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Estimating the fatigue life of an Al-MMC brake drum component

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Research Article

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Posted Date: September 5th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10772122/v1

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Additional Declarations: Competing interest reported. The authors declare that they have no conflicts of interest.

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Abstract

This study evaluates the suitability of an aluminium die casted metal matrix composite material used in a brake drum component based on fatigue life estimates. A three-dimensional FEM model of a three-wheeler automobile vehicle is subjected to loading conditions in order to estimate the fatigue life of an Al-MMC brake drum. Under extreme conditions, the Al-MMC brake drum component works safely under fatigue loading for 67,500 cycles.

Keywords: Cyclic Fatigue, metal matrix composites, SN curve, simulation modelling.

Nomenclature

$3D$	three dimensional
ADC	aluminium die casting
Al-MMC	aluminium metal matrix composite
FEM	finite element analysis
MMC	metal matrix composite
SiC_p	silicon carbide particulate
Dofs	degree of freedoms
SN	stresses at number of cycles
E_{Max}	maximum energy density
$\sigma_{p\text{-}max}$	maximum principal stress.
$\sigma_{v\text{-}max}$	maximum von Mises stress
σ_{UTS}	ultimate tensile stress
σ_y	yield stress
FSU	factor of safety for ultimate stress design
FSY	factor of safety for working stress design

1. Introduction

Light weight metal matrix composites (MMCs) are in demand due to their excellent material properties such as wear resistance, lightweight, stiffness, corrosion resistance etc. Due to their higher strength/density ratio, lightweight aluminium MMCs is suitable for the automotive components, which has the performance requirement of excellent wear, damping and fatigue properties [1]. The brake drum is one of the most suitable components for the introduction of MMCs into automotive applications (replacing cast iron brake drum), due to its properties like

wear resistance, better thermal behavior, and strength/density ratio as compared to cast iron. In an automobile, Brake drum component is subjected to cyclic loads, therefore evaluation of cyclic behavior or Al-MMC material is important for its industrial application.

Several attempts have been made to study the fatigue behaviour of metal matrix composites. In MMC, the fatigue behavior depends on the synthesis routes, size of reinforcements [2-7], composition and coatings on the material surface [8]. Some researchers [9, 10] have evaluated these effects in order to analyse the fatigue strength of MMCs. The effect of load ratio [11-17] and the surface roughness on the material surface [18, 19] also have important role. To evaluate metal matrix composite material, temperature effects [20-23], porosity effects [24], and friction stir welding effects [25] on fatigue strength have been taken into account. These studies demonstrated the effect of different parameters on the fatigue properties of metal matrix composites. Microscopic examinations of MMC fatigue behaviour were also conducted [26-28]. In most cases, researchers evaluated low cycle fatigue [22, 3, 9, 10, 17, 18, 5, 6, 14, 15, 23, 28] to examine metal matrix composite material, whereas some researchers evaluated high cycle fatigue [2, 8, 12, 13, 19, 21, 4, 6, 25, 24] and crack growth behaviour [2, 16, 11, 20, 27, 28] to evaluate fatigue behavior of metal matrix composite material fatigue behaviour. The fatigue performance of components made up of MMC material had also been carried out by some researchers [29-33]. The fatigue analysis has been performed for passenger car steering knuckle [29], connecting rod [30], MMC rings [31], leaf spring [32] and camshaft [33]. Fatigue analysis of cast iron brake drum [34] and hybrid Al-MMC brake drum [35] were also reported but the fatigue life estimation of ADC-12 metal matrix composite brake drum component on the basis of principal stress/working stress and factor of safety using experimental SN curve yet not reported in the available online literature.

To understand the suitability of ADC-12 MMC brake drums under fatigue loading, a performance evaluation is required. To achieve the goal, a fatigue test of Al-MMC material was performed on a fatigue-rated Instron machine according to the ASTM E-466 procedure. The experiments were conducted in tension-tension mode with a load ratio of 0.1. Constant amplitude fatigue cycles were performed until the test sample failed. The tests were carried out with the varying amplitudes of fatigue load while keeping the load ratio value constant at 0.1. This test also determines the endurance limit of a metal matrix composite. To ensure the safety of the brake drum component under fatigue loading condition, the performance of the brake drum component is evaluated numerically until the experimentally determined material SN curve.

2. Material synthesis using stir casting process

In the present work, aluminium die casting alloy (ADC-12) and silicon carbide particulate (SiC_p) is processed using stir casting process. In this process, the aluminium die casting alloy was heated upto a specific temperature to transform solid alloy into molten state. For the proper grain refinement, TiB_2 rods have been used and flux has been applied to reduce slag formation within the matrix. Then, SiC particulates have poured in the molten metal and stirrer was applied at a constant speed to disperse SiC particulates with uniformity throughout the melt. This process was continued until the particulates reinforcement completely dispersed with ADC-12 alloy. Then, ADC-12 metal matrix composite is poured into the mould using gravity and finally gets gravity casted metal matrix composite material for the fabrication of tensile and fatigue samples. The fabricated tensile samples were having gauge length of 40mm, and a gauge width of 10mm is shown in Fig. 1. The tensile tests were performed at 10^{-3}/s strain rate following the procedure given in ASTM E8 code using servo hydraulic Instron machine. The standard fatigue samples having constant varying radius geometry with a minimum diameter of 10mm had been prepared is shown in Fig. 2. Furthermore, fatigue samples were tested using a fatigue rated Instron machine with a fixed load ratio of 0.1 in accordance with ASTM E466. Tables 1 and 2 illustrate the chemical composition and mechanical properties of the synthesised ADC-12 MMC, respectively.

3. Evaluation of SN curve

The S-N diagram is shown in Fig. 3(a) for aluminium metal matrix composite. In the evaluation of SN curve at first tensile test results had been used to decide the fatigue cycle amplitude for the conduction of fatigue test using fatigue rated Instron machine with 100kN capacity. Step down method has been used to understand the fatigue behaviour of ADC-12 MMC. In this process samples are tested sequentially. Following the testing of the first specimen at an initial stress level, the best guess for the median fatigue limit is typically estimated based on the experience of the first sample test. Depending on whether the first specimen survives or fails, the stress level for the next specimen is increased or decreased at regular intervals. To determine the stresses with respect to the number of cycles, fatigue samples were evaluated in tension-tension mode with the corresponding load values. During the fatigue sample evaluation, the load ratio and frequency were set to 0.1 and 5 KHz, respectively. The first sample was tested at above yield strength (71.9 MPa) of Al-MMC with a corresponding load of 6 KN, and it broke after 10 cycles. The second fatigue sample was tested at 86 MPa stress and 5.5 KN load, and the sample broke

after 7770 cycles. As a result, the third sample was tested at 75 MPa stress with a corresponding load of 5 KN load, and the sample broke after 27000 cycles. This process is repeated until the last sample reaches its endurance limit. The final sample was tested at 54 MPa stress with a corresponding load of 3.5 KN and found to be unbroken after 10^6 cycles. This stress value was considered the endurance limit in the current analysis. Figure 3(a) depicts the obtained stresses with their corresponding cycle counts. The experimental fatigue strength is now compared with the brake drum analysis to determine the fatigue strength of the brake drum component based on the boundary conditions used.

4. Investigation of fractured ADC-12 MMC sample

After fatigue testing, SEM samples have been prepared for fractured surface investigation as shown in Fig. 4. Microstructures were taken from by the scanning electron microscope JEOL 5600 to investigate the fracture surface. Interface debonding was found in between SiC and aluminium and cleavage fracture was also observed on the surface as illustrated in Fig. 5.

5. Mesh convergence study of Brake drum component

In this paper, a mesh convergence study of a brake drum was carried out to investigate the variation of magnitude caused by changing the global seed and the number of elements in the thickness, circumferential, and radial directions. In the current convergence study, fourteen different FEM mesh models with varying number of elements were considered. In brake drum geometry, various mesh division combinations have been used to vary the mesh elements from 6129 to 76881. The effect of element variation has been studied in brake drum geometry to determine variations in von Mises stresses and principal stresses at different mesh element counts. Variations in maximum principal stress and maximum von Mises stress were investigated as a result of changes in the brake drum model's finite element mesh. The magnitude of two studied design parameters varies with the number of finite elements used in the brake drum model evaluation. The brake drum model is found to be converged at 53,512 mesh elements, with the assigned numbers of elements in global seeds (5 global size), thickness (5 divisions), radial (64 divisions), and circumferential direction (more than 50 divisions) [36].

6. FEM model of brake drum component

Figure 6 shows a schematic representation of a three-wheeler brake drum component. The present study used Abaqus software [37] to model a three-dimensional solid geometry of a three-

wheeler brake drum component, as shown in Fig. 6. Along with this geometry, two brake pad geometries were developed to account for frictional forces acting on the brake drum component while applying braking force, as illustrated in Fig. 7. The model of a brake drum is discretized using first order reduced integral eight noded hexahedral elements. The Brake drum geometry was examined using a total of 53,512 hexahedral elements and 65,540 nodes in the current work. Figure 4(c) shows the details of the brake drum solid model the FEM mesh. The true stress strain curve of Al-MMC was used as an input in the Brake drum model to define material non-linearity. In this analysis, a monotonic loading stress strain curve was used. Young's modulus and material density are assumed to be 2.7 gm/cm^3 and 70,000 KN/mm^2, respectively. Table 3 illustrates the applied loading and boundary conditions considered in this study. The three-wheeler vehicle's self-weight and friction coefficient between road and tyre were assumed to be 1300 Kg and 0.4, respectively. The generated magnitude of centrifugal force (111 rad/sec) at 80 km/hr speed was taken into account when evaluating the brake drum. The normal load applied to the brake pad was 150 N, and the corresponding applied pressure was 0.03 N/mm^2. The breaking force is applied to the drum at a distance of 200mm from the centre of the Brake drum in the direction of the moving vehicle using tie constraints by coupling it with the Brake drum, as shown in Fig. 7. The brake drum holes were restrained for rotational and translational movement, and the details of the applied boundary conditions on the brake drum used in the current analysis are shown in Fig. .

7. Evaluating the fatigue performance of AL-MMC Brake Drum

The experimental fatigue testing was performed on a fatigue-rated Instron machine, and the resulting SN curve is shown in Fig. 3(a). To obtain the SN curve, the stress levels were determined using the staircase method with the appropriate number of cycles. A non-linear FEM analysis was performed in ABAQUS software to evaluate the fatigue performance of an Al-MMC brake drum. The performance of a gravity casted Al-MMC brake drum was evaluated in this study using a rotation speed of 80 km/hr and a brake pad pressure of 0.03 N/mm^2 with a centrifugal force of 111 rad/sec applied in the direction of the moving vehicle, and the results were compared to experimental fatigue results to define the component behaviour under working conditions. To bring the vehicle to a stop, a braking force of 1733 N was applied. The obtained maximum principal stress and von Mises stress values are 71.75 MPa and 51 MPa, respectively. To evaluate the fatigue behaviour of Al-MMC, the value corresponding to the maximum principal stress was used. The obtained maximum principal stress is now evaluated using the

experimental SN curve, as shown in Fig. 3(b). The results show that under fatigue loading, the component can work safely for 67,500 cycles.

8. Conclusion

The possibility of using an aluminium metal matrix composite material in the brake drum of a three-wheeler automobile vehicle is investigated in this study. The variation of design parameters of a brake drum, such as speed/r.p.m. and normal pressure on the brake pad, was considered. In ABAQUS, a three-dimensional FEM solid model of a three-wheeler brake drum was created. Using an explicit solver, a hexahedral mesh was generated and analysed, and the magnitude and location of maximum von Mises stress, maximum principal stress, and maximum energy density were determined and reported in the current study. It was observed that the brake drum condition is safe under various extreme loading conditions, with 1 factor of safety under working stress and 1.63 factor of safety in ultimate stress design condition, ensuring the safety of the vehicle and the passengers. After evaluating the brake drum component, it was noted that it can perform well at 71.75 MPa stress with a corresponding 67,500 number of cycles under fatigue loading.

Data Availability Statement

All data generated or analysed during this study are included in this published article.

Availability of data and material

All data generated or analysed during this study are included in this published article.

Competing interests

The authors declare that they have no conflicts of interest.

Funding

The authors did not receive support from any organization for the submitted work.

Authors' contributions

Conceptualization, script writing, editing, experimental and simulation work, results and analysis.

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Table1. Chemical composition of ADC-12 MMC

Element	% composition
Al	71.7
Si	21.88
Fe	0.54

Cu	1.05
Mn	0.2
Mg	0.21
Ni	0.1
Zn	0.65
Others	3.67

Table2. Mechanical properties of ADC-12 MMC

Material	Modulus of elasticity	Ultimate tensile strength	Offset yield strength	Vickers hardness	% elongation	Endurance limit
ADC-12 MMC	70 GPa	117 MPa	71.9 MPa	79	1.5%	54 MPa

Table3. FEM results of Al-MMC Brake drum

S.No	Speed (km/hr) (1)	Equivalent Load (N) (2)	Centrifugal force (rad/sec) (3)	Pressure (N/mm^2) (3) = (2) / Area (4)	Max von Mises stress ($\sigma_{v\text{-}max}$) (MPa) (5)	Max. Principal stress ($\sigma_{p\text{-}max}$) (MPa) (6)	Working Stress Design FSY = (σ_y / (4)) (7)	Ultimate Stress Design FSU= (σ_{UTS} / (5)) (8)
1	80	150	111	0.048	51.00	71.75	1.00	1.63



Before Test

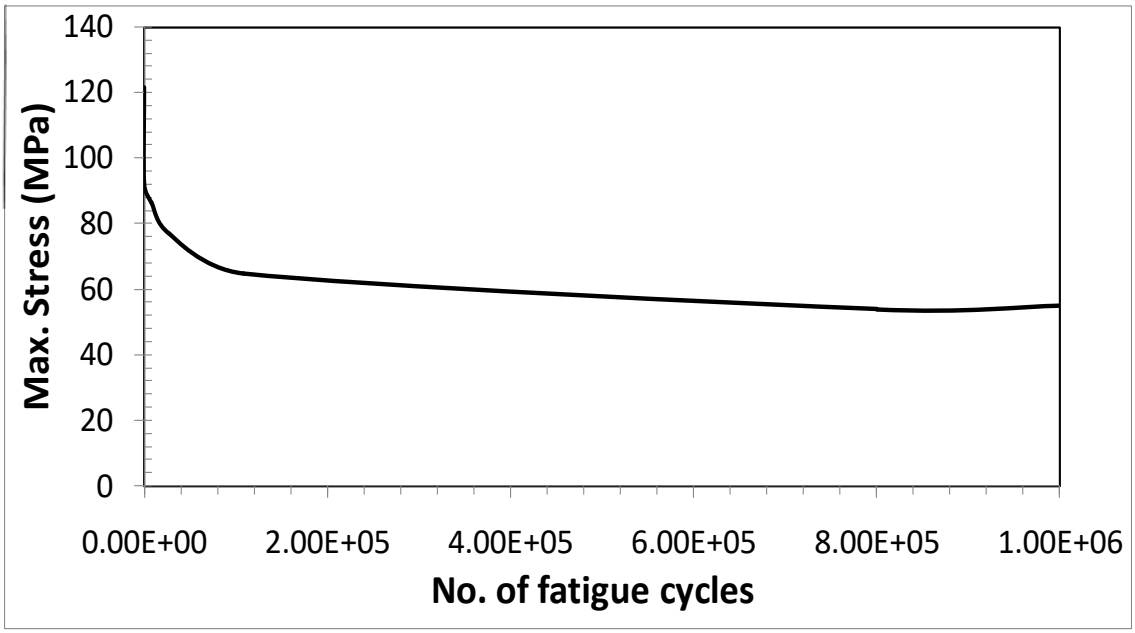
After Test

Fig. 1 Tensile specimens of ADC-12 MMC



Fig.2 Glass hour fatigue specimens of ADC-12 MMC

(a)



(b)

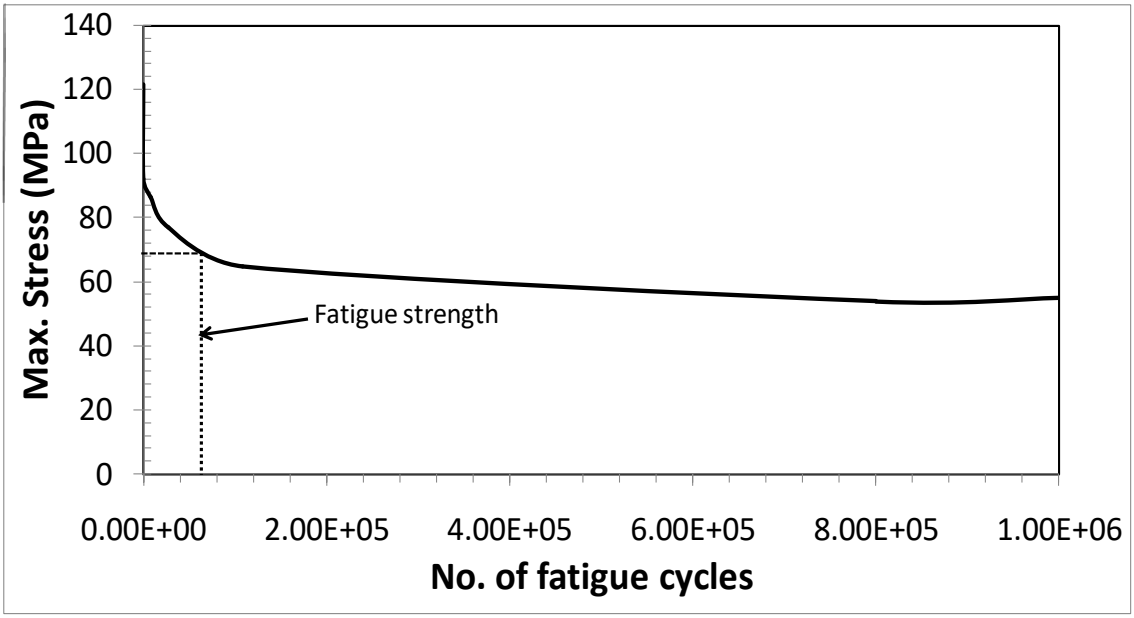


Fig. 3 SN curve: (*a*) *Obtained after experiment* (*b*) *For fatigue life estimation*



Fig. 4 Samples used in fracture surface investigation

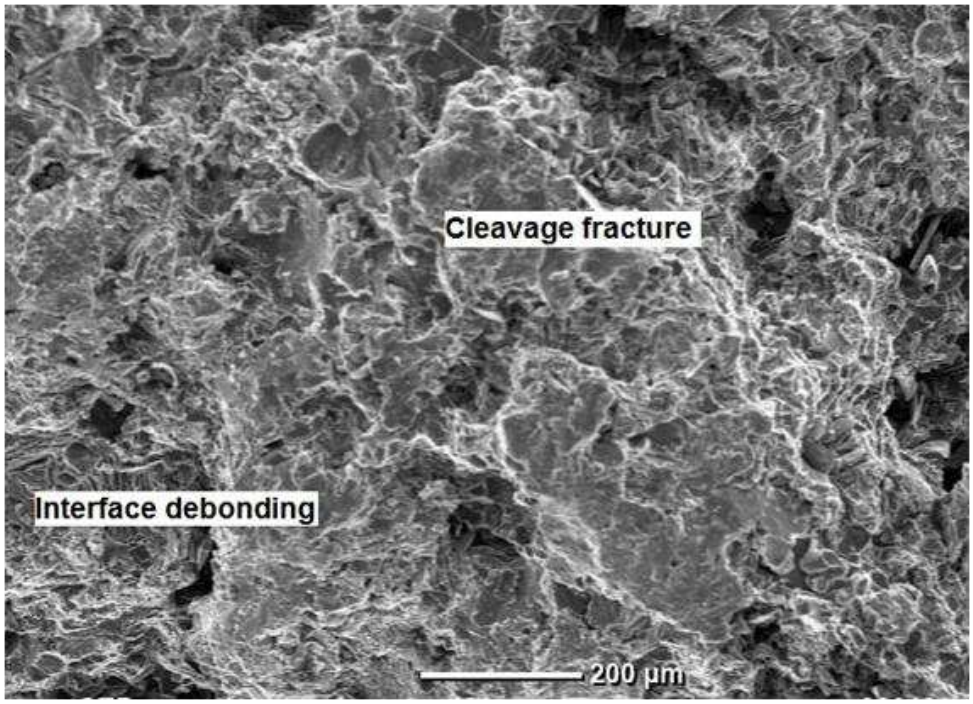
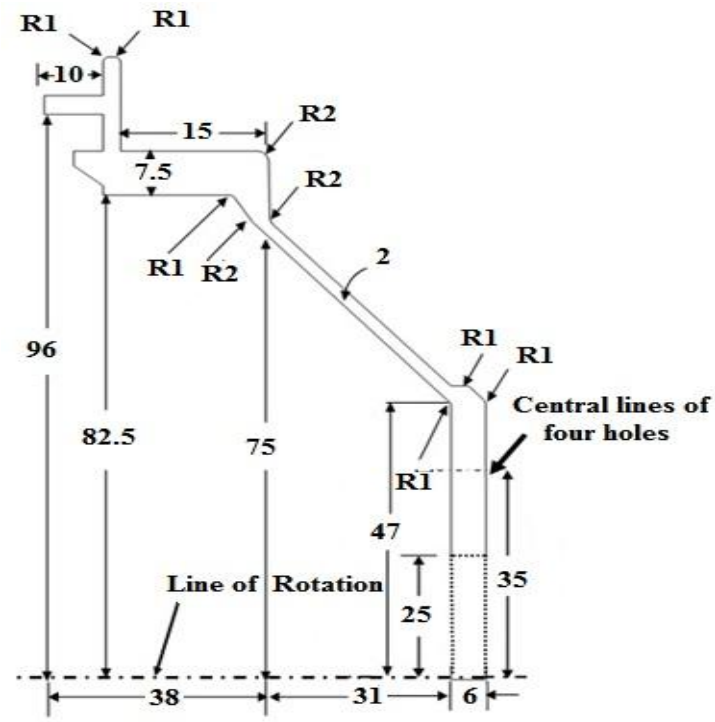


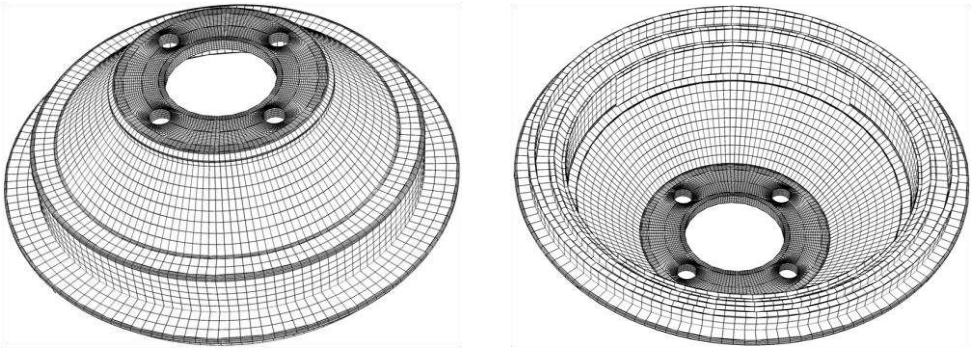
Fig. 5 Fracture surface investigation using SEM



(a)



(b)



(c)

Fig.6 Three-wheeler brake drum component: (*a*) *schematic view*, (*b*) *Solid model*; (*c*) *Hexahedral FEM mesh model*

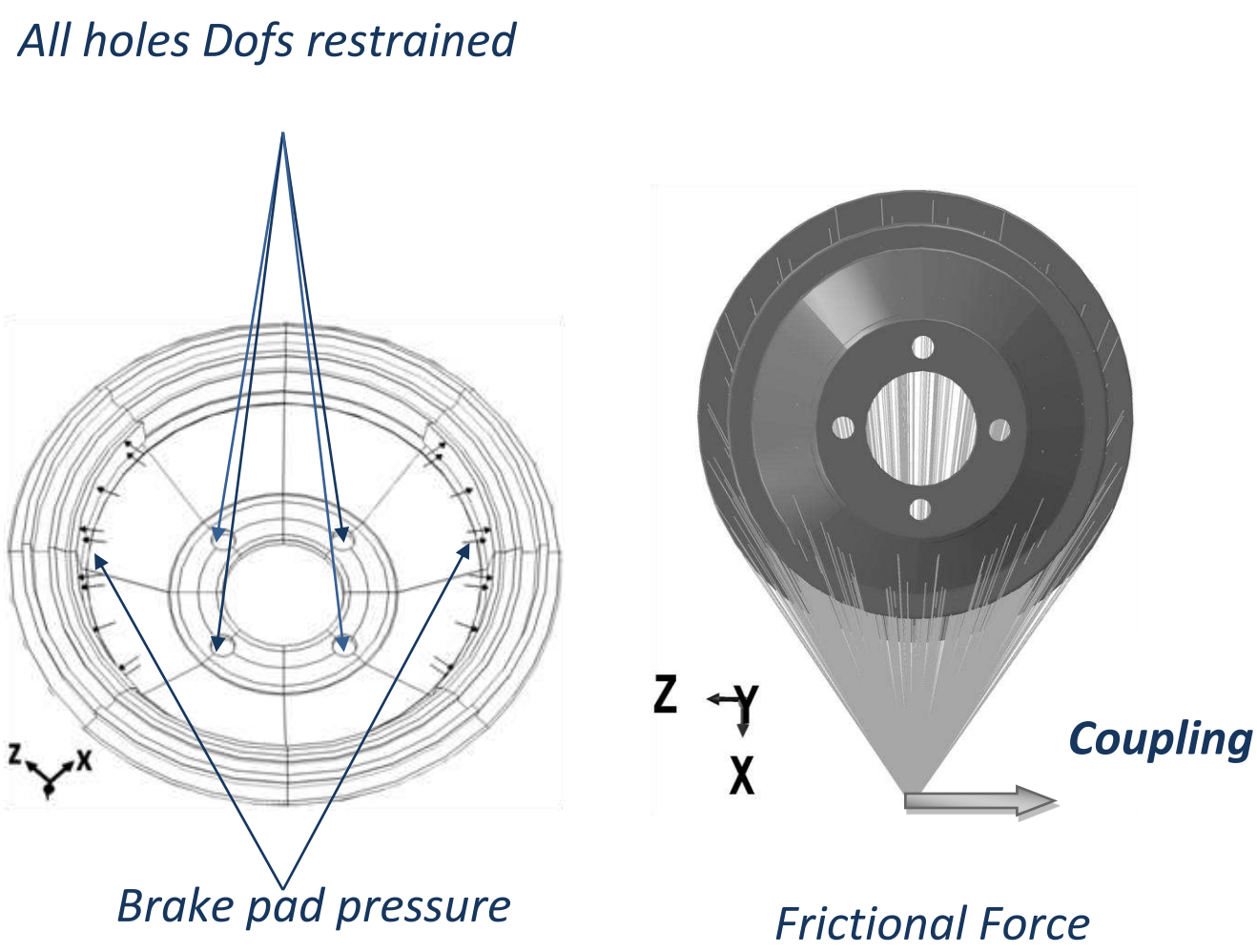


Fig.7 Applied loading conditions in Brake drum FEM modelling