Extended Mobility Tires and their Effect on Loads to the Wheel Structure

Ruediger Heim, Ivo Krause
Fraunhofer Institute for Structural Durability and System Reliability LBF

ABSTRACT

State-of-the-art development in the field of tire technology do show a clear trend toward extended-mobility-tires. These tires – also known as runflat tires – have reinforced side walls to guarantee basic mobility properties even in the case of air pressure loss. Since the individual layers as well as the complete build up are different to traditional tire technology, the enhanced layer stiffness generates higher loads to the rim flanges, wheel well and wheel disc. Although these tires seem to be perfectly compatible to conventional wheels with regard to design and mounting process, the stress loading as well as the structural durability of the wheel may be an issue, which has to be examined carefully: Are the design and cross-sectional properties of the wheels appropriate for the complete life cycle of the vehicle?

Since automotive wheels are relevant for operational safety, these parts must not fail causing an accident. This has to be ensured by experimental methods such as rig based durability tests. While simplified test procedures such as cornering fatigue tests or radial fatigue tests do not cover the complete load mechanics by the tire, the unique BiAxial Wheel Fatigue Test facilities (ZWARP) were used to generate technical expertise in the field of runflat tires and their relation to the loading of the wheels. Since both loading as well as assembly interaction in the ZWARP are incorporated in a realistic manner, costs and time are saved due to an appropriate accelerated life testing and the elimination of specialized on-road testing.

INTRODUCTION

Although vehicle ride is interrupted by air pressure loss once in 10 years or so, spare wheels are still used on almost all passenger cars even today. While exchanging wheels seem to be manageable, a few items related to this should be pointed out:

- the additional mass of the spare wheel including tools is about 15 to 30 kg
- the size of the trunk is reduced by 100 litre at max.
- the inflation pressure of the spare wheel is not checked regularly and may differ from nominal value significantly
- the tire is as old as the complete vehicle is – may be 10+ years

Since tire bursts and/or air pressure loss can cause severe operational incidents, tire technology enabling runflat conditions definitely is beneficial for vehicle safety as well as for the driver's sensation (figure 1.). Actually US customers were looking for extended mobility tires in 1995 as the most wanted safety feature.

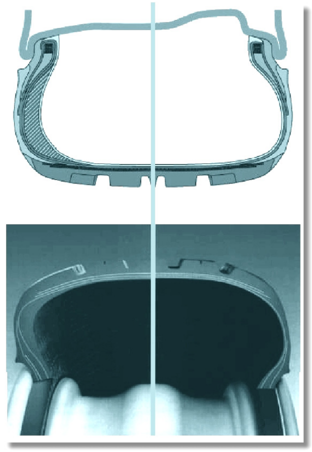

Fig.1 – RFT vs. Standard tire cross sections

Recent studies do report of >400 fatalities per year in the US and about 40 in Germany caused by tire failures.

Consequently the German vehicle manufacturer BMW recently introduced runflat tires for the current 3-series and plans their extended use for all future platforms.

Since the first self-supporting tire was presented by Goodyear in 1978, there was a long way to current runflat tire technology. Currently almost all of the big manufacturer offer tires having reinforced side walls enabling runflat condition. Especially wide rim tires beneficially can be modified by using stiff layers in the side wall to guarantee extended mobility up to 200+ km, even completely deflated. Here traditional rim design is used as well as the tire mounting procedure does not differ from conventional tires.
Different to this, the support ring type of application uses non compatible design of wheel and tire, which makes it by far more expensive. One of the best known derivatives of this technology is the PAX (formerly PAV) system, which was introduced by Michelin in 1997.

While PAX/CSR systems as well as mini spare wheels are expected to have only slight growth of market share, the market significance of self-supporting tires will increase notably till 2010.

RUNFLAT TIRE TECHNOLOGY

GENERAL

With regard to vehicle dynamics the tire is the basic load transfer element, which interfaces the moving vehicle and the stationary ground. All loads acting on this interface are being transmitted by the tire – actually longitudinal forces enabling acceleration and braking, lateral forces giving steering stability and last but not least vertical forces supporting the vehicle mass. Since all vehicle manoeuvres imply transient characteristics, these forces act dynamically – although high frequency excitation is not given by these manoeuvres directly, but by superimposed road conditions especially for the vertical direction. Hence the vehicle loading can be described by the interference of the basic vehicle manoeuvres and the transient excitation by the ground condition. Both is influenced by the tire technology and especially the different load characteristics of runflat tire technology may interact with adjacent components such as wheels and/or parts of the suspension.

Since the wheel was invented – that was approximately 5,500 years ago and happened concurrently in Sumer and central Europe – these components become really lightweight structures. While the mass of an average tire/wheel combination of a passenger car is about 20 kg, the rated wheel load is at 600 kg – that is 30-times the mass of the assembly. Actually this load ratio as well as the implication of a failure when driving make it quite obvious, that the tire/wheel system is a lightweight and safety relevant component.

By adapting runflat tire technology, the single component becomes heavier by one third approximately. Comparing the mass of a tire having the dimension 225/45 R 17, the standard tire is about 9.6 kg while the runflat is at 12.7 kg (figure 2.). Hence the overall mass benefit of the new technology is less than 10 kg compared to the use of 5 standard wheels – including spare.

Fig. 2 – Standard tire /left/ and runflat tire /right/ (225/45 R17)

While the first generation of runflat tires was designed to enable driving without air pressure for about 200 km, the current focus is on »soft« runflat tires, which can be used for max. 80 km in deflated mode. Hereby the tire characteristics are tuned according to improved vehicle dynamics and ride comfort while keeping basic runflat capabilities.

The tire stiffness in vertical direction gives an indication about the ride comfort: The higher the tires stiffness the bigger the forces generated by bumps on the road. The examination of the vertical stiffness's statically by using a flat base test bench showed that the runflat tires are much stiffer than the standard tire. Although the same tire load index was used by reducing the air pressure for the runflat tires (200 kPa) compared to the standard tire (230 kPa), the vertical stiffness is at 320 N/mm for the runflat and 260 N/mm for the standard (figure 3.).

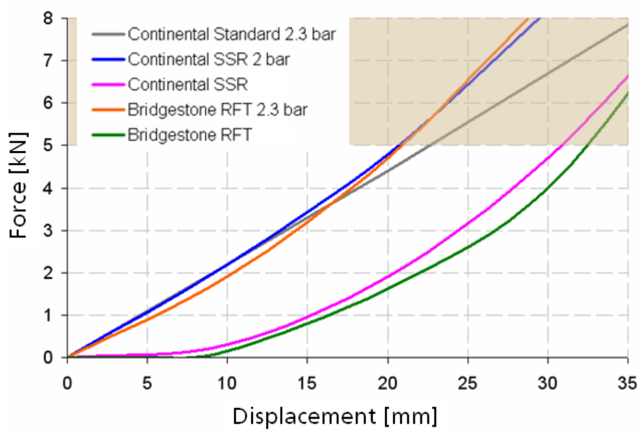

Fig. 3 – Vertical tire stiffness's

By using an empirical ratio for the vertical loads

$$n_{v,max} = 1 + 2.6 \cdot \frac{C_1}{F_{v,stat}}$$

$n_{y\ max}$: vertical **p** load scaling

C_1 : vertical tire stiffness

$F_{y\ stat}$: rated wheel load

it becomes obvious, that the vehicle is much higher loaded when runflat tires are used.

From other examination it is known, that the parameter sensitivity of runflat tires as a function of the speed is much bigger than for standard tires: Both vertical stiffness as well as resultant bump forces increase significantly by the vehicle speed and/or excitation frequency. Since this is not covered by the above equation, multibody simulation (MBS) were performed for different vehicle configurations using rather basic tire models. Therefore, CarSim®

simulation tool was used to create a virtual test track giving vertical excitation by bounce sine sweep (figure 4.)

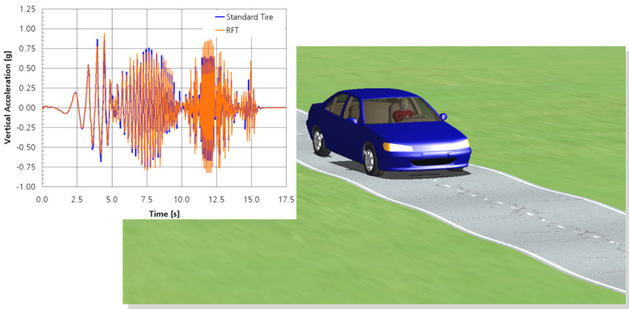

Fig. 4 – Math modelling for vehicle bounce sine sweep

The computational results were compared to road load data (RLD), which was examined experimentally by using wheel load sensor technology. These normalized RLD diagrams allow a mapping of load scale factors and the corresponding wheel loads (figure 5.).

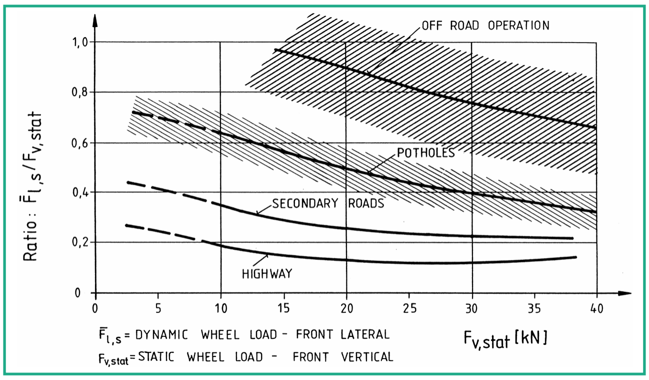

Fig. 5 – Normalized RLD diagram for different road conditions

Hence the validity of the math models were evaluated by comparing the individual peak forces with the normalized road load data. Since the agreement between different vehicle configuration and experimental RLD was evaluated positively, math modelling was used to examine the influence of runflat tire technology in a semi-quantitative manner.

VEHICLE EXCITATION

An uneven road was used to compare the characteristics of runflat tires with regard to the vertical acceleration of the vehicle as well as its wheel loads. The road excitation was represented by bounce sine sweep conditions, starting with large wave lengths. Based on the given spring/damper characteristics of the vehicle, the CoG (centre of gravity) acceleration is not influenced by runflat tires significantly except of the high excitation frequencies at the end of the test track.

For the wheel forces the situation is different: Runflat tires imply definitely higher forces. While the overall peak forces are generated on the large wave length section, the differences become more significant at the end of the test track again (figure 6.). The overall peak forces may differ about 5% between runflat and standard tire, but the section at the end of the test track induces differences of about 20% because of the transient excitation characteristics.

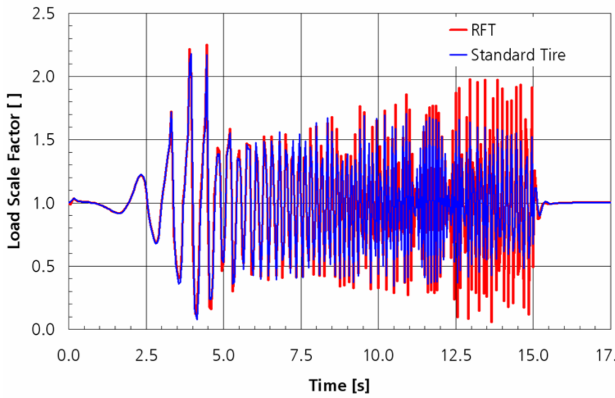

Fig. 6 – Wheel load scale factor for uneven road

Hence not only the peak wheel forces have to be examined, but the complete excitation spectra may differ significantly when using runflat tires. Therefore the virtual test track was repeated by using different velocities – actually a range from 35 kph to 65 kph was evaluated by cumulative cycle counting.

By using the range pair counting method the force-time histories were transformed into force spectra. This semi-log spectra represents the content of the vertical excitation in terms of forces and their cumulated number of cycles.

The wheel force spectra for the vehicle using the runflat tires is obviously different from the one based on standard tire technology: Actually the peak forces are increasing as well as the shape of the total spectra is more bellied. After extrapolating the virtual test track to a distance of 6,000 km – representing rough road excitation, the excitation content is significantly different (figure 7.).

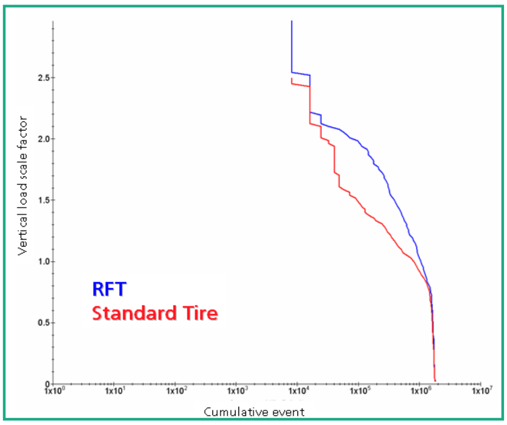

Fig. 7 – Rough road design spectra

Hence the forces induced by runflat tires do show a much higher excitation density, that can be quantified by the area between the curves representing the individual spectra. From load management point of view the runflat tire technology leads to an increase of the external vertical loads, which are applied at the tire footprint. This has to be considered for the design of the wheels, which are directly loaded by these forces.

Actually the runflat tires with reinforced side walls imply different force transfer characteristic and damping compared to standard tires. This again is part of the different load scheme induced by runflat tire technology: The same external wheel forces may result in different local wheel stresses. This is due to the different side wall layers and rim flange force elements of the runflat tires.

EXPERIMENTAL STRESS ANALYSIS ON FLAT BASE

The implication of the different tires on the local wheel stress level was examined by experimental stress analysis (ESA): Therefore an OE certified aluminium wheel from current production was equipped with strain gages at the wheel well area as well as at the disc inner and outer close to the wheel bolts. The wheel was designed for aluminium forging process having 8 J 17 dimension. It is used for standard tires as well as for runflat tires such as CONTINENTAL SSR or BRIDGESTONE RFT.

The ESA was performed on the LBF flat base roll bench, which is used for the stress level identification of the wheel at small rotating velocities. The flat base is represented by a number of small rotational solids that can be adjusted relative to the rotational axis of the wheel. Compared to the true deformation kinematics on the road, the situation on the flat base roll bench becomes kinematically reversed: To apply lateral forces the flat base is rotated around the vertical axis.

Different load combinations were applied on the tire/wheel system which represented physical wheel forces related to manoeuvres such as heavy cornering or straight driving on rough roads. The rated wheel load was 4.9 kN – corresponding peak forces were derived from the normalized RLD diagrams as well as from MBS modelling for the run flats.

With regard to structural durability the stress amplitudes are the most important metric to evaluate the strength properties: Hence the cyclic stress time history was evaluated to extract max. and min. stress level.

While the strain gages #1 and #6 were applied on the wheel disc area, the strain gage #3 was applied in the wheel well area. The latter is more sensitive to vertical loading, which is quantified by a stress ratio for $\sigma_{a,s}/\sigma_{a,c}$ (index s: straight driving; c: cornering).

Strain Gauge	$\sigma_{a,s}/\sigma_{a,c}$ – standard tire	$\sigma_{a,s}/\sigma_{a,c}$ – CONTINENTAL SSR	$\sigma_{a,s}/\sigma_{a,c}$ – BRIDGESTONE RFT
#1	0.50	0.61	0.79
#3	1.18	1.24	1.32
#6	0.54	0.63	0.68

It is interesting that this stress ratio as well as the true stress level depend significantly on the specific runflat tire too: The BRIDESTONE RFT induces higher stress ratio than the CONTINENTAL SSR. Both runflat tires shift the stress ratio toward $\sigma_{a,s}$, that is the maximum stress amplitude for straight driving on rough roads.

The comparison of the maximum stress levels for strain gage #3 again indicate the essential differences between standard tires and run flats: The peak stresses increase by an average of 68% for straight driving and about 56% for heavy cornering (figure 8.).

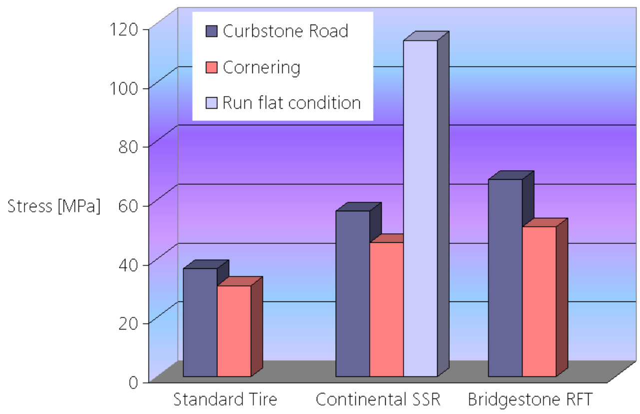

Fig. 8 – Stress comparison

WHEEL DURABILITY

GENERAL

Since structural durability and fatigue phenomena depend on cyclic stresses acting locally, a component such as a wheel is loaded in a complex way. Often the wheel well and the rim area are quite sensitive with regard to vertical forces, while the wheel disc reacts on lateral forces primarily. This was the reason for using different lab test methods such as rotating bending and radial fatigue: While the rotating bending method is based on a kinematically reversed loading of the wheel disc, the radial fatigue test is using an outer drum applying a constant load for examination the rim durability.

Since the load mechanics for the wheel cannot be perfect by using these simplified methods, Fraunhofer LBF developed the BIAXIALWHEEL FATIGUE TEST MACHINE, which is used by many international OEM as well as wheel manufacturer.

BIAXIAL WHEEL TEST

In the BIAX WHEEL FATIGUE procedure the complete wheel end is assembled and the tire acts as the load transfer element rotating inside a drum. Biaxial actuators create vertical as well as lateral loads inside the system, which represent the operational conditions realistically. The machine is available for passenger car/SUV wheels (≤ 20") as well as for commercial truck wheels (≥ 22.5") (figure 9.).

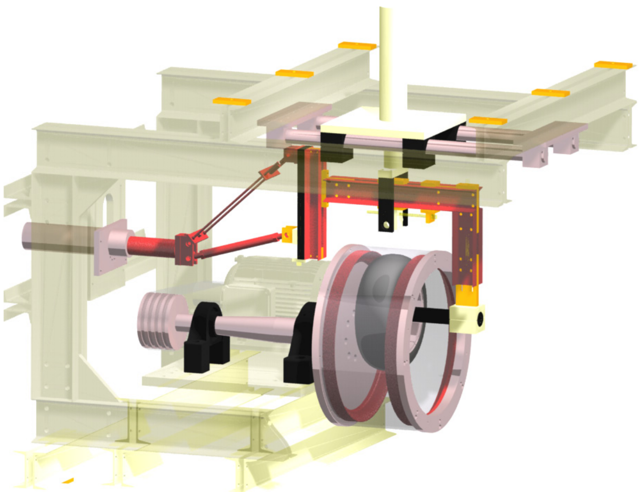

Fig. 9 – BiAxial Wheel Test Machine (LBF type "A")

Different load sequences are considered by using specific load files, which include pure vertical loading as well as a superposition of vertical and lateral forces representing special manoeuvres and operational conditions.

This procedure was developed 25 years ago, and it became a standard for many OEM and suppliers as well as it is introduced as an SAE recommended practice.

Major test machine manufacturer such as MTS Systems Corporation or Fraunhofer LBF itself have built more than 40 BIAXIAL WHEEL FATIGUE TEST MACHINES world wide. The drum diameter is realized in different sizes capturing all ranges from passenger car wheels up to big commercial truck. Since the test mode is kinematically reversed compared to the road operation, the load mechanism is generally quasi-static. But, this is used to stress all structural areas circumferentially, not to peak load certain areas randomly: The time duration of the individual load sequences have to be adjusted to cover at least one wheel revolution. From practical point of view, the load vs. time history is generated by compiling the stochastic nature of road transport utilization into load block sequences.

Therefore, it is necessary to analyze the life-cycle load content carefully. With regard to the usage loading for rotating components, the major manoeuvres are straight driving and cornering operations, while brake as well as acceleration torque do not induce severe damage for traditional wheel or hub design directly.

The statistical examination of road & on-track measurements show, that straight driving is the predominate part of the usage spectra, while cornering is about 4% of the total vehicle mileage only (figure 10.).

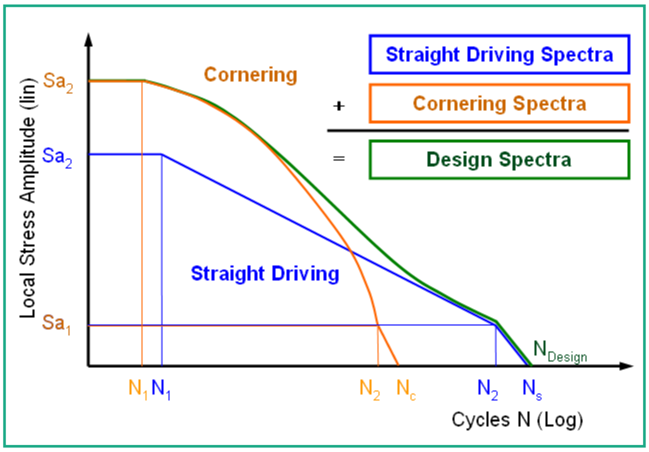

Fig. 10 – Wheel design spectrum

For cornering operation there is a strong correlation between vertical and lateral forces acting on the tire footprint. Hence the test load sequences representing cornering operations can be derived from vehicle dynamics relatively easily. Different to this, at rough road driving the lateral forces are not correlated to the superimposed vertical loading. Hence the test load spectra has to use representative load sequences applying inboard as well as outboard forces, which become added to the vertical loads.

By means of analytical damage calculation, the test spectra is derived from this generic load spectra. Since overstress acceleration of the test spectra could cause severe impact on the damage mechanism by generating stresses beyond the shape yield limit, the more appropriate strategy is to apply usage rate acceleration: Therefore, the shape and content of the cumulative distribution are modified to reduce the time duration needed for the durability evaluation process (figure 11.). The test spectra represents a compressed load program in terms of number of load cycles (approx. 8,000 to 10,000 km), while keeping the damage content of the generic load spectra (usually 300,000 km).

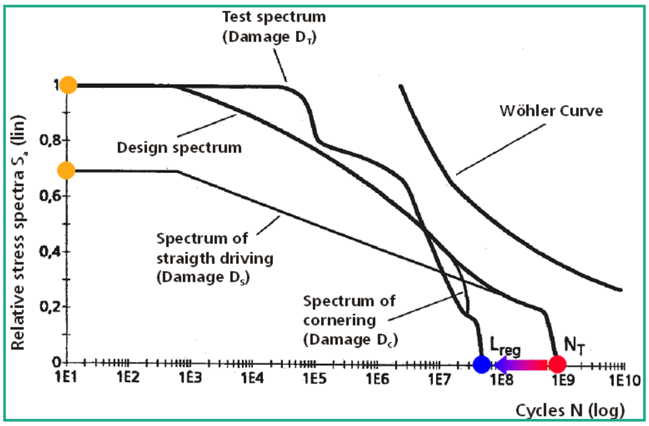

Fig. 11. – Test spectrum vs. design spectrum

The continuous test spectra is then practically applied as a sequence of different load blocks, which are stochastically ordered to represent appropriate conditions for accelerated life testing.

EXPERIMENTAL FINDINGS FOR RUNFLATS

Since both peak forces as well as the shape of the cumulative straight driving spectra is different for the runflat tires, the BIAX test spectra should reflect these conditions. By using the load file parameter for the adjustment of the global vertical and horizontal actuator forces of the BIAX WHEEL TEST MACHINE the »LBF RFT Cycle 2006« was created (figure 12.).

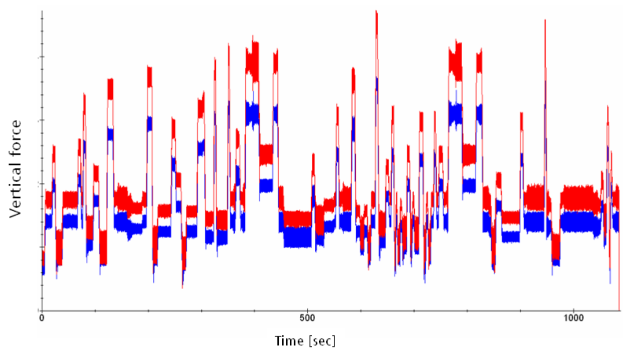

Fig. 12 – BiAx load files for standard tires (blue) and RFT (red)

The base load file for the runflat alignment was the well known »Eurocycle«, which was developed a couple of years ago and is today standard for the BIAX WHEEL TEST in Europe.

The theoretical damage calculation for the strain gage #3 (wheel well) was performed assuming a generic S/N curve having the slope k = 4.5 and k'=8 for N > 107. By shifting the S/N curve in vertical direction to realize an resultant damage value D = 0.5 the so called required fatigue strength (RFS) is computed. This RFS is an indication for the local strength properties which have to be provided to assure appropriate durability performance.

The ratio of $RFS_{runflat}/RFS_{standard}$ is about 1.25 for strain gage #3, which clearly shows the influence of higher external loads and different load mechanism by the runflat tire technology. Typically a ratio of 1.1 represents a reduction of durable life of about 50%. Hence the above ratio for the wheel well could cause some durability issues. This was evaluated by BIAX WHEEL TESTS, that were performed with standard tires as well as the run flats. The test spectra is 10,000 km for aluminium wheels – no major cracks and/or severe operational incidents are allowed.

After the accelerated life testing with standard tire the wheel was examined regarding structural issues: Even after an enlarged test duration of 15,000 km no cracks were reported. When run flats were used the results were different: Air pressure loss due to a major crack in the wheel well was reported at 10,300 km. Actually this has to be rated as critical issue just on the minimum lifetime requirement. Although this failure was clearly issued by the use of run flats, the fail-safe functionality of these tires avoid fatal failure modes by loosing air pressure (figure 13.).

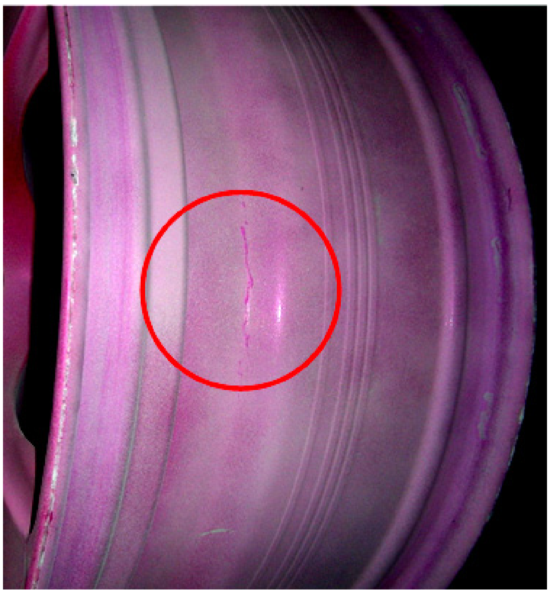

Fig. 13 – Fatigue crack in wheel well

Definitely the different load characteristics as well as the higher external forces induced by the run flats imply serious effects with regard to the durability performance of wheels. Especially for the wheel well there are major differences in terms of stress level and required fatigue strength, which can lead to insufficient life time of these components. Hence the design as well as the cross sectional properties of wheels for runflat tires must be evaluated carefully. The use of conventional wheels may cause severe operational incidents although their design is appropriate for mounting run flats.

CONCLUSION

Runflat-technology certainly improves vehicle safety by keeping the car running in a special mode. The most advanced design is related to reinforced side walls of the tire, which can be used on traditional wheels without any changes on wheel design and/or tire mounting process.
Since the load characteristics of runflat tires are different to those of standard tires, both external tire forces as well as internal wheel stresses become increased – especially for rough road conditions. Hence the wheel's durability performance has to be examined by the consideration of all major effects related to the use of runflat tires.

Therefore the BiAx Wheel Fatigue Test procedure was enhanced by developing a specific RFT load file. Math modelling was used to generate a comparative study on the test spectra for standard & runflat tires, which was evaluated in terms of excitation intensity. These results were used to create a new RFT load file, which is based on the standardized load file »Eurocycle« by shifting vertical & lateral load scaling individually.

The first results of using this RFT load file in the BiAx Wheel Test clearly showed a specific risk for generating fatigue failures in the wheel well, which were not seen when using standard tires. Hence this is a clear indication, that the BIAX WHEEL FATIGUE TEST is the superior method for design and approval of wheels incorporating new tire technology and loading standards.

CONTACT

Main author: Ruediger Heim
Fraunhofer Institute for Structural Durability and System Reliability – LBF
Head of Competence Centre »Wheel/Hub/Spindle«
Bartningstr. 47; D-64289 Darmstadt, Germany
E-Mail: ruediger.heim@lbf.fraunhofer.de