



# Passenger Cars Wheel Performance Test Simulation for Service Life Evaluation: A Review

Suresh Babu Koppiseti · Ramanaiah Nallu · Ramamurty Raju Penmetsa

Submitted: 4 May 2022 / Accepted: 29 June 2022 / Published online: 20 July 2022  
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**Abstract** This paper focuses on reviewing publications related to wheel performance tests and simulation of these tests using finite element analysis to evaluate the service life. Publications from the last five decades are studied. A brief introduction on the evolution of wheel performance tests and their importance is discussed. Developments related to experiments and finite element analysis performed by considering material and manufacturing aspects are summarized. Performance tests and simulations performed using different methodologies and adapted optimization procedures are presented to provide readers with a quick overview of past and recent trends in the wheel industry. Different statistical approaches to validate the wheel's reliability to withstand the service loads are also discussed.

**Keywords** Wheel performance tests · Wheel test procedures · Durability assessment · Fatigue testing · Impact testing · Service life · Biaxial fatigue testing

## Introduction

The wheel is one of the most critical safety components subjected to dynamic loads. The existence of the wheel was known to be before the nineteenth century. However, the

wheel with spokes continued to use until the 1870s, when wire-spoke wheels and pneumatic tires were invented. Eventually, steel wheels were being used from the 1920s [1]. Initially, when steel wheels were introduced, the evaluation of wheel life was not a concern as the life of the vehicle components was not studied for their durability due to various factors. Going forward, when the engines became sophisticated, concern began for the durability of the vehicle components and their performance as they influence the vehicle's speed, mileage, and driving comfort. Various components of the vehicle were being studied, and wheels were identified as one of the critical safety components of the vehicle. Due to the dynamic loads that are being experienced by the wheels, two tests were developed to evaluate the life of the wheels, the dynamic radial fatigue test (RFT) and the dynamic cornering fatigue test (CFT). Also, a wheel impact test is developed to evaluate the wheel's performance for impact loads. The wheel performance tests aim to find out the safe service life on the vehicle for which it is designed.

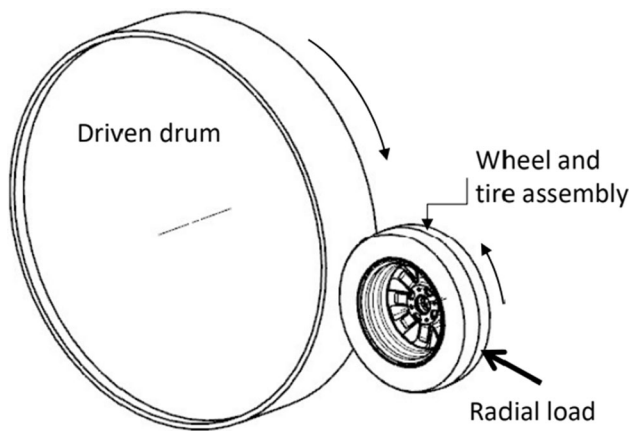
The dynamic radial fatigue test is simulated by applying the load onto the wheel through the tire, which is being rolled over a large radius drum that can significantly simulate the actual condition when the wheel with a tire is running on a straight road with the constant load as shown in Fig. 1 [2]. The load that is being applied would be proportional to the weight of the car, with the factor incorporated for accelerated testing.

The dynamic cornering fatigue test is simulated by applying a bending load onto the wheel, which will be experienced when a car takes a turn. For this to simulate, the wheel is mounted onto a fixture that can hold it firmly, and load is applied onto the end of the shaft that is connected to the wheel hub. In this case, the load is applied

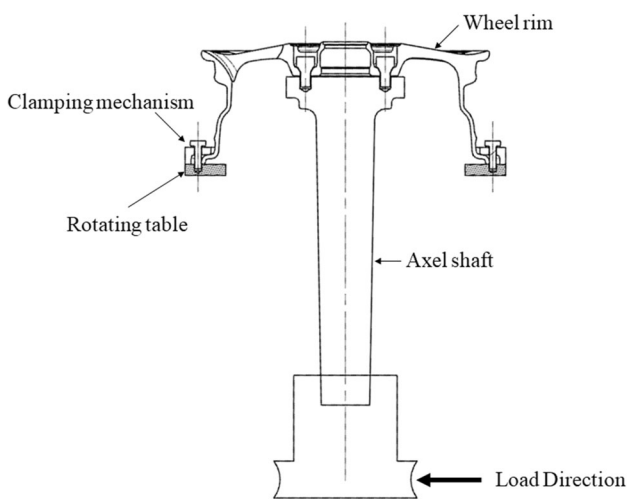
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S. B. Koppiseti (✉) · R. Nallu  
Department of Mechanical Engineering, College of Engineering,  
Andhra University, Visakhapatnam, India  
e-mail: sureshbabu.koppiseti@gmail.com

R. R. Penmetsa  
Department of Mechanical Engineering, S.R.K.R. Engineering  
College, Bhimavaram, Andhra Pradesh, India



**Fig. 1** Radial fatigue test setup block diagram

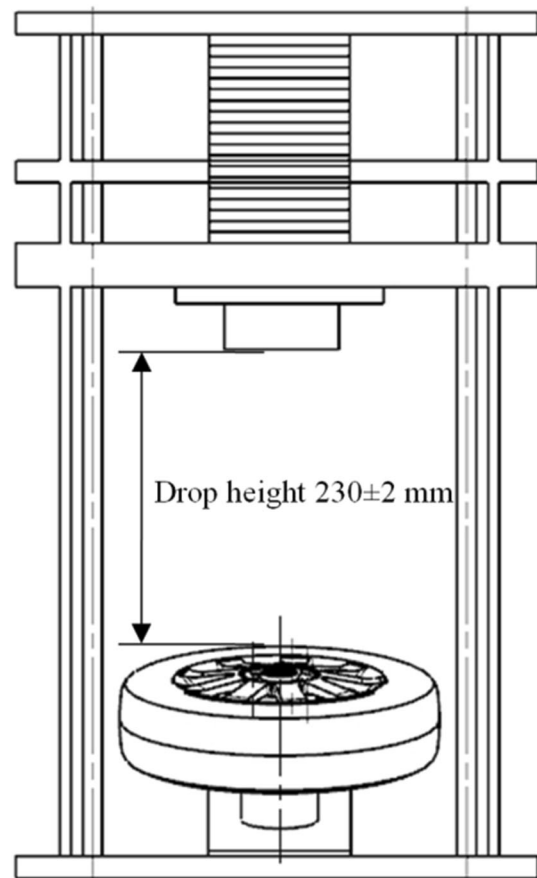


**Fig. 2** Dynamic cornering fatigue test setup block diagram

perpendicular to the wheel axis to transfer a bending load on the wheel, as shown in Fig. 2 [2].

Whereas, wheel impact test is simulated by dropping a steel striker from a specific height onto the wheel, which is mounted by tilting with its axis to a specific angle so that the impact load will hit the rim flange, as shown in Fig. 3 [3]. This test is proposed to understand the wheel’s performance when it hits a curb.

Many developments have been made in the last five decades to understand the criteria of a wheel performance test. New standards were developed to validate the service life of the wheels. Experiments were performed to improve the standards further, which can minimize the cycle time of durability testing. These durability tests come under the destructive type of testing, and if the wheel fails in one of these tests, the design needs to be modified till it qualifies for all the tests, which are very expensive and time-consuming. On the other hand, if the wheel is designed conservatively with enough material to withstand these



**Fig. 3** Impact test setup block diagram

tests without any challenges, there is always a chance that wheel weight is not optimal. To address these challenges, finite element analysis (FEA) is introduced to simulate the performance tests using commercial software and correlate the results with the physical test performed. The main aim of using finite element analysis is to validate the wheel for its service life during the design phase itself to produce an optimal design for its durability [4].

Different methodologies to perform finite element analysis for the three performance tests are developed based on the application of loads, materials, constraints, and validation of the same with respect to the experiments performed. This paper focuses on discussing the literature published on the aspects mentioned above.

The present paper is to explain the history of wheel performance tests, their development, and the application of finite element analysis to validate the design for its service life. The procedure for performing these laboratory tests with the failure criteria is explained. Different loading concepts that can actually simulate the wheel for real-time loads are discussed. The finite element simulation methodologies suggested by different authors for different performance tests were discussed in detail. Methodologies

suggested for wheel optimization using finite element analysis and experimental stress analysis (ESA) are summarized from the published data. Different wheel materials used, manufacturing processes adapted, their merits and demerits are also summarized. Research data related to the mating components and their effect on wheel performance is also discussed.

### History of Wheel Performance Testing

In the early 1970s, specific methodologies were adapted to perform experimental stress analysis on the wheels to identify critical stress locations and corresponding stress amplitudes. The identified stress was compared with the related material S–N data to predict fatigue. One such procedure involves applying a coating of brittle paint to the wheel then slowly rotating the assembly while using the rated load. The direction of main stress can be predicted from the crack propagation pattern. A wire strain gauge was then placed on the critical location as per the outcome of the brittle lacquer test, and corresponding stress amplitudes were measured. The fatigue life was calculated based on the frequency of the peak amplitudes and the fatigue materials characteristics, as shown in Fig. 4 [4].

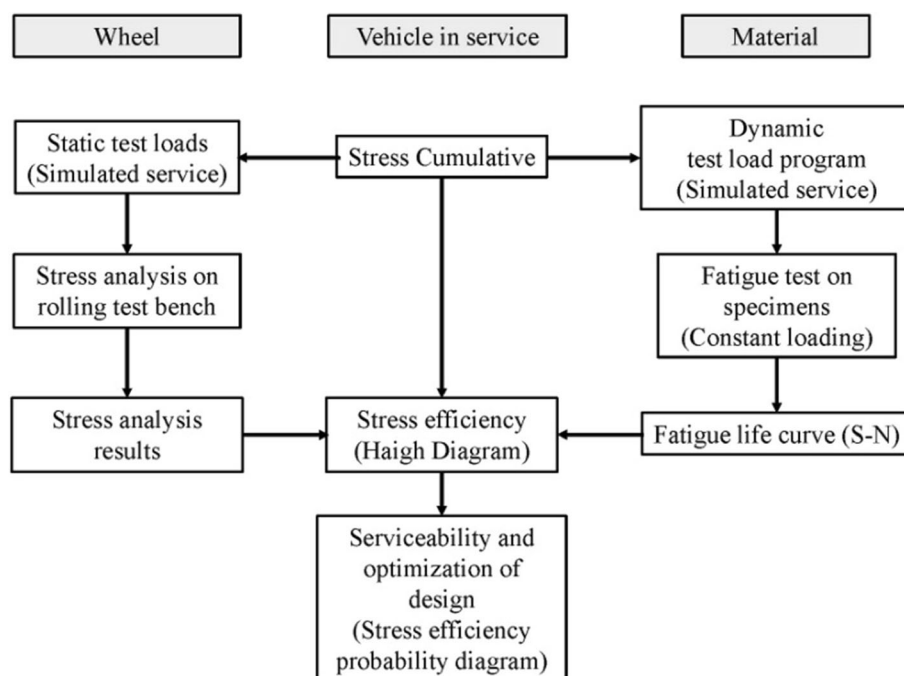
Most of the research explored different test setups to perform stress analysis to attain a good correlation using the material fatigue data. However, as the investigation progressed and new methodologies were being adapted to evaluate the performance of the steel wheels, new challenges were raised in terms of lack of material data for

different loading conditions and different materials used by wheel manufacturers and evolution of new techniques in tire manufacturing processes. In addition, radial tires were becoming popular, adding another parameter as the radial tires are stiffer and load the rim toward the flange. This further increased the stress at the disc area compared with the belted tires. Finally, it was acknowledged by the industry that a wheel testing standard is required to address the issues mentioned above.

The SAE J328 [2] for passenger cars and light truck steel wheels was introduced in 1968. Eventually, the test standards were updated considering the requirement for different wheel materials, vehicles for which they will be used, manufacturing processes, and acceleration test factors to be used, to consider different operating groups like original equipment manufacturers (OEM's) and Aftermarket segments. SAE J2530 specification was released in 2004 by the aftermarket group. These specifications also helped create the ISO 3006 and 3894 [1, 5, 6]. Meanwhile, JIS D 4103 was established in 1984, and it was revised as JIS D 4103: 1998 [7] with the incorporation of impact test procure. Therefore, the SAE J2530 was developed to determine the sample size for testing of wheels based on the wheel material type and minimum cycles to run to qualify in testing based on the Weibull statistical method. This process was adopted by manufacturers of aftermarket segments where it is preferred to test less number of wheel specimens for quick durability assessment.

Since the durability testing for wheels is consuming considerable time in the overall wheel development cycle and the cost associated with it, the requirement in

**Fig. 4** Outline of wheel testing by comparing results of stress analysis with material properties from service fatigue test on test bars[4]. Reprinted by permission from: Springer, SAE International, A Comprehensive Method for Wheel Testing by Stress Analysis, George Kraus, Copyright 1976



durability testing to perform wheel testing within minimal time and cost without compromising the reliability of the wheel life was identified. The SAE J 2562 [8] is designed for the biaxial testing method to simultaneously apply both the radial and lateral loads on the wheel using sophisticated equipment. This process is time-saving by eliminating two different tests and the number of specimens to qualify the wheel. Furthermore, the loads used in this method are real-time loads which are reduced based on the critical amplitudes and the occurrence to estimate the fatigue life of the wheel, thus minimizing the test time.

Now that a reliable standard for wheel testing procedure is in place, the next step is to have a valid material database. A lot of effort was spent developing the material data to estimate the fatigue life of the steel wheels and aluminum-alloy wheels. It was concluded from the series of experiments conducted to assess the nature of loading on the wheel that the cornering fatigue test has reversed bending load with stress ratio of  $R = -1$  and the radial fatigue test has  $R = 0.1$ , as the maximum load on the wheel was due to the inflation of tire on to the rim. The fatigue curves for most of the wheel materials were available for a fully reversed loading type from the existing literature. Thus, it became mandatory to develop a fatigue curve for  $R = 0.1$  to assess the fatigue life of wheels under radial loads. Some studies were performed to establish fatigue curves from the specimens extracted from the sections of aluminum alloy rims to take manufacturing effects into account [9, 10]. Also, a statistical analysis procedure was suggested for generating an S–N curve with a minimum number of specimens by using log-normal and Weibull distribution [11–14]. The research is followed by some observations that the fatigue strength for some materials will decrease with respect to the increase in the number of cycles after hitting the knee point. Therefore, to avoid failures of components subjected to loads below the bend of the S–N curve must be considered [15, 16].

When the fatigue testing methodology and service life validation standards were established, research was being carried out to explore the new materials with the same strength as steel with reduced weight [17]. The analysis was carried out where important criteria for the design of cast aluminum wheels were discussed. Cyclic stress–strain properties, crack behavior, and fatigue strength were studied to differentiate between steel and aluminum material characteristics. It was concluded that the weight reduction from steel to alloy wheels could be 35–40% [18]. The research was also performed in the “Service Strength Analysis methodology”, as shown in Fig. 5. This method allows determining areas critical to fatigue strength and the over-dimensioned regions, where weight and cost may be saved [19].

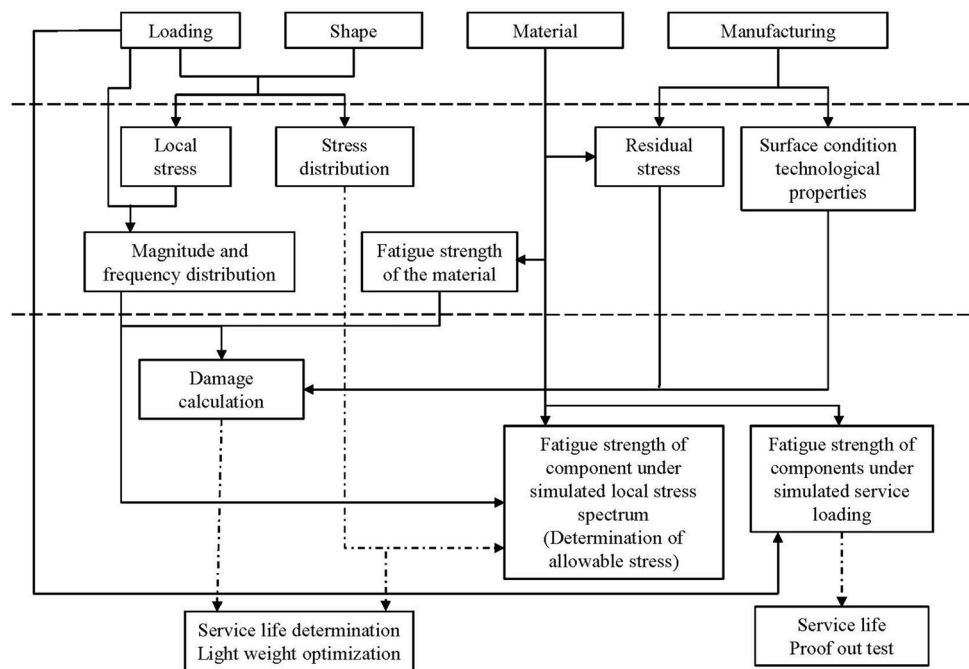
Most of the experiment work was performed between the 1970 and 1980s, where a lot of cost and time was also involved in conducting physical tests for generating material fatigue data for different loading conditions and finding out the components’ service life. Computers were introduced to process extensive data with high computational speeds due to emerging technology. In no time, the application of computers in the automotive field also increased. This helped in developing sophisticated workstations with huge memory, which are very critical in solving finite element models. New software were developed over time to support the research work in automotive fields with emerging modules capable of solving most of the engineering problems.

As sufficient data is available on the results obtained by simulating the radial fatigue, bending fatigue, and impact tests, it is observed that most of the research used the finite element results to compare with the components test data. Also, enough study is present in concluding the safety factor to be considered for correlating the experimental test results with the finite element results, as the experimental data include variations due to manufacturing processes and defects. This methodology holds well if the area of interest is only in finding the final life of the component. However, it does not provide any information about the actual stresses within the wheel. To optimize a wheel for particular loading conditions, it is necessary to predict the real stress components within the wheel. The methodology adopted was to perform an experimental stress analysis to extract the different stress components at a particular location using strain gauges. The data is then correlated with the finite element analysis to arrive at a factor. Since the stresses components are known at a particular location, optimization can be performed to reduce stresses at critical areas, and also material can be reduced where ever the stresses are far away from the failure criteria.

### Finite Element Analysis for Service Life Prediction of Wheel

As per the earlier studies conducted using experimental stress analysis, enough data is available to understand the nature of loading, stress, and strain distribution at some of the critical locations of the wheel. The challenge is to simulate the experimental conditions using finite element analysis and correlate the design parameters from experimental stress analysis results. This process is not straightforward, as the results from the finite element analysis do not capture the variations of the material in the wheel due to manufacturing defects and consider the material to be homogeneous and isotropic. Therefore, a good amount of research was performed to correlate both

**Fig. 5** Procedure for service strength analysis [19]. Reprinted by permission from: Springer, SAE International, Criteria and Methodology for Lightweight Design of Vehicle Components Subjected to Random Loads, Vatroslav Grubisic, Copyright 1985



the results. The variation in the analysis due to the incorporation of the tire in the radial fatigue test was also a challenge. A good number of experiments were conducted to determine tire directional stiffness and circumferential stiffness to eliminate the tire and apply forces onto the wheel directly. Reliable tire simulation techniques using finite element analysis were also proposed, which were used by many researchers to validate the wheel performance by impact test.

In 1976, the first attempt was made to perform a finite element analysis of a part of the wheel. Only the rim cross-section was modeled by a grid composed of elements of finite size, and the displacement of each element was calculated [20]. In the early 1980s, the finite element method was first introduced to simulate the automotive vehicle wheel for the cornering fatigue test. Structural analysis was performed, and optimization was further carried out for stamped steel and cast aluminum alloy wheels. Finite element modeling techniques were discussed, and the outcome was published [21]. Later, the rim impact test was simulated using finite element analysis. Since explicit solvers were not available at that time, a simple dynamic model was built with mass, spring, and dampers to represent a wheel system. Dynamic analysis was performed to estimate the force acting on the wheel as a function of time. Finally, the dynamic analysis's obtained force was applied on the wheel flange as a static case. It was concluded that the plastic work ductile fracture correlation could be utilized to predict the wheel impact test performance of an aluminum wheel [22]. Simulation of radial fatigue analysis using finite element analysis was first performed by

converting the radial load from the tire onto the rim as a cosine function force over an 80° arc of the circumference of the wheel [23]. The standard finite element analysis procedure followed by most researchers to simulate the durability tests is summarized in Fig. 6. The research was performed to validate the radial load from the tire onto the wheel using different experiential techniques, which will be discussed in detail in the upcoming sections.

Some studies state that the influence of adjacent components also varies the service life of the wheels. The behavior of mating components with the wheel was also studied to understand the assembly's overall behavior and impact on the wheel.

Service strength analysis was carried out to optimize the wheel hub and chassis for weight reduction [24–27]. The influence of wheel fasteners on the mating components like bolt holes, brake disks, and bearings was also discussed [28]. Fatigue strength of steering wheels made of AM50 magnesium alloy by die casting process was determined to investigate the effects of stress concentration and surface finishing [29]. A study to understand the nut loosening and failure of studs was carried out [30].

A special-purpose rig was developed for tire impact tests. Results for the experiment were compared with numerical data, and it was observed that the test rig developed was capable of accurately predicting the impact of a mass on the tire [31]. The experimental and the numerical service strength evaluation of cast, forged, and welded aluminum-alloy safety components were presented [32]. The investigations were carried out with specimens



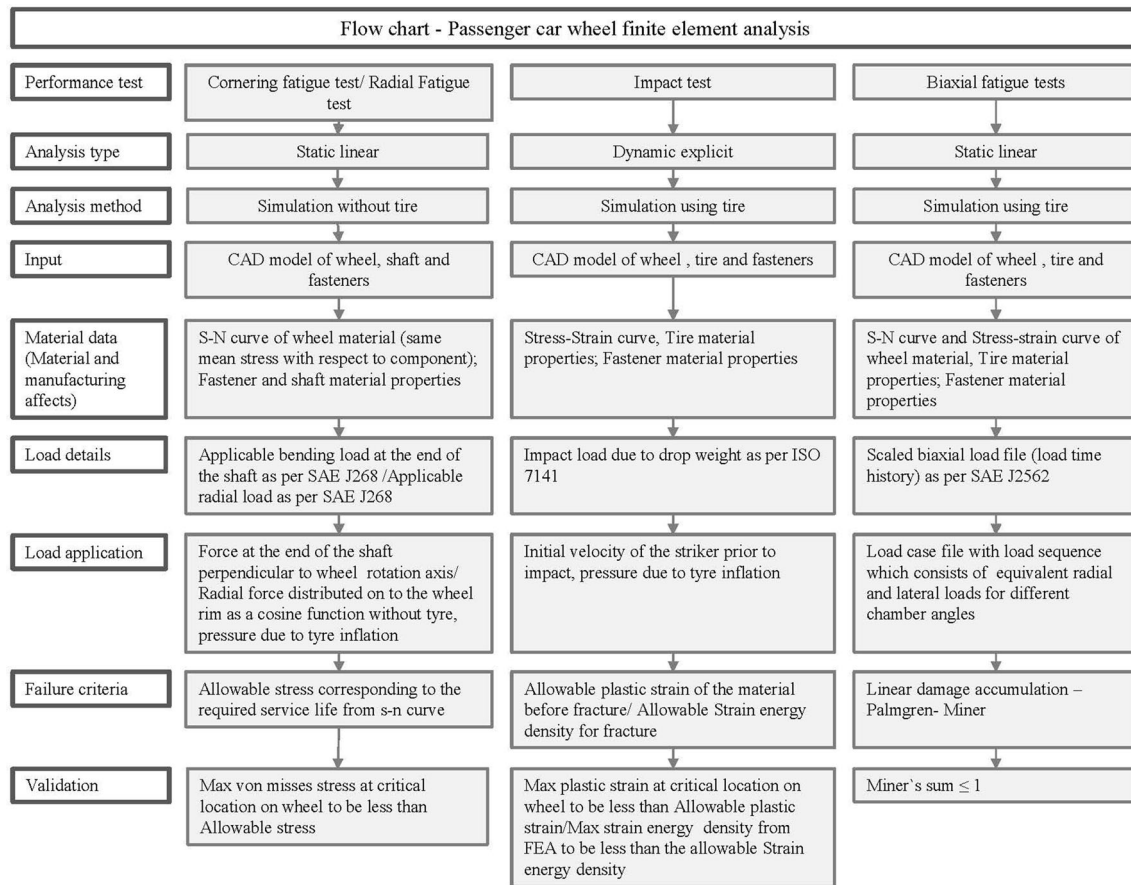


Fig. 6 Passenger car wheel performance test–finite element analysis procedure flow chart

extracted from the steering knuckle of the cast aluminum alloy EN AC-42000 T6 [33].

**Simulation Studies of Wheel**

**Radial Fatigue Tests**

The radial fatigue test is one of the critical and the first invented performance tests suggested to evaluate the wheel when subjected to radial loads while moving on straight roads. To qualify for this test, the wheel has to pass the test criteria as per SAE J328.

The radial load (N) to be applied to the wheel shall be determined as follows.

$$F = WK \tag{Eq 1}$$

$W$  = radial wheel load N;  $K$  = acceleration load factor.

Generally, two methods are followed for simulating the radial load, one using the wheel and tire assembly and another by applying the forces from the tire onto the wheel without using the tire in the simulation, as shown in Fig. 7. The quick method is to apply the forces extracted from the

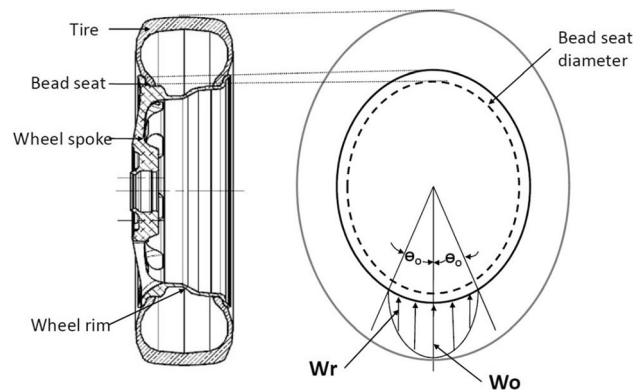


Fig. 7 Radial load distribution as cosine function

tire onto the wheel as this will be a simple linear static structural analysis. Whereas using the wheel and tire assembly will be more complex, the behavior of the tire is highly nonlinear due to its material characteristics. Even the contact between the tire and wheel is at the bead seat location, where the forces from the tire transmitted to wheels are also nonlinear. The whole assembly will be a complex nonlinear problem that will take a considerable

time to solve compared to a static case. In the case of optimization, this will become a bottleneck.

So researchers tried to solve this problem by performing some experiments wherein an experiment was conducted to find out the distribution of tire load on the bead seat of the wheel rim as shown in Fig. 7. Equation 2 Different loading approximation functions like cosine loading, Boussinesq, and Eye-bar were proposed and validated by measuring the deflection of the rim using strain gauges [34, 35]. It was observed that the loading shape is in the form of a cosine function about a central angle of approximately  $40^\circ$  from either side of the point of contact with the ground [23, 36–39] as per Fig. 8. Experiment results were also published to validate that the angle of radial load distribution is somewhere around  $20\text{--}40^\circ$ , which was in good agreement with the experiment results [40], as shown in Fig. 7. Investigations were performed to measure the normal contact stress between tire and rim contact location under static and dynamic operation conditions [41].

The distributed pressure,  $W_r$ , on the bead seat is given by expression

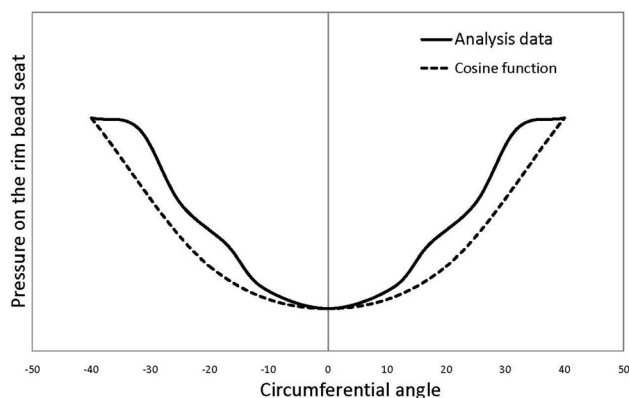
$$W_r = W_o \cos\left(\frac{\pi \theta}{2 \theta_o}\right) \quad (\text{Eq 2})$$

From the above equation, the total radial load  $W$  is calculated. The maximum radial load at point of contact,  $W_o$ , is given by:

$$W_o = \frac{W\pi}{br_b4\theta_o} \quad (\text{Eq 3})$$

where  $r_b$  is the radius of the bead seat, while  $b$  is its bead seat width,  $\theta$  is the loading angle, and  $\theta_o$  is the angle at maximum load.

Some more observations were made based on a rotating wheel's stress and resultant displacement response under the influence of radial load [42]. This methodology gives accurate results and reduces computational time drastically as performing analysis using tires is highly nonlinear. Most



**Fig. 8** Radial load distribution comparison

of the research work performed for radial fatigue test simulation using finite element analysis used this methodology to simplify the model [9, 43–48].

Concern was expressed that when the tire is eliminated from the finite element analysis, the stiffness due to the tire shall be considered to simulate the actual condition, considering only the force from the tire directly onto the rim may not be sufficient. So, research was performed to study the deformation of the tire when both radial and bending loads are applied individually and simultaneously. A special setup was used to conduct experiments by placing strain gauges inside the tire and wheel assembly to extract the forces experienced by the strain gauges. This method is beneficial to understand the distribution of load within the tire for different loading conditions throughout the performance cycle. The data are also helpful while designing new tires and wheel design [49–52]. To study the cornering force characteristics of radial tires during the design stage, a detailed finite element model of the radial tire was developed. The material characteristics of rubber were studied and published. The finite element results of the tire model were compared with the experimental results [53]. Some researchers also performed experiments to investigate the possibility of predicting the force–displacement characteristics of tires on a flat surface with enough accuracy so that it can be helpful for tire model parameterization [54].

While studies were being conducted for tire load distribution on the wheel, one more concern raised was the variation in the study's outcome due to the different tire types, sizes, and materials used for the experiment. To overcome this, different standard test results on the different tires under static conditions were tested and were used to determine tire directional stiffness and circumferential stiffness [52]. A bench test study was performed by finite element method as well as an experimental method to predict the wheel stresses due to straight driving conditions. Results were compared and concluded that the tire would have a considerable role in influencing wheel load distribution [45]. The research was also performed to evaluate the wheel's capability to withstand loads by using run-flat tires [55]. A software concept for the durability evaluation of wheels, hubs, and bearings under normal usage conditions was developed. Physical tire models were derived from the experimental results [56].

Once enough experimental data is available to map the force of the tire onto the wheel, various numeric analysis simulations of radial fatigue test for steel wheels were performed, and a computational methodology was proposed to predict fatigue life in correlation with the experimental results [57]. The investigation was further extended for fatigue evaluation of the air ventilation holes of a heavy vehicle [58]. The same technique was used to

simplify the finite element analysis methodology and perform variable thickness concepts for optimizing the steel wheel for its weight without affecting the primary functions such as fitment, airflow, and fatigue life. The stresses in the existing wheel design with uniform thickness were compared with the variable thickness design and documented conclusions [47]. A new method of the forged aluminum alloy wheel by updating the radius of the rim dimension is proposed. It was concluded that the stress values of the modified design were lower when compared with the existing design [33].

Studies were conducted to explore the new methodologies and feasible options to improve the performance of the wheels. Attempts were made to develop a forged hybrid wheel with a forged aluminum wheel base, and steel side rings to lock the tire, which can be used with the conventional tube tires eliminating the excess investment for the end user to adapt alloy wheels which are specially made to use with tubeless tires. It was observed that the required fatigue strength value matches with the FEA and ESA results [48]. A partitioned seam weld modeling method was proposed, and pressure distribution between tire and hub was summarized. It was concluded that the fatigue life of the wheel would reduce due to seam weld existence. Inhomogeneous material effects need to be considered to predict the fatigue life of the wheel rim due to seam weld [49]. Cracks propagation behavior of wheel materials with a pre-defined crack under bending moment conditions was analyzed using finite element analysis and published results [59]. A recent study on the inner rim compression behavior of wheels was investigated experimentally and numerically and also shows the existing fatigue damage detection and measurement techniques [60, 61]. A study was performed to summarize the analysis results of the wheels for air-tightness control in modern test facilities [62].

### Cornering Fatigue Tests

The cornering fatigue test is one of the critical performance tests suggested to evaluate the wheel when subjected to cornering loads. The wheel must pass the test criteria as per SAE J328 to qualify for the test.

The bending moment on the wheel due to rated wheel load is given by:

$$M = W(Ru + d)S \quad (\text{Eq 4})$$

$M$  = bending moment N·m;  $W$  = Rated wheel load by the wheel manufacturer N;  $R$  = static loaded radius m;  $u$  = coefficient of friction between the tire and the road;  $d$  = the inset or outset of the wheel m (use the positive sign for inset and negative sign for outset);  $S$  = load factor.

The simulation of the cornering fatigue test using finite elements is straightforward as a bending load to be applied

to the wheel through a shaft that is bolted to the wheel hub. The wheel is constrained at the flange of the rim as per the applicable standards. Proper care should be taken in applying constraints on the flange, as in actual test conditions. A fixture is used to hold the wheel at four equally distributed clamps circumferentially. Due to the clamp holding grips, local stress might develop at the holding location.

When the wheel bending tests setup was initially developed, a tire was also used for the simulation. The test setup used to be similar to that of a radial fatigue test bench, where the wheel's axis and tire assembly are tilted to an angle to develop a bending load on the wheel. However, due to the high load factor used during accelerated testing, the tire was damaged many times without progressing the test. Even special tires were developed to withstand the rated load but failed to perform. A new test setup was developed to mitigate this issue where the wheel and tire assembly were attached to a test rig, and the load was applied through a shaft bolted to the wheel hub. This method improved the tire life during the testing phase, but the wheel's clamping was not stiff enough to hold the wheel and tire assembly tightly. This caused various issues since the assembly had to withstand heavy loads rotating at higher revolutions per minute (rpm). Thus, finally, a method has been proposed where the tire is eliminated from the test, and only the wheel with the shaft bolted to the wheel hub. A test setup without a tire was developed, which provided a better solution in terms of accelerating the test with higher loads and also avoiding the variation in testing due to associated complexities by using the tire [1].

Using the developed test bench setup for the fatigue tests, research was published on the testing and evaluation techniques used to assess the suitability of a commercial vehicle wheel for its prescribed task. A study was conducted to show the distribution of failure, which was plotted from a group of failures. It was suggested that “any test whether legislative or manufacturers must have a statistical basis.” It was also concluded that “the attainment of optimal design requires a test specification that includes factors that reflect the intended service conditions” [63]. Also, to predict the stresses in individual wheel areas, experimental stress analyses were performed using strain gauges. The strains measured were converted into corresponding stress to validate the failure criteria. This is important, especially if the equivalent stress for a multi-axially stressed wheel area is sometimes compared with allowable stresses determined based on results obtained from uniaxially stressed test specimens [64].

Eventually, the research was extended to simulate cornering fatigue testing using finite element analysis, as shown in Fig. 6. A prototype computer-based program was developed to predict the fatigue life of wheels under



rotating bending tests by using linear finite element structural analysis [65]. The finite element analysis was performed for simulating the wheel subjected to bending loads, and the fatigue life of the wheel was determined using the S–N curves for a constant reversed loading condition [66]. Explicit analysis was carried out on a forged magnesium wheel model to simulate fatigue testing for bending loads. Fatigue failure has been verified by experimental tests [67]. A linear transient dynamic finite element analysis and a local strain approach method for simulating dynamic cornering fatigue testing of automotive steel wheels were proposed. Experimental stress analysis was performed on steel wheels using strain gauges to measure the strain due to the bending loads. The experimental and analytical results were compared, and percentage error was calculated [68].

Experiments were conducted to assess the fatigue life behavior of aluminum alloy A356—T6. Specimens were extracted from selected locations in the wheel. Stress–strain curves were generated and compared. The finite element method simulated the wheel’s constant amplitude rotational bending fatigue test. The results from the finite element model were compared with that of the strain data from experimental data at the selected location [69].

The application of finite element analysis was also extended to determine the effect of manufacturing defects on the wheel performance. The effect of defects such as shrinkages and porosity on fatigue life of the A356-T6 wheel and die-cast magnesium was also studied by performing microfractographic analysis on the fractured wheels [70]. Finite element analysis was carried out and compared with experimental results, and it was concluded that crack was always initiated from the shrinkage and porosity zones [71]. A predictive model was proposed which is useful to predict applied stress, by studying effects of casting defects by performing rotary bending fatigue test for A356.2-T6 material specimens extracted from wheel [72]. Biaxial load notch strain approximation to evaluate the fatigue life of passenger car wheel during cornering fatigue test was introduced using fracture mechanics concepts. Life predictions of wheels were performed, and results were compared for two different wheels of the same designs. The elastoplastic strain components were calculated analytically using the total deformation theory of plasticity [73].

As the research progresses, new methodologies using advanced technologies were suggested to predict the fatigue life of passenger car wheels accurately. A test setup was developed to perform cornering fatigue testing of passenger car wheels. This test setup was developed in such a way that different components of the wheel assembly can be tested [74]. Using subsystem interactions between two or more parts, studies were performed to

simulate the wheel. The advantages of using this methodology were explained, and it concluded that this methodology helps in understanding the design requirements correctly [75]. Studies were performed to understand the effect of multi-step stamping process of spokes using finite element analysis [76]. Cornering fatigue tests were conducted on the specimens to study the effect of different parameters like thickness variation due to forming operation, pre-strain, cyclic elastic-plasticity, and mean stress due to residual stress. The methodology was documented to explain a practical alternative approach for predicting the cornering fatigue life of steel wheels with laboratory-level specimen tests. The fatigue properties evaluated from the uniaxially pre-strained specimens were found to be significantly affecting the prediction of fatigue life of steel wheels without performing the actual tests [77–80].

Cornering fatigue tests for steel wheels were performed to evaluate multi-axial fatigue life. From prototype testing, it was observed that the stress states of the wheel are biaxial tensile and normal compression stresses. It was concluded that the principal plane is changing with respect to the loading direction, and suitable damage criteria were suggested to predict the crack initiation location with respect to the actual tests [81–83]. A method was proposed to accelerate the dynamic cornering fatigue test of wheels. A comparison was made between the stress levels for regular and accelerated tests, which were recorded using a strain gauge. It was concluded that there is a decrease in 18% test duration by the adoption of this methodology, and this methodology is validated by comparing the stresses at critical locations of the wheel [84]. A feasibility study was performed to evaluate the fatigue life of wheels by comparing the design for five different materials. It was concluded that by considering fatigue strength, aluminum alloy and carbon fiber-reinforced plastic (CFRP) are comparatively close to each other, but CFRP is almost 40% lighter than aluminum [85].

A recent study on steel wheel rims was conducted to evaluate the service life under severe cornering loads. Finite element results were compared with the experimental strain analysis data and found to be in good agreement with respect to failure location and life. Design changes were proposed to the existing design to meet the expected service life [86]. Fatigue performance of ferrite–martensite (FM) and ferrite–bainite (FB) dual-phase (DP) steels used in automotive wheels has been compared in terms for high-cycle and low-cycle fatigue performance [87].

### Impact Analysis

The impact test is one of the critical performance tests suggested to evaluate the impact damage on a wheel when

the wheel hits a curb. As described by the impact testing procedure ISO 7141 [3] or SAE J175 [88], wheel impact testing establishes minimum mechanical requirements and evaluates wheels' lateral curb impact collision characteristics. In-wheel impact testing, a wheel with its tire is mounted to a stationary fixture inclined at 13° to the horizontal. A striker with mass related to the static load imposed during normal operations is freely dropped from a height of  $230 \pm 2$  mm on the uppermost rim flange of the wheel.

The striker mass,  $m$ , is expressed in kilograms

$$m = 0.6W + 180 \quad (\text{Eq 5})$$

where  $W$  is the maximum static wheel load in kilograms.

A good number of studies were carried out for simulation of the wheel for cornering and radial loads, but the impact analysis was not much explored due to its high nonlinearity behaviors due to the involvement of tires. As impact test is a dynamic problem and needs to be solved using explicit solvers, much computational speed is required to get the solution converged. At first, a model was analyzed under static loads to provide an effective spring constant for the dynamic analysis. In the second phase, dynamic analysis was performed to produce the forces acting on the wheel as a function of time. The third step was to apply the peak force determined to the wheel finite element model and calculate the stress and distribution of the energy distribution in the wheel due to maximum force. It was concluded that the plastic work ductile fracture correlation could be utilized to predict the wheel impact test performance of an aluminum wheel [89].

While simulating impact tests using finite element analysis, a lot of computation effort goes into solving the problem using tires due to their highly nonlinear behavior. It was suggested that suitable numerical simulations of wheel impact testing are essential in wheel development, shortening design time, reducing wheel mass, and enhancing engineering performances [22]. In an effort to simplify the numerical modeling of wheel impact testing, a study was conducted to study the percentage of the kinetic energy of the striker absorbed by the tire during the impact test. Comparing wheel plastic deformations for both experimental and numerical methods demonstrates that a 20% reduction in the striker kinetic energy effectively simplifies the modeling [90]. Another study performed on an aluminum alloy wheel and its tire concludes that the concept of total plastic work of ductile fracture mechanics can predict wheel failure [91].

The importance of performing dynamic impact simulation of aluminum alloy wheels using tires was discussed in detail. In many cases, dynamic impact analysis was performed without using tire to simplify the analysis due to its complexity in modeling and high material nonlinearity. In

actual conditions, the tire not only absorbs a fraction of the kinetic energy of the striker but is also involved in the change in the dynamic loading condition on the spoke. This leads to inaccuracy of simulation results if the tire was eliminated from the dynamic impact analysis, and these considerations are not taken into account. A numeric simulation approach was proposed to evaluate the impact performance of the wheel using a composite tire model. The outcome of the study shows that the tire has a dual effect on the wheel performance during the wheel 13-degree impact tests [92]. A similar analysis was performed for a 90-degree impact test to validate the safety and reliability of automobile steel wheels that experience harsh loads during driving due to road pits, using a composite tire model [93].

A study was performed by developing a nonlinear material model of an aluminum alloy wheel with its tire. Simulations were conducted to study the performance of the wheel during impact. It was observed from the analysis that the tire simulation is in good agreement with the experimental predictions, which is performing well in transmitting the impact loads to the wheel [94–96].

The studies were further extended by performing an experiment using strain gauges at different locations of the wheel to correlate with the finite element analysis performed [97]. An attempt was made to replace the dynamic explicit analysis with static structural analysis by increasing the striker load. It was observed that the distribution patterns of both the strain energy density and the equivalent plastic strain are similar to those with the dynamic simulation. Validation was performed by comparing the strains of finite element analysis with that of the measured values using strain gauges, and the difference between the measured and estimated maximum principal strain is about 10.64% [98].

As most of the studies were classified as impact analysis with and without a tire, a study was performed by simulating the impact test of the aluminum alloy wheel with tire and without a tire. Conclusions from this study state that the maximum von-mises stress at the critical location for analysis with the tire is 5 MPa less than that of the analysis performed without the tire. This is attributed to the fact that the tire absorbs the impact energy from the striker, resulting in less impact energy transferring to the wheel [99].

In most of the research works performed, the failure locations and the strain values for both the analytical results and experimental results were observed to be the same with negligible deviation. Since the finite element analysis results were obtained by considering the material to be homogenous, which is not the case in actual conditions due to the variation in the manufacturing processes, two different wheel designs were studied by comparing the

results obtained from finite element analysis and experimental data. It was observed that for both the designs, the failure locations are in good agreement with the experimental results. It was also stressed that the computational time of the model highly depends on the complexity of the geometry used for the validation [100].

While the computational speeds were improved as high-end workstations evolved with more core processors and large random-access memory (RAM) sizes, it became feasible to run the explicit analysis of an alloy wheel rim with the tire in a reasonable time frame, as shown in Fig. 6. The research was also extended by replacing the steel wheel with aluminum alloy and magnesium alloy wheels. Optimization was performed based on dynamic bending and radial fatigue tests, and an assembled wheel with a magnesium alloy rim and an aluminum alloy disc was designed. Finite element analysis of 13–90° impact test was performed for the optimized model for the effective strains. It was concluded that the weight of the optimized wheel is 28.59% less than that of the cast aluminum alloy [101]. A magnesium wheel was manufactured and tested in another study based on the analysis output. Based on the structural design and topology optimization theory, a suitable design to improve the vibration performance of the wheel was suggested. The dynamic impact analysis was performed for the optimized wheel, and the dynamic speed response of the magnesium alloy wheel was obtained. The weight of the optimized magnesium alloy wheel was found to be 13.9% less than the aluminum alloy rim of the same design [102].

To understand the advantages of using magnesium over aluminum and steel, studies were conducted to compare the bending and buckling characteristics of the three materials. It was concluded that the energy absorption capacity of magnesium is 50% more than aluminum and over ten times more than mild steel. It is also concluded that the magnesium alloy can withstand considerably more energy than steel of equal weight. Force–deflection curves for different materials were compared and presented [103]. Based on the above conclusion, it is evident that magnesium alloy wheels have better impact strength than other wheel materials. Some studies compare the impact and modal analysis simulation for different alloy wheel compositions [104].

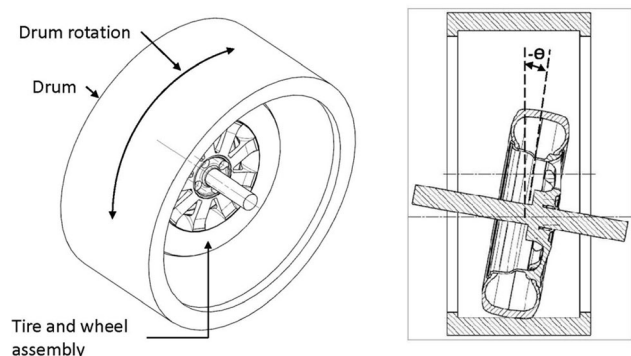
Recent developments in the wheel impact test were a 90-degree impact test for different wheel designs and comparing the final plastic deformation with the finite element results for correlation [105]. Some studies were also performed to understand the behavior of a passenger car tire alone without the wheel under the impact. The forces and deformations generated were analyzed for their structural response [106]. Similar research was performed to extract material properties from a conventional

aluminum wheel through a reverse engineering process to validate the complete component's behavior in a crash simulation [107].

### Biaxial Fatigue Test

Different standards are available to evaluate the service life of wheels for passenger cars. These tests were validated and used for most passenger cars and commercial vehicles by both the wheel and vehicle manufacturers for a long time. As the current wheels in operation are validated through these standards, It is evident that the standards were well established based on the overall wheel service life requirement. The industry's confidence in these testing methods cannot be challenged. However, it is to be noted that the testing loads that the standards are using are not real-time loads. The amplitudes of the loads that the wheel experience in the life span may be higher than that of the conventional test loads, but the frequency of the occurrence of the peak loads may be very limited. The wheel may experience peak amplitudes only due to unexpected loads like hitting a pothole, road divider, or an accident. These load amplitudes are also very unpredictable in nature. Designing a wheel to withstand these loads might not be achievable in terms of the actual requirement of light-weight wheels that the wheel industry is interested in. So a new standard SAE J2562 was developed covering the biaxial testing methods, where vehicle radial and lateral loads are applied together in pairs, which are derived from the actual vehicle loads found during the durability testing. The pairs are then reduced to the critical fatigue damage, and the test is then accelerated [64, 108].

A biaxial wheel test machine was first introduced for testing truck wheels. The test setup consists of a chamber and wheel positioned inside the chamber with a tire mounted. It is similar to the radial fatigue test setup where the wheel with tire rotates on a large radius drum, whereas the biaxial wheel test machine rotates inside the large cylinder. This test setup can simultaneously load the wheel



**Fig. 9** Biaxial fatigue test setup block diagram

in vertical and lateral directions, as shown in Fig. 9 [64]. Thus, any combination of vertical, lateral, and longitudinal wheel forces in service can be simulated. In addition, the facility is program-controlled, which allows the reproduction of load spectra of typical vehicle tests. The full test course is approximately 20,000 km, which takes 12 days to complete the test [14].

SAE J2562 comprises scalable test load spectra whose maximum test loads are projected to be within the envelope of those experienced in vehicle service. The load uses the concept of accelerated testing where high cycle, low fatigue damage events are replaced with fewer cycles at higher fatigue damage. It was assumed that the net effect of the test time acceleration does not introduce fracture modes that will not be seen in vehicle service. This study carried out tests on several wheel models and more than a hundred wheel specimens. All of the wheels were tested to fracture. At the same time, some wheel designs have proven unusable in-ground vehicle tests. However, the remaining wheel designs have sufficient fatigue strength to sustain the intended service for the vehicle’s life. Using empirical data with industry-accepted statistics, it is possible to predict a minimum requirement, below which a wheel design will likely have samples unserviceable in its intended service [109].

Studies were carried out to validate the theoretical fatigue life calculations by means of the local strain approach, as shown in Fig. 10. A test facility to simulate the actual service loads was used, and tests were performed for variable amplitude biaxial loading. Strain data at critical locations were recorded under these loading conditions

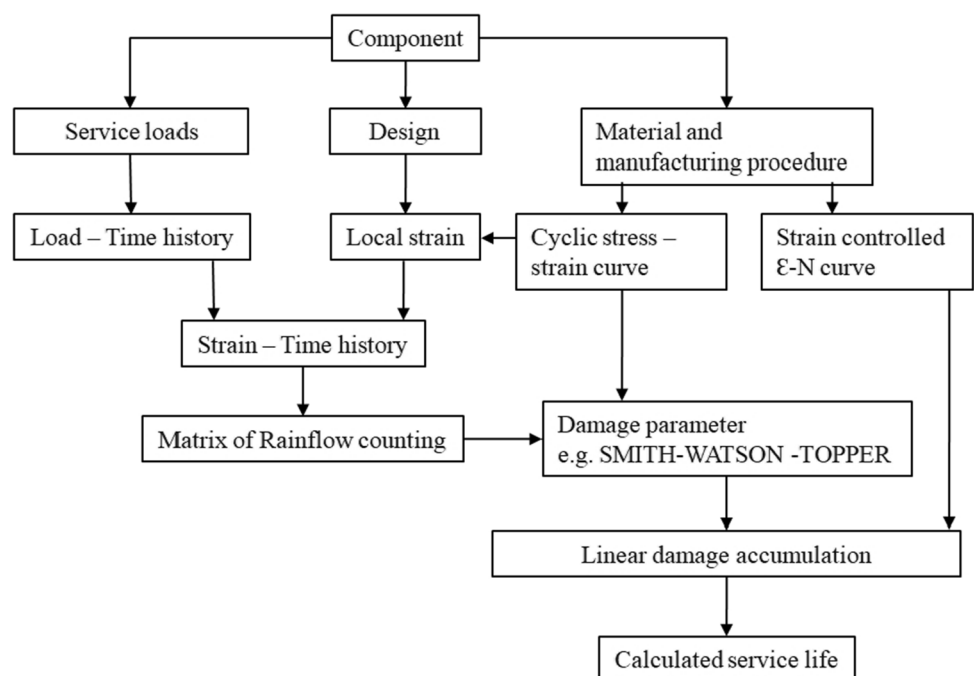
and compared with the theoretical fatigue life prediction data. It was concluded that the Miner’s sum of 0.5 was to be used to predict the initial crack with sufficient accuracy [110].

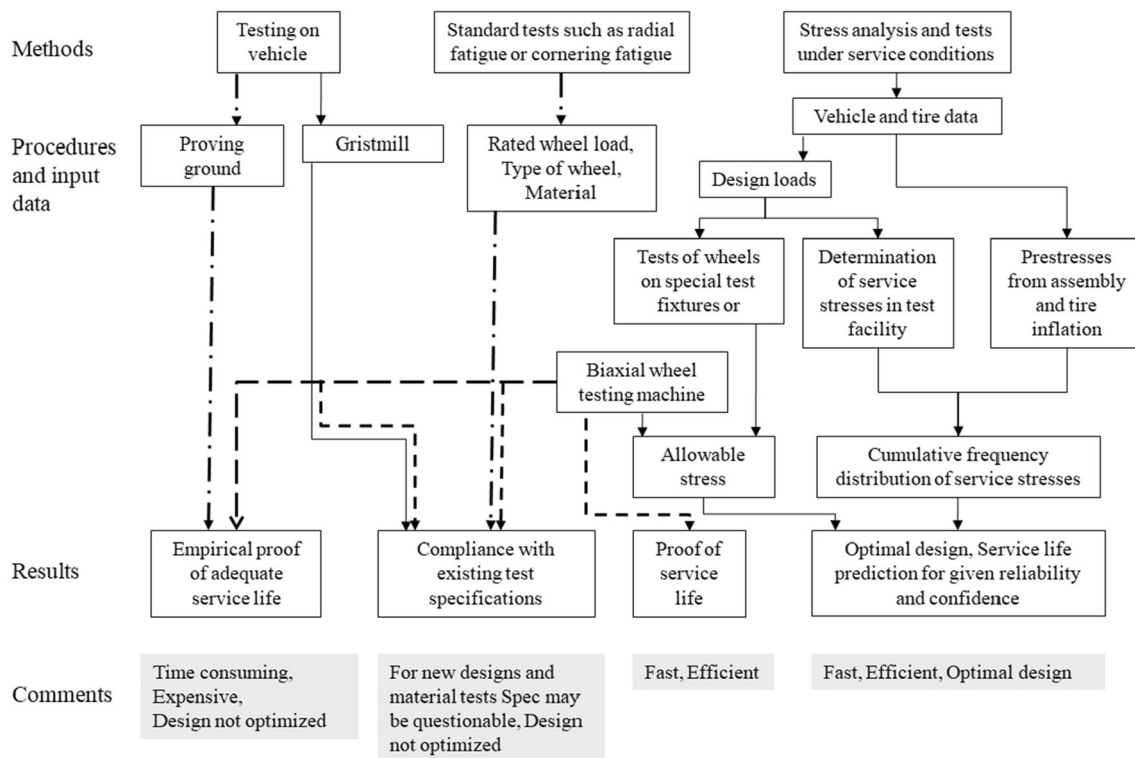
The requirement of using real-time loads for different road conditions of the wheel was identified. Studies were performed to predict the real-time loads by using sensors like wheel force transducers which can measure the real-time loads. The procedure is also defined on how to extract the biaxial loads from the real-time load data and procedure for wheel testing and development as shown in Fig. 11 [64, 111–116]. The methodology was proposed to design accelerated durability schedules that obtain less expensive and fast durability validation procedures and be reliable and fitted to the market and durability targets [117].

As the process of extracting biaxial loads from the real-time data is streamlined, a methodology was developed to perform static analysis with selected load cases from the biaxial load file from EUWAES3.23 [118]. Fifty-three load case file, which contains different lateral loads, radial loads, and chamber angles, were identified to evaluate the durability of the wheels. Finally, the durability of the wheel was calculated using Miner’s sum. It was concluded that the performance requirement of the steel wheel was met for the cornering fatigue test and radial fatigue test when uniaxial loads were applied. The same wheel could not meet the performance requirement for biaxial loads [119].

A new approach for simulation of biaxial wheel fatigue test is proposed for the alloy wheels of passenger cars. Different scenarios are discussed to model the test using a

**Fig. 10** Life prediction based on local strain concept [110]. Reprinted by permission from: Springer, SAE International, Possibility to Determine Aluminum Wheels Fatigue Life by Local Strain Concept, Vatroslav Grubisic, Copyright 1988

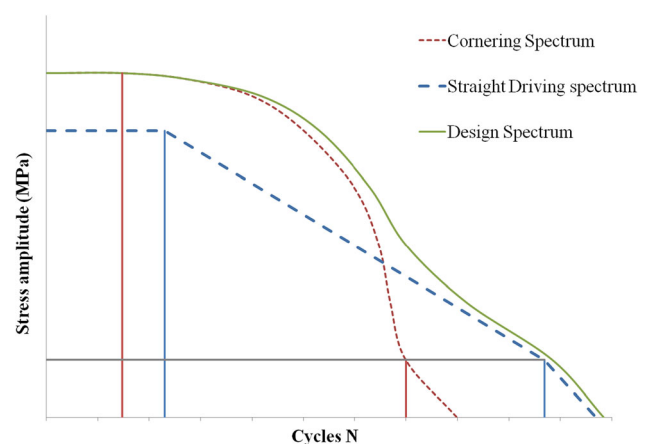




**Fig. 11** Methods for wheel development and testing [64]. Reprinted by permission from: Springer, SAE International, Automotive Wheels, Method and Procedure for Optimal Design and Testing, Vatroslav Grubisic, Copyright 1983

wheel, tire, and inner assembly to simulate the biaxial fatigue test compared to the application in real time. A multi-body finite element model of a test bench in which the tire was experiencing a non-trivial load cycle in an unusual road shape was developed. An experiment was performed, and the results were compared with that of the above-said approach. A good correlation was achieved between analytical and experimental results [120]. A similar study is also conducted to simulate the effects of shrinkage cavity and secondary dendrite arm spacing (SDAS) when biaxial loads are used [121]. A recent study shows that in-wheel switch reluctance motor (SRM) for the electrical vehicles (EVs) was examined for the increased unsprung mass, and it was concluded that suspension of a small car with the motor fitted inside the wheel was completely safe [122].

Another methodology was suggested where studies were conducted by simulating biaxial fatigue test applying both cornering and radial loads simultaneously, and results were used to calculate the fatigue strength of the wheel. Different loading spectra are combined to form design spectra based on the service loads, as shown in Fig. 12. Finite element analysis was carried out by applying loads as per the biaxial load file, which contains the real-time loads using a program. Mean stress from the cornering and radial fatigue tests at critical locations was compared with the



**Fig. 12** Stress spectra for straight and cornering driving conditions [123]. Reprinted by permission from: ELSEVIER LTD, International Journal of Fatigue, Required Fatigue Strength (RFS) for evaluating of spectrum loaded components by the example of cast-aluminum passenger car wheels, European Structural Integrity Society, Copyright 1979

required fatigue strength (RFS) of a biaxial load test. RFS value is calculated from Goodman's equation. It is observed that the biaxial fatigue test is more stringent when compared to the individual cornering and radial fatigue tests for its durability and lifecycles [47, 123]. To design and verify the operative durability test, recently a new



approach was suggested by combined loading conditions based on the concept of fatigue damage spectrum [124].

### Optimization Techniques for Wheel

The wheel is a safety component subjected to random fatigue loads during its operation. The fatigue life of the wheel mainly depends on the loading conditions, the complexity of geometry, material properties, and its manufacturing process. Therefore, for optimizing a wheel, necessary care should be taken as the design of the wheel is based on its service life requirement. By considering this requirement, wheel optimization can be performed to produce a wheel with lightweight, high strength at an optimal cost to achieve a reliable outcome.

In the early 1980s, experiments were conducted to understand the stress distribution within the wheel. It is emphasized that “If the realistic wheel stresses as measured in the laboratory can be bought in relation to the frequency of occurrence in service, the basis for a method for optimal dimensioning” also, optimization of a newly designed wheel requires knowledge of the loads the wheel will be subjected to, including their frequency of occurrence throughout the expected life, as well as the allowable stresses including manufacturing and other pre-stresses. A laboratory test method was published to find out the services stresses at the critical locations by simulating the service loads [64, 125]. The methodology includes service load stress analysis, derivation of stress spectra, strength evaluation, and simulated service load testing. This method allows you to determine critical areas for fatigue resistance and oversized areas where weight and cost can be saved. It was suggested that statistical prediction methods must also be used to conclude the products’ expected service life and reliability. Another critical factor was the overload that the wheel would experience due to unexpected situations. Safety was largely determined by the component’s ability to cope with unexpected overloads without catastrophic failures. Thus, aside from the basic design of the part, material properties under extreme loading conditions are very important [19].

It is understood from the above research that the following points need to be taken care of while optimizing wheels.

- (1) To meet the expected service life
- (2) To withstand overloads due to catastrophic failures
- (3) Reliability of the wheel

A general article to evaluate and compare established numerical methods of structural topology optimization that have reached the stage of application in industrial software

has been published to understand the established methods of structural topology optimization [126, 127].

Since steel wheels occupy a considerable market share due to their relatively low price, high fatigue strength, and high impact strength, authors focused on optimizing the steel wheel rim to enhance its performance further. A variable thickness concept for optimizing the steel wheel is for its weight without affecting the primary functions such as fitment, airflow, and fatigue life was suggested. It was concluded that the weight of the optimized design was 15–20% less when compared with the existing design, and FEA using the road load and tire model closely predicts the experiment’s results [47]. A novel steel wheel design method was presented based on multi-objective topology optimization. Improved dynamic frequency characteristics and lightweight effect are achieved in the topology optimization design [128].

An equal strength design of steel rim to optimize and reduce the weight of the wheel rim was also proposed. The asymmetric analysis was performed to predict the calculated stress distribution on the cross-section of the rim. The fatigue life was evaluated under different loading conditions for the dynamic cornering fatigue test and dynamic radial fatigue test. Best thickness was proposed based on the optimization performed. It was concluded that the optimized steel wheel met the design requirement, and the weight of the wheel rim was reduced [129, 130]. Also, some studies were performed on the basic truck steel wheel structure design. Design modifications such as vent hole location and profile modifications were proposed to solve the common fatigue failure problems. Research has shown that optimizing the shape of the wheel profile, increasing volume by 2.4% can extend both the bending fatigue life and the radial fatigue life by 73.8 and 289%, respectively [131].

Optimizing the wheel for its weight and service life is a concern, and the effect of the design changes of the wheel on other mating parts is also a challenging task. Studies were performed to understand these effects, and suitable solutions were suggested. An innovative design was demonstrated to overcome the commercial vehicle wheel overheating problem as overheating may cause premature tire wear, air valve heat damage and air leak issues, frequent puncture problems, and failure of other mating components. A disc gutter wheel was developed and tested for its functionality and serviceability. It is concluded that the new wheel design performs a cooler service by around 10–20% on an average [132]. Some studies were also conducted to study the influence of wheel structure design and optimization on the aerodynamic drag of cars and the heat transfer performance of brake discs [133].

In due course of time, different commercial software’s are available different optimization techniques which can

build the parametric model from other CAD environments which accelerated the overall optimization process time as shown in Fig. 13. A parametric design and optimization technique were developed for both the dynamic cornering fatigue test and the Impact test. In addition, the effect of the wheel parameters on the principal stress based on minimizing the weight was explained. This process of parametric optimization provides an optima wheel design in terms of weight and performance [134, 135].

Some research also suggested topology optimization for the aluminum alloy wheel to optimize the material distribution in the given space with fatigue stresses to ensure the life of the components. Different road conditions were considered for estimating the fatigue life using damage calculations [136]. Topology optimization was also performed on the alloy wheel using static loads, and results were compared for three different materials such as aluminum alloy, magnesium alloy, and steel as shown in Fig. 13. It was concluded that the wheel design with magnesium alloy weighs 35.1% less when compared with aluminum alloy material for the same design. The finite element model was verified by comparing the modal analysis results with the test data [137].

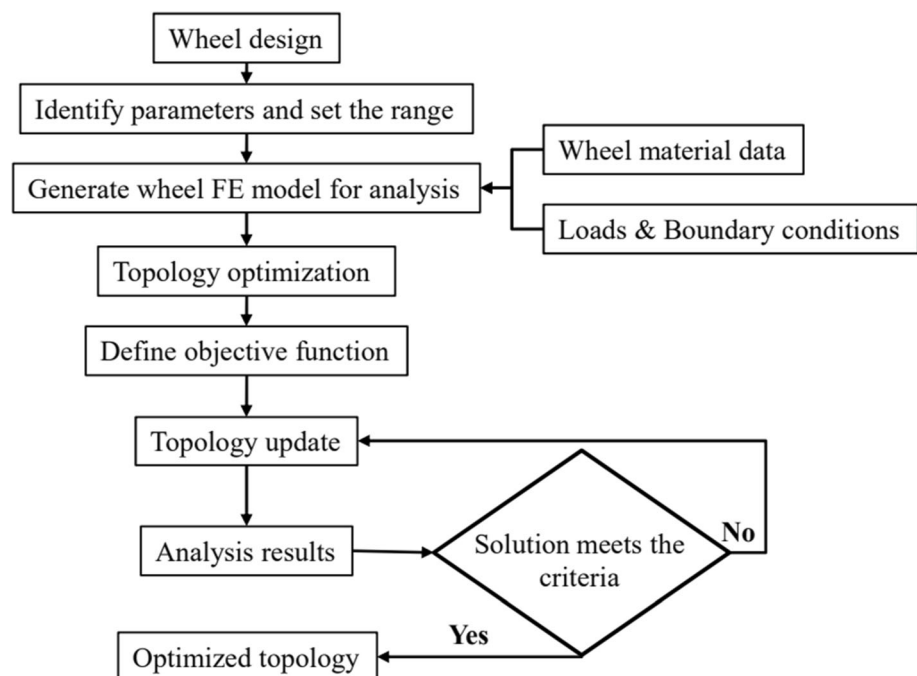
A recent study has published the results of hybrid wheels made of 6061 aluminum alloy wheel spoke and ZK61M magnesium alloy wheel rim using a bolted connection. The bending fatigue simulation of the bolted wheel assembly was established and compared with the experimental results. In addition, the parametric simulation model of the assembly was established, and multi-objective optimization was performed. Optimization results show

that the fatigue life of the spoke and the connecting bolts shows an excellent correlation to the simulation results [138].

Since the research is evolving in exploring new materials, processes, and different techniques in wheel development, the finite element simulation is getting more complex by adopting new methods. Some researchers suggested simplifying the optimization by performing topology optimization at the initial stage by applying proper constraints to get the optimized geometry within the design space. The outcome was then used further for shape optimization to fine-tune the wheel dimensions. It was also suggested to perform multi-objective optimization for dynamic bending and radial loads to get the required output. Based on the candidate point's outcome, the impact analysis was to be performed to validate the wheel for impact loads. This process can reduce the optimization time to a great extent as the run time to solve each iteration for impact loading using explicit solvers is very high compared to static cases for bending and radial loads. Finally, the strains from the analysis were compared with that of the test results to validate the model's credibility. A similar process was adapted for both aluminum alloy and magnesium alloy wheels [101, 102].

It is of great importance that the optimization outcome depends on the constraints provided and the output requested. The optimization outcome may not be feasible if the problem is not defined clearly. Good knowledge about the component, its function, and the manufacturing process is required to validate any optimization outcomes. It should also be noted that some of the highly complex design

**Fig. 13** Wheel topology optimization flow chart



concepts may not be feasible to the current manufacturing processes, but a suitable new manufacturing concept can be evolved based on the new requirements [139].

### Application of Different Material Types and Manufacturing Processes

Based on the requirement of producing a wheel with high performance, less weight, and cost-efficient, different materials were explored, and different manufacturing processes were established. The materials fatigue characteristics of the wheel may vary drastically with respect to the manufacturing process adapted. Good numbers of publications are available, which describe various materials used to produce a reliable wheel to meet the required service life. Various publications were studied to summarize the different material and manufacturing techniques adapted.

A solid forging manufacturing process for aluminum disc wheels was suggested, which has realized wheel weight reduction of about 30% [140]. Studies performed concluded that a two-piece wheel rim is proposed over a five-piece wheel rim to reduce the von Mises stress by 56.4% [141]. Static structural analysis work was carried out by considering four different aluminum alloys, namely 6061 and 6066. Their relative performances have been observed, respectively, in terms of strength and weight [142]. The advantages of using magnesium alloy for wheel manufacturing in terms of weight and damping were explained. A magnesium wheel was manufactured and tested based on the analysis output [101, 102, 137].

By the combination of casting and forging processes, an innovative technique called hybrid aluminum forging (HAF) has been developed. The wheel realized with the new  $AlSi_3Cr$  alloy shows significant strength comparable to that of forged wheels [143]. The recent research in the development of forged magnesium road wheels was reviewed. Methods of flow-forming, spin forging of manufacturing a forged magnesium alloy wheel were introduced, and fatigue characteristics were studied [144]. The impact testing, radial fatigue testing, and bending fatigue testing results show that AZ80 + wheel can meet application requirements in the automobile industry [145, 146]. A recent study studied the effects of aging treatments on low-cycle fatigue behavior of extruded AZ80 for automobile wheel disks, and observations were documented [147].

The authors conducted metallurgical studies on various defects and their probable root causes. Metallographic and advanced characterization techniques have been used to analyze the defects' root cause [148]. A prediction method considering shrinkage cavity, secondary dendrite arm

spacing (SDAS), and mean stress level of cast aluminum alloy materials was proposed [149–151]. Studies were also conducted on the failure types in wheel rims, where the wheel rim thins down locally and cracks at the weld [152]. The decisive parameters like operation loads and fatigue properties, which depend on the material, manufacturing technology, and design, were discussed. The procedure for an optimum lightweight design was suggested. A test procedure was suggested for reliable and cost-saving validation of new designs, materials, and manufacturing technologies [153].

A new methodology was developed based on high-pressure resin transfer molding (HP-RTM) to produce full carbon-reinforced plastic rims for sports cars [154]. In addition, an investigation was performed on the simulation method of the bending fatigue test considering the anisotropic property of the long glass fiber-reinforced thermoplastic composite (LGFT) [155, 156].

Studies were also conducted to use carbon fiber-reinforced epoxy resin (CFRP), which has excellent specific strength and specific stiffness compared to aluminum's properties. It was concluded that the stiffness at the reinforced location has increased by 25% with an additional weight of 200 g. This technology can be further extended for various vehicle parts to improve its performance [157]. A methodology was suggested to develop a full carbon wheel for sports cars with high-volume technology [158]. The main aluminum applications as state of the art in European cars were presented. The primarily established aluminum alloys and their application in automotive parts were presented with recent developments [159, 160].

### Reliability Study for Wheel

As studies show the validation of the wheel using different performance testing for its service life using service strength analysis, it should be noted that the strength analysis should always be supported with a valid statistical approach of the probability of failure. As we are aware of the fact that the performance of the wheel may vary to one other due to the variations in material and manufacturing process, these variations include inherent defects like porosity, shrinkage, variation in surface roughness, variation density, and also variation in dimensions due to machining parameters. It is to be noted that the test result for any two wheels produced using the same process will not be the same and may scatter based on the deviations in the processes by which the wheels are produced. Therefore, the probability of failure of a component is determined by the scatter distributions of service stress. These scatters of service stresses can be controlled through improved manufacturing uniformity and quality. It should also be

emphasized that the tests must be statistically evaluated and controlled to assure that the service life estimates are realistic [19]. So, a statistical approach needs to be adapted, by which the number of wheel specimens required to test can be assessed to ensure that the wheel will not fail during the service life for which it is designed. A study was also conducted to link the prediction using simulation results with historical test data [161]. For wheel testing using a minimum number of samples, a suitable sample size was determined based on the Weibull statistical methods, and SAE J2530 was established. The sample size and minimum cycles requirement with respect to load factor ( $S$ ) is represented in a graph as shown in Fig. 14 [1].

Studies were performed by testing two different sets of the same wheel design. Results were plotted graphically for the distribution of failures for a particular load for both the test results. Different cases were explained, where the minimum performance of the wheel differs for the wheel and the vehicle manufacturer based on the test results for different samples. It was concluded that any legislative or manufacturer test must have a statistical basis to have greater confidence that the wheel will not fail for the required service life [63].

An algorithm was developed by incorporation of reliability theory into a fatigue analysis. This probabilistic approach allows designers to differentiate the difference in the performance of the wheels of the same design due to the variations in material properties, geometry, and a load of engineered components. Such information would serve to improve the speed and accuracy of current design techniques [162].

## Summary

It is evident from the reviewed literature that the researchers showed much interest by contributing to the design and testing of wheels through experiments and finite

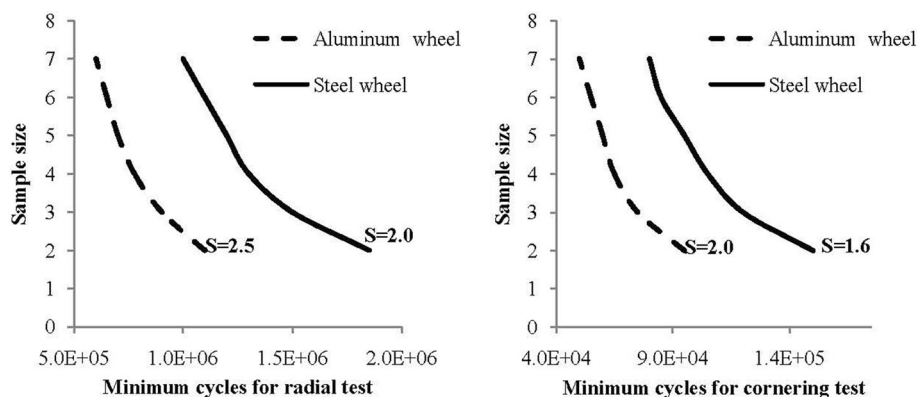
element analysis. The information published is very valuable and helpful to the research community.

The radial fatigue test is one of the most widely used test methodologies to study the behavior of the wheel as well as tire due to radial loads. Good numbers of publications are available that focus on the validation of the test results to finite element analysis. As the tire simulation is mandatory to perform this test, much effort was spent in modeling the tire as well as studying its behavior to replace the tire with a suitable distributed force onto the wheel rim. Finally, a suitable angle for the distribution of radial force was achieved, which was used by most of the researchers to eliminate the tire from analysis, thus simplifying the finite element model. A statistical approach to predicting the service life of the wheel based on the probability of failure is still valid for this method.

It can be noted that the cornering fatigue test is of choice for most of the researchers to validate the service life using experimental as well as finite element analysis. The simulation approach is straightforward for the wheel's cornering fatigue test, as the tire is eliminated from the analysis as per the standards. The time required to perform this test is less when compared to the radial fatigue test as higher acceleration test factors can be used. Large numbers of publications are available for cornering fatigue tests for which experimental and finite element analysis were performed. In the bending fatigue test, the critical areas are located at the root of the wheel spoke, and at this area, the maximum principal strains are much higher than in other areas.

The authors provided excellent literature in understanding the dynamic response of the wheel impact analysis. Merits and demerits of using the wheel and tire assembly for finite element analysis in terms of accuracy of results and solution time are discussed. Different failure criteria were being used to support the wheel strength against impact loads. A statistical approach to predicting the impact strength of the wheel to optimize for its weight is still needed to be explored.

**Fig. 14** Radial and cornering fatigue wheel test sample size and cycles requirement



The loads in the biaxial fatigue test are derived from real-time loads, which are different and more stringent than traditional performance tests like cornering and radial fatigue tests. The location of wheel failure cannot be predicted due to the combination of different loads as per the load file used compared to traditional tests. In terms of test duration, the biaxial test of a wheel is quick since the wheel is being evaluated for both the radial and bending loads simultaneously, and also fewer specimens are required to validate the wheels for their service life. Even though a sophisticated test rig is required to perform the biaxial fatigue test, this methodology is cost-efficient compared to the overall cost and duration for the traditional wheel evaluation process. A statistical approach to predicting the service life of the wheel based on the probability of failure is still valid for this method. No performance requirements have been established for this procedure.

Different techniques used for wheel optimizations are summarized. As the wheel aesthetic appeal is one of the significant parameters that most designers and vehicle manufacturers consider, there is a limited possibility to optimize without making significant modifications to the actual design. Topology optimization can be performed on the wheels, where the designer can modify major features of the wheel or if the design is made from scratch. It is also to be noted that most wheel designs evolved from topology optimization may not be feasible to manufacture. So a new manufacturing methodology or process can be evolved based on the design. Shape optimization can be easily adapted for wheel design as it is feasible to operate some wheel parameters without modifying the wheel's styling face. Also, most shape optimization outputs can be easily adapted for manufacturing if the ranges of the parameters are selected cautiously.

Application of various materials and different manufacturing methods are discussed. The advantages of replacing steel wheels with aluminum and magnesium alloys are presented. New technologies to develop hybrid wheels and wheels made up of composite materials are detailed. Studies were conducted to use long glass fiber reinforced thermoplastic composite (LGFT) and carbon fiber reinforced epoxy resin in wheel manufacturing, and it is concluded that composite material can be extended to various parts in vehicle manufacturing. The application of composite materials for passenger cars is minimal as of today. It is mostly used in high-performance cars, where limited production is required. The methodology for mass production of composite wheels is still under research.

## Future Work Directions

Evaluation of structural durability using biaxial wheel testing is still a high complex process, and also an end-to-end process for wheel optimization needs to be established.

For radial fatigue test simulation, since the nature of the load is cyclic, it is possible to further simplify the finite element model by using cyclic symmetry boundary conditions.

Apart from traditional testing standards, there could be other models of failure that a wheel may experience in actual operating conditions. Analysis of wheel failures and their root cause needs to be studied to understand the real-world scenario.

As the wheel force transducers are very expensive, the research related to extraction of real-time loads of wheel from the vehicle on which it is operating is minimal.

The effect of different road conditions on the wheel's performance needs to be explored.

Eigen frequencies and mode shapes need to be measured to study the wheel's noise, vibration, and harshness (NVH) characteristics.

Research in the areas of service life prediction of wheels with cracks using fracture mechanics concepts for different wheel materials and manufacturing processes needs to be carried out.

The methodology of wheel performance study in assembly conditions needs to be evaluated by both experimental and finite element procedures. In addition, the impact of the adjacent components on the wheel performance needs to be studied in detail.

The cost for producing composite wheels is high, as the existing composite technologies could not provide component cost reduction by increasing the production volume. Therefore, research needs to be extended in this direction.

Not much literature is available on the manufacturing and testing of wheels made of carbon fiber reinforced plastics (CFRP). There is still enough scope to perform CFRP wheel fatigue and impact testing research.

As electric vehicles are becoming more popular for reducing emissions, it is essential to assess the durability of wheels for electric vehicles based on their requirement.

**Conflict of interest** We have no conflicts of interest to disclose.

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