The Dynamic Behavior of the Vehicle Wheels Under Impact Loads—FEM and Experimental Researches

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Abstract Results of the analysis of dynamic impact effect for vehicle light alloy wheels of various types, which may occur in various road situations (head-on crash, drift, collision with another car) are given. This study applied to simulate the impact behavior caused by a dynamic loading of vehicle wheels by impact testing according to the scheme of certification tests with static and dynamic strain measurement for definition of deformation fields and impact stresses. New approach to creation of FEM model of virtual impact tests of wheels with use of program complex of nonlinear dynamics Ls-Dyna is developed and validation of models by comparison with results of dynamic strain-gaging is carried out.

Keywords Finite element method · Wheel · Dynamic impact

1 Introduction

Aluminum alloy wheels, both cast and forged, are used for cars. While it is critical for car safety, such wheels' behavior at dynamic impact has not been adequately explored. Impact effects occur in a variety of emergencies (head-on crash, drift, collision with another car etc.). Statistic studies of typical accidents show that the average head-on crash angle is 27.6°. Impact loading of aluminum cast wheels at 30° angle (so called "oblique impact") is a mandatory phase of car wheel certification

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testing [1, 2]. Standard oblique impact test simulates a 1t car going at 60 km/h, running with its wheel over a fixed obstacle at an angle of 30°. Complicated design of modern wheels, especially cast ones, requires analysis of the space stress/strain state (SSS) that normally uses the finite elements method in static position (FEM) [3–5]. Experimental impact tests of wheels are carried out on specific benches, which design is conventionally reflected in regulatory documents, however, it may affect the results significantly. Moreover, such impact testing requires considerable computational efforts, especially when the cast wheel configuration needs to be varied in design analysis.

This paper contains the results of computational studies of stress/strain state of an aluminum cast wheel for a car in case of oblique impact. The object under investigation was a 7JX16H2 modern standard aluminum cast wheel. Experimental SSS study of the wheels was made by strain measurement. Of interest, therefore, are calculation/experimental research of static and dynamic behavior of a cast aluminum wheel, when loaded in impact bench testing, to identify FEM model adequacy and possibility to use the dynamic factor for preliminary comparative structure analysis based on static calculation to evaluate their behavior at impact, without detailed dynamic option analyses. The dynamic factor is the ratio of the maximum impact deformation to deformation caused by similar static loading.

2 Experimental Study

The study was carried out on an impact test bench (see Fig. 1a) both for static and dynamic loading that was applied to the wheel rim against (see Fig. 1b) and between the spokes (see Fig. 1c). The wheel was mounted on the impact bench support at 30° to the horizontal surface and rigidly secured to the bearing surface with bolts. The tests were carried out both with a tired and bare wheel.

Two loads (basic mass and striking bar) represented the loading element with the total weight amounting to one t interconnected via a spring simulating a car suspension. The wheel was turned about its mounting axis to ensure various test load applications. The height of the striking bar above the tire is determined by the maximum static loading F_v applied to wheel being subject to investigation [1].

Resistive strain gages were mounted on the disks to measure deformations (strain gages' register surface—3 mm) on flat areas in radial axis of the spokes, and on the rim along the wheel axis (see Fig. 2) [6]. Areas chosen for installation of the strain gages were next to the highest expected deformation points. Impact deformations were recorded at strain-measuring channel polling frequency.

16-channel strain-measuring equipment was used for measurement and digital recording of loaded wheel deformation values. In case of static tests, a load was slowly applied to the wheel rim edge. Dispersion and mean values were calculated in result of automated test data statistical processing. Bare wheel static loading results are shown in Fig. 3 in form of deformation curves measured by 16 resistive strain gages. Testing data analysis proved no after flow and showed that tired and bare

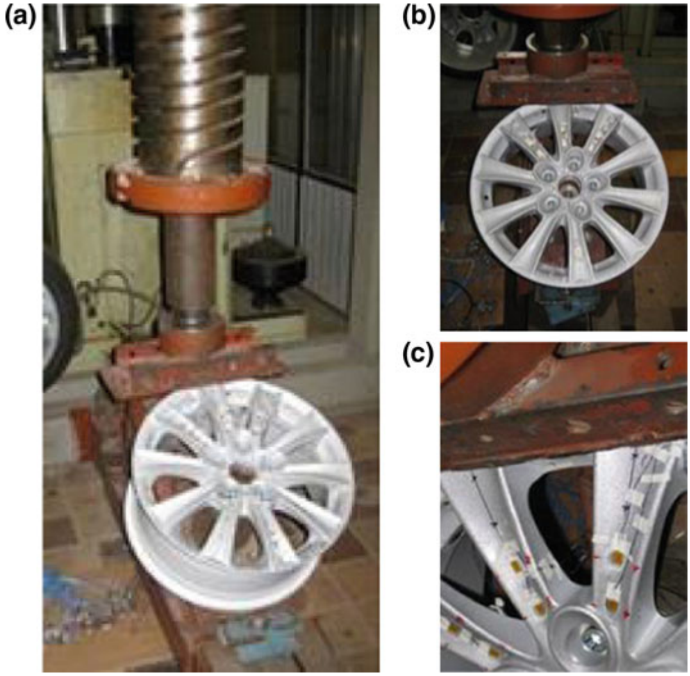

Fig. 1 **a** Impact test bench and installation diagram of resistive strain gages on **b** outer and **c** inner surface of the wheel

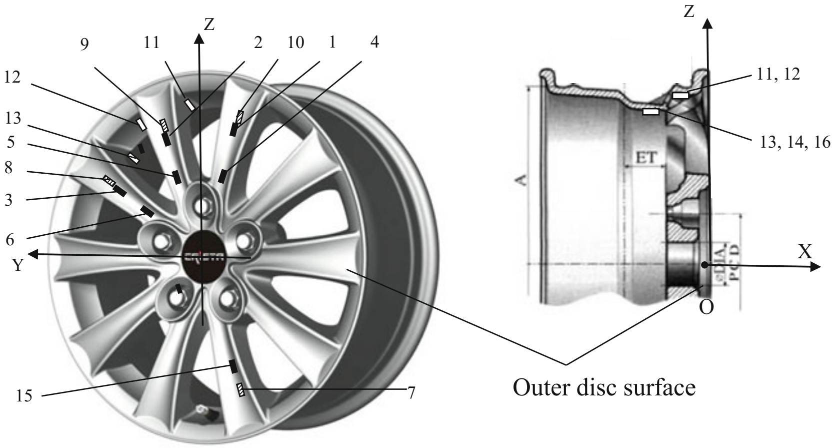

Fig. 2 Installation diagram of resistive strain gages on outer and inner surfaces of the wheel

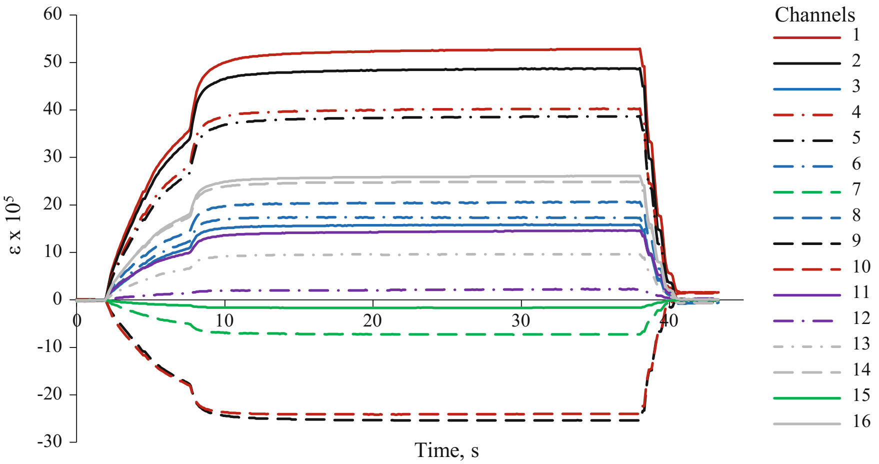

Fig. 3 Deformation curves for static loading

wheel deformations were practically the same under static loading (spread in values, when applying loading to a tired and bare wheel spoke did not exceed 5 and 7% for inter-spoke impact).

Impact loading was also performed in two areas: against and between spokes. The obtained research results are represented as impact load deformation curves in Fig. 4. For all loading options, it is found that rapidly, damping oscillations similar to harmonic ones occur after an impact impulse. Analysis of resistive strain gage readings allowed to identify that complete damping of oscillations takes place within ca. 2.5 s. Oscillation time and damping in all measurement points turned out to be virtually the same: averaged by all measurement points, the oscillation time T = 0.256 s. Determination of damping logarithmic decrement (1) value was based on comparison of subsequent oscillation amplitudes resulting in assessment of the conventional absorption factor value φ of the wheel material which amounted to ca. 0.6–0.7. The obtained value indicates a substantial internal friction in the wheel aluminum cast material leading to significant absorption of impact energy [7]. Additionally oscillation processes could be analyzed using technique designed and described in [8].

$$\delta = ln\ A_s / A_{s+1} \tag{1}$$

Maximum impact-caused deformations occur in the spoke middle on the wheel face. No considerable impact-caused permanent plastic deformations or breakages occur. Research results (see Table 1) allowed establishing the ratios of impact-caused deformations ε_{din} to deformations caused by static loading ε_{st}, which turned out to be practically the same regardless of the measurement points. Thus, an approximate engineering judgment of impact-caused wheel SSS can be recommended by using the obtained average value of dynamic factor (2) and static loading computation results [9].

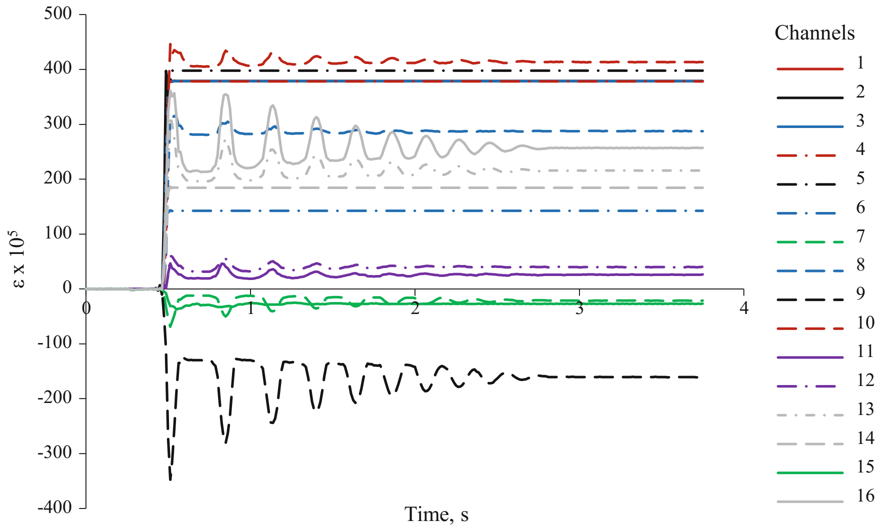

Fig. 4 Deformation curves for impact loading

Table 1 Static and impact loading caused deformations measurements

Strain gage no.	Impact $\varepsilon_{\text{din}} \times 10^5$	Static $\varepsilon_{\text{st}} \times 10^5$	Dynamic factor K_D
1	378.6	37.6	10.07
3	378.5	34.7	10.91
4	378.4	36.8	10.28
5	397.8	39.8	9.99
6	350.0	28.7	12.20
13	197.3	14.8	13.33
14	184.7	15.3	12.07
16	354.4	31.2	11.36
		Average value K_D:	11.28

$$K_D = \varepsilon_{din}/\varepsilon_s \tag{2}$$

3 Structural Analysis SSS at Static Loading and Dynamic Impact Using FEM

Calculation of wheel impact SSS was done using LS-Dyna multifunction software package [10], designed for solving nonlinear dynamics tasks. Description of the elements motion was based on Lagrange formulation, the solution of the system of

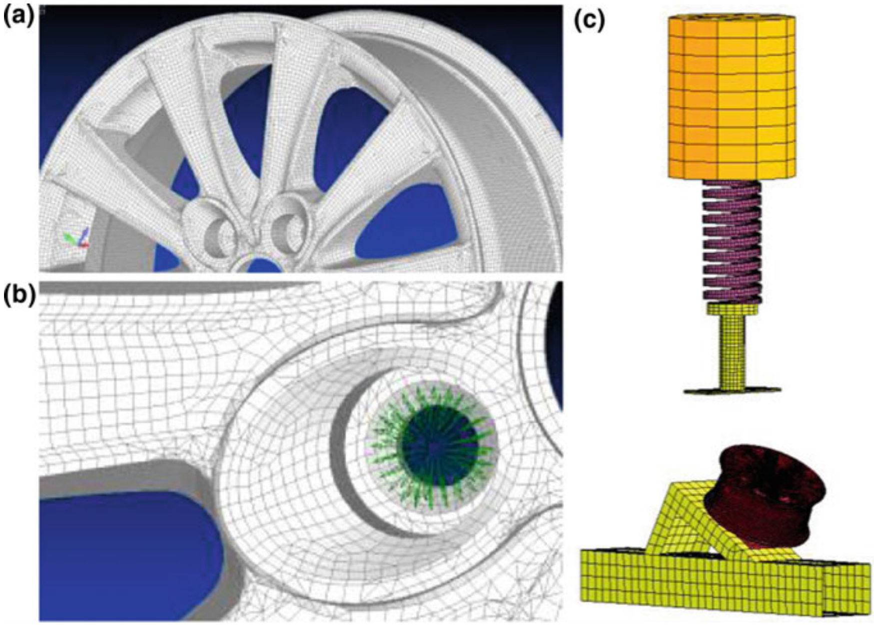

Fig. 5 Computed FE model of the **a**, **b** wheel and **c** impact test bench

dynamic equations and state equations performed using of the explicit integration method [11].

As shown by our research, the calculation results depend on materially on the quality of wheel FE [12, 13]. The computed finite-element model (see Fig. 5a) of a wheel under static loading applied at an angle of 30° (oblique impact conditions) accounts for the main mechanical properties of the wheel, its geometrical peculiarities, holding forces (see Fig. 5b). The comparison of tests and the calculation results carried out without regard for the tire. 3-D FE model consisted of 224,175 nodes and 483,910 components which average size amounted to 3 mm. 8-node hexagonal components prevailed in the model volumewize. The external edge of the flange-secured model was statically loaded at an angle of 300 to the wheel plane and uniformly distributed at 25 points where the striking element contacts with the outer wheel edge.

For dynamic loading the FE model of the wheel consisted of 48,281 nodes and 38,480 elements, with 8-node hexagonal elements prevailing in the construction both in quantity and in volume. Moreover, FE-model comprises test bench components [12, 13] making possible to account for their stiffness, location and conditions of wheel fastening on the test bench support (see Fig. 5c), so that studies are in fact virtual experiment [14]. The wheel support consists of a cylinder system made of 8-node hexagonal components and channel welded structure modelled by 4-node shell members. The impact load consists of three parts comprising 8-node hexagonal

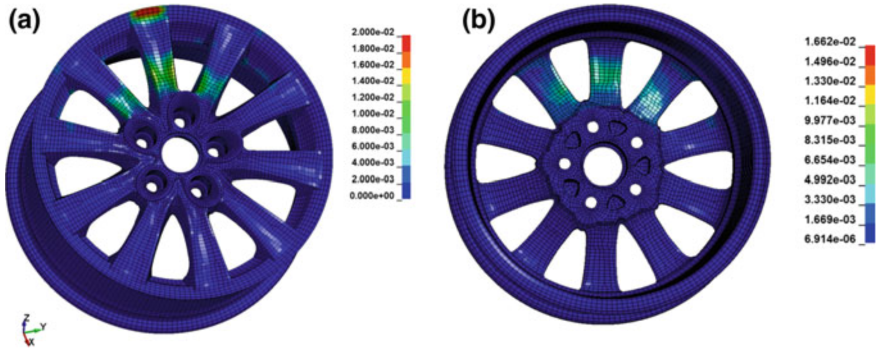

Fig. 6 Distribution of deformation rate on the **a** outer and **b** inner wheel surface

Table 2 Comparison of the main oscillatory process parameters obtained in result of calculations and experiment/test

Parameter	Calculation	Experiment	Inaccuracy (%)
Oscillation time T, s	0.246	0.260	5.4
Oscillation frequency ν, rad^{-1}	25.559	24.127	5.9
Damping logarithmic decrement	≈0.27	≈0.31	≈13

components. The wheel is bonded to the support surface of the test bench using of equivalent compressing force applied from two sides to the system of rigid beam elements of the support. In the design model, the wheel is exposed to permanent loads occurring when tightening the fastening bolts, as well as variable loads resulting from contact interaction with the impact element.

In the course of calculations, an impact was simulated both against and between spokes just as during the test. The height of load fall complied with certification test requirements and test conditions.

SSS components in the wheel are determined based on the values of deformation velocity in each node. In order to account for effect of deformation velocity on the form and key points of the wheel's material deformation curve, including the dynamic yield stress, the calculation uses Cowper-Symonds stiffening condition [15]. Damping properties of materials are accounted for as well. Figure 6 shows the deformation rate values obtained with impact on the wheel rim in the spoke area.

For comparison with test results, the calculation estimated values of oscillation frequency, oscillation time and the damping logarithmic decrement for the first six amplitude deformation values. These values shown in Table 2 and Fig. 7. The difference between the calculated and experimentally recorded values of oscillation frequency, oscillation time and damping logarithmic decrement is within 13%.

Table 3 shows comparison of the maximum deformation rate values under static and dynamic loading. Results obtained within impact computational simulation

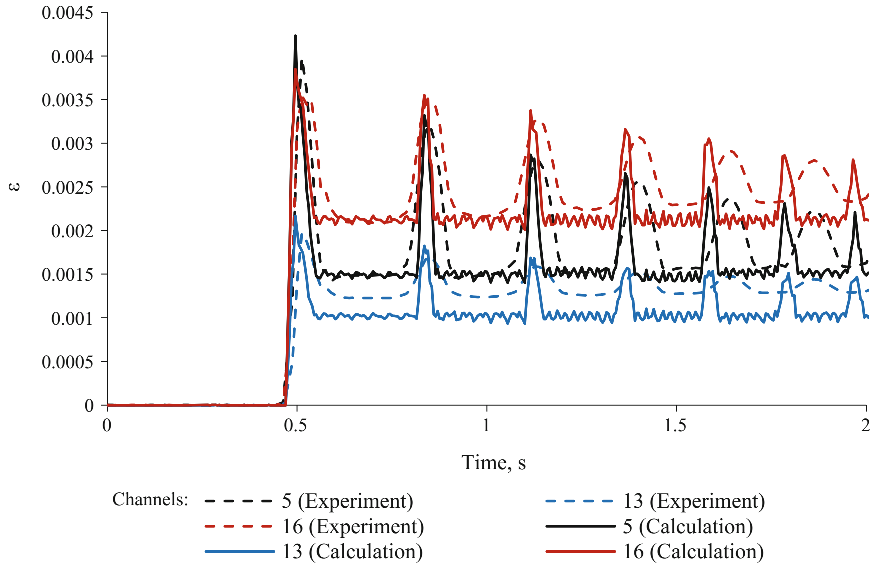

Fig. 7 Calculation and experimental deformation values over time

Table 3 Comparison of the maximum deformation values under static and dynamic loading

Strain gage no.	Impact ε_{din} (calculation)	Impact ε_{din} (experiment)	Inaccuracy (%)	Static ε_{st} (calculation)	K_D
1	0.4478	0.3786	18	0.0549	11.06
3	0.4274	0.3785	13	0.0165	11.07
4	0.4203	0.3784	11	0.0449	9.77
5	0.4232	0.3978	6	0.0449	9.08
6	0.3875	0.3500	11	0.0182	12.26
13	0.2167	0.1973	10	0.0104	11.22
14	0.2003	0.1847	8	0.0314	10.75
16	0.3848	0.3544	9	0.0296	10.87

reflect ca. 11% deviation from the test results in respective measurement points. Analyses of comparative results of deformation calculations under static and impact loading conditions (with loads been applied against the spoke) show, that the average value of ratio between the impact calculated deformations and calculated deformations in similar areas under static loading, close to $K_D = 10.94$ with the standard deviation of 0.82. These value, in fact, fully concurs with the same result obtained during the testing.

4 Conclusion

The carried out comprehensive calculation and experimental researches of deformed condition of aluminum cast wheels under static and impact loads applied to different areas of a wheel rim demonstrated the adequacy of the wheel design FE models and possibility to carry out a virtual impact test when creating and elaborating new structures. Moreover, the research made it possible to establish the mean value of the dynamic factor for aluminum cast wheels under an impact which amounts to ca. $K_D \approx 10$ (ratio between dynamic and static deformation). This ratio can used for all cast wheels made from aluminum-silicon alloys in the approximate engineering analysis. It established that the dynamic behavior of a cast wheel at an oblique impact does not practically depend on the availability of the tire and determined mainly by mechanical properties of the material and the design.

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