200 km/h for 6 months with 8000 routine braking cycles. Initially the cracks didn't propagate but it attributes to decrease in the initial braking speed changed from 300 km/h to 200 km/h [10] [12] [14].

Fig-3: Presence of hot spot and thermal cracks on the disc surface [2]

4.2 Chemical analysis of brake disc:

Chemical analysis of brake disc was conducted to investigate the degree of oxidation around the thermal cracks on the friction surface. For the brake disc operated at 300 km/h, there was large amount oxidation. These oxidized areas show small pits and appeared light grey. For 200 km/h speed the oxidized area was much smaller and was distributed to the cracks. The discs used in routine braking were not showing any sign of oxidation. The size of oxidized areas shows temperature rise on the friction surface during braking. The existence of surface cracks lead to non-uniform temperature distribution. The presence hot spot can cause non uniform contact on the friction surface and form bumps on the surface. The cracks would be seen as the gaps among the small areas. After the severe braking processes, the temperature in these areas each the oxidation temperature and form oxide on the surface. The oxide cause stress concentration during cyclic braking process. Thus oxide layer on the friction surface can be the source of crack initiation and crack propagation [2].

4.3 Finite element simulation:

Transient FE method was used for the simulation of braking processes for different braking conditions. Thermal simulation was carried out for determination of temperature on the disc and convective heat transfer during braking and cooling was taken into consideration.

The fig.4 shows the temperature distribution during emergency braking at 300 km/h. the non-uniform temperature distribution causes changing in the contact area between pads and the disc. The temperature and braking pressure variation is plotted in the graph. Most of the thermal cracks propagate in the radial direction and the cyclic circumferential stress is the driving force for it. Four positions at distance of 0 mm, 5 mm, 10 mm, and 18 mm, were selected in axial direction of disc to find out circumferential stress distribution. At the beginning of braking tensile and compressive stress was distributed along radial direction. For the 10 mm position the stress was compressive. The stress on the friction surface changed from negative to positive after cooling for certain period of time. The residual tensile stress could be caused due to localized plastic deformation on the friction surface. In order to eliminate residual tensile stress near the friction surface a ramp braking mode with low braking pressure can be considered. Under this condition, the temperature of the brake disc rises slowly and uniformly and hence the circumferential residual stress can be reduced along with smooth temperature variation.

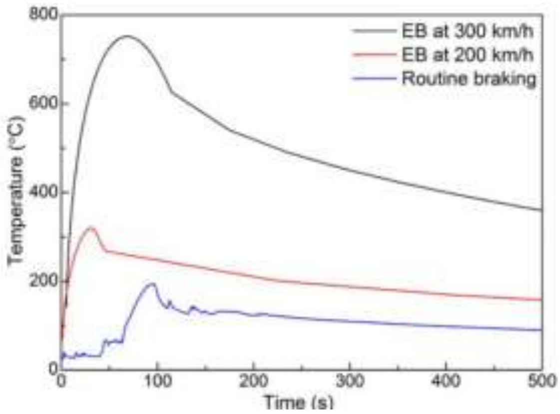


Fig-4: Temperature distribution along the velocity [2]

5. FIELD TRIALS AND FINITE ELEMENT FORMULATION BY INDIAN RAILWAY

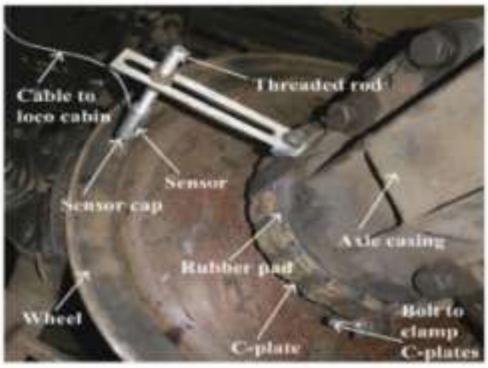


Fig-5: Setup of the field trial[1]

Indian railway conducted two sets of field trials in order to investigate variability in braking. 1) Continuous measurement of train speed, brake cylinder pressure, brake pipe pressure and locomotive wheel rim temperature. 2) Measurement of rim temperatures of all wheels in passenger and freight trains at one time instance during their journey.

The set up for the trials is shown in the fig. The locomotive axle has gear box on one of its end and fixture holding the sensor was mounted on another end. Infrared non-contact type sensors were used and they were located at 70 mm distance from the wheel at any orientation (radial or angular). At this distance, the spot diameter whose temperature is to be monitored by sensor is 8 mm. The non-contact type sensors were connected to the fixture using sensor caps which also provide protection to sensor lens. The sensors were connected with one meter long data cable which further connected to 25 m long shielded data control cables that can reach to loco pilot's cabin. The sensors were powered by 5 V supply from a USB connection on laptop on which the data being recorded. 5 V is sufficient to measure the temperature up to 350. For higher temperature the power supply can be increased to 30 V. Rim temperatures of all wheels in a passenger train were measured using infrared thermometer. Time taken to manually measure the rim temperature for about 11-15 coaches and 1-2 locomotives was 15 minutes. A calibrated model which account for convective and radiative heat loss from the wheels to ambient air was used to estimate wheel rim temperature.

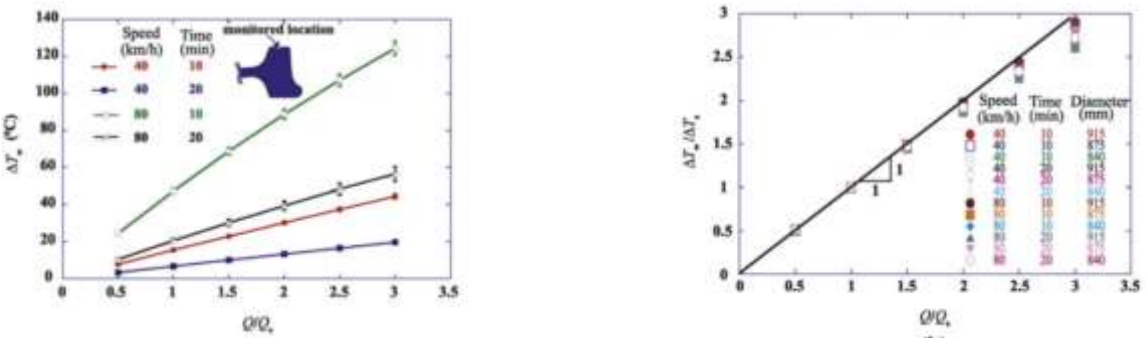
In finite element formulation, commercial finite element analysis software ABAQUS 6.1 is used for estimating temperature evolution in locomotive wheels. The axi-symmetric thermal analysis was done. For linear axi-symmetric heat transfer quadrilateral elements are used to represent wheel cross section while doing the analysis. In FE formulation two types of analysis are conducted. In first type speed and braking histories of locomotives in the field trial are used to estimate heat generated during braking events. Linear heat generation was taken in to consideration while braking event. Ratio of minimum heat generated at the end of braking and the maximum heat generated at the start of braking is kept identical. Analysis is done for 1074 mm wheel diameter of locomotive. Wheel temperatures are validated with that obtained from field trials. In the second type, rim temperature evolution in each coach wheel is monitored for different train running conditions and coach wheel diameter. In both the cases, heat evolved at wheel and brake block was used. Heat transfer to the axles was neglected and heat transfer to rail during stationery condition was zero. The convective heat transfer coefficient of wheel surface which was exposed to air in idling and running condition were taken to be 6 and 12 W/m^2k respectively. Fig shows the boundary conditions used for straight plate locomotive wheel in the analysis. Finite element meshes with 1282, 1446, 1529, linear axi-symmetric heat transfer quadrilateral element which were used to discretize 840, 875, 915 mm diameter coach wheels. Thermal conductivity, density, specific heat, for the wheel steel were taken 49 W/mK, 7850 kg/m^3, 460 J/kg K respectively [6] [7].

6. RESULTS OF THE ANALYSIS

6.1 Validation of finite element model

The analysis was done on loco which covered 130 km distance from Kharagpur to Tatanagar, India. The velocity, brake cylinder pressure, locomotive wheel temperature were observed in the field trial. Heat generation rates during braking are estimated from velocity and brake cylinder pressure variation in the field trial. Peak temperature in locomotive wheels observed in the field trial are quite similar to that predicted from finite element analysis. Multiple braking events occurring over a short time period leads to rise in wheel temperature in early stages of loco operation. Heat loss to rail through conduction and ambient air through convection and through radiation during loco steady running conditions are well captured in the analysis. Difference in braking across the wheel is evident from standard deviation in measured temperature in four locomotive wheels. Standard deviation in rim temperature rise which was observed by sensors mounted on four axles were about 5^0C. The mean and standard deviation of % error in finite element prediction for wheel rim temperature rise is about 5^0C.

6.2 Effect of operating conditions and wheel diameter on wheel temperature rise



(a) (b)

Fig-6:(a) Mean and standard deviation of temperature rise (b) Normalized temp rise during synchronized braking [1]

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Temperature rise in wheels directly corresponds to heat dissipated during braking. Finite element simulation is done for different train running conditions and wheel diameters. Temperature rise is monitored in the rim region that is accessible from the fig. Fig 6(a) shows mean and standard deviation of temperature rise for 840, 875 and 915 mm diameter wheels subjected to different operating conditions. It is clear the wheel diameter is having minimum effect on wheel temperature rise monitored at 10 or 20 min of braking event. Operating speed and braking frequency have significant effect on temperature rise.

Fig 6(b) shows normalized temperature rise during synchronized braking which is equal to normalized braking effort i.e. normalized heat generated during braking Q/Q_S, for different operating speeds, braking frequencies and wheel diameters. Where Q_S denotes heat generated at brake wheel interface in synchronized braking and Q denotes heat generated at brake wheel interface in actual scenario.

6.3 Cumulative distributive functions of wheel temperature rise

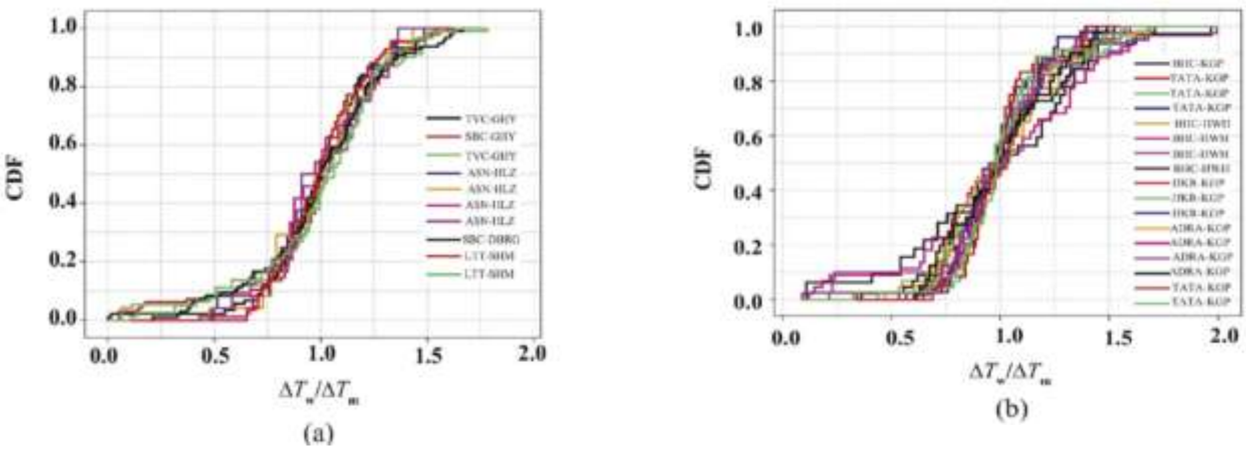

Fig-7: CFD for normalized temperature rise for (a)Express,(b)Passenger[1]

The graph shows cumulative distributive functions (CFD) obtained by software Minitab15 for normalized coach temperature rise for different passenger and express trains. CFD is used to determine % of wheels experiencing a given normalized temperature rise or below. Passenger trains travel for shorter distance and with many stoppages. The express trains have large distances with few stops. All the trains having peak speed of about 110 km/h and express trains have twice number of coaches as compared to passenger trains. In all cases rim temperature was measured from platform side. We can make observation from the fig that braking is more uniform in express trains. Standard deviation in normalized temperature rise varies from 0.21 to 0.34 for express trains and 0.20 to 0.41 for passenger trains. As per current maintenance practice by Indian railways, number of braking events between two successive maintenance schedules is 3 to 4 times higher for passenger trains.

7. CONCLUSION

- Braking effort is found highly non-uniform in case of freight trains. Issues related to distributor valves and dirt collectors are mainly responsible for excessive brake loads.
- Among express and passenger trains, braking is found more uniform in express trains because higher number of stops between two successive maintenance schedules is to result in greater non-uniformity in braking for passenger trains.
- Wheel rim temperature rise is maximum during initial few braking events.
- Finite element adopted in this work, which accounts for heat loss to brake block, rail and ambient air is seen to predict accurately wheel temperatures based on the input of train speed and braking history for a given journey.
- The fatigue crack on the brake disc surface, including crackle, radial crack and circumferential crack, exhibit different initiation and propagation behavior under different braking conditions.
- Braking test of fatigue cracks exposed that the fracture surface were covered by oxides and the shape of the fracture surface were elliptic type.
- Radial cracks appear and propagate on the friction surface of brake disc that serve at 300 km/h. Only cracks appear at 200 km/h and no crack appear at routine braking.

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