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# Numerical and experimental testing of vehicle tyre under impulse loading conditions

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ABSTRACT

The paper deals with modelling and testing of a logistic trucks supporting military operations tyre under strongly dynamic loading conditions. A detailed discrete model of a tyre was developed and validated with the actual one. As a consequence, the blast loading tests were carried out taking into consideration two different explosive distance of the tyre tread. The tests were repeated using numerical methods. During the investigations, a characteristic of tyre structure destruction was compared and the pressure distribution in numerical simulations was analysed. In the finite element modelling, the Simplified Rubber constitutive model, available in commercial LS-Dyna code, was implemented with material characteristics obtained experimentally. The mechanical properties of rubber were assessed within various strain rates: from quasi-static conditions to strongly dynamic ones. Considering erosion in an FE model, the results obtained from comparison with the actual wheel (tyre) showed good accuracy.

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## 1. Introduction

Nowadays, rubber is considered as one of the most important materials used in many applications. Due to its mechanical characteristics, including ability to reversible deformation under the loading of mechanical forces, rubber is very popular in various forms in many industries. Elastomeric structures, due to their low stiffness modulus and high damping characteristics, are used to absorb energy in dynamic (impulse or impact) loadings as isolation bearings, shock absorbers, etc. For example, the automotive industry, often uses materials and rubber-based composites to produce tyres with high strength and durability.

Nevertheless, development of a pneumatic tyre structure with a high operating standard is associated with carrying out a series of experimental studies for determining stability and reliability of its implementation. It also involves large financial outlays and time constraints. Nevertheless, some scientists conducted a tyre (wheel) testing under different load conditions. In [1] the results of the measurement of noise generated by vehicles with different mass and construction are presented. The analysis of registered acoustic signals was carried out on the basis of time–frequency representation. The obtained results showed a possibility to recognise a vehicle type using acoustic signals generated by wheel and vehicle motion. The authors of the paper [2] present the investigations of the breaking process, the associated oscillations and their influence on a suspension system and vehicle body vibrations. On the other hand, low-profile tyre tread slips and the measurement of force acting on the tyre surface are shown in [3]. Also, [4] presents Improvised Explosive Devices (IED) explosion under the LAV Rosomak and highlights the influence of detonation under the vehicle wheel on reaction of the driver. The author estimates a level of acceleration in the gravity centre of the vehicle and determines the effect of damages on the crew safety.

An option for experimental testing is numerical modelling using the Finite Element Method (FEM), which enables estimation of deformation and stress states in the tyre structure and to perform necessary design modifications, even before the production stage. Thus, for effective and correct analyses, a precise numerical model of it should be developed. The authors of papers [5–9] present concepts of discrete tyre modelling and the validation process. The final form and characteristics of the tyre numerical model are affected by many factors, including knowledge and availability of the input and material data. Therefore, an accurate assessment of the tyre rubber mechanical properties in various operational conditions is essential in tyre numerical modelling.

A tyre is a very complex structure consisting of several strengthening layers made of parallel fibres. These fibres, depending on tyre application, are made of polyester, nylon and steel. Immersed with different orientations in the rubber, they form a special ring-like

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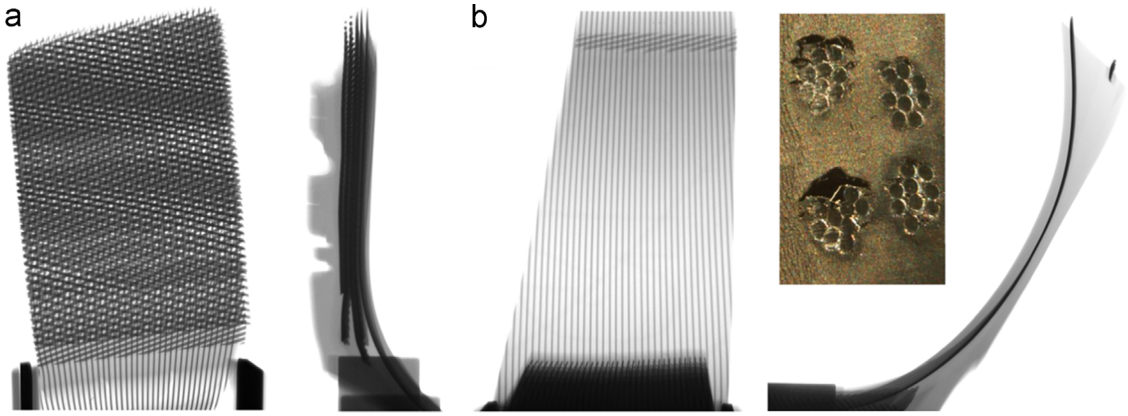

**Fig. 1.** CT scan of (a) tread and (b) sidewall with visible cords layers arrangment (additioinal photo of cords size in microscope scale).

laminate. Generally, it consists of several interconnected elementary parts with different material parameters, i.e. a sidewall, a tread, a bead core, etc. [5,7,8,10,11]. It could be found that most authors use a simplified technique for tyre discretization, however, with good overall correlation with the experiments [12–14]. On the other hand, a number of papers, i.e. [7,8,15,16] include investigations of a tyre (rolling resistance, cornering characteristics, impact tests, etc.) which is complex and was developed using several types of constitutive material models, i.e. orthotropic, elastic–plastic, elastic or nonlinear. In [17], the authors perform a simulation of the tyre–terrain interaction. A detailed numerical description and tests of an aircraft tyre can be found in [18,19]. It should be also emphasised, that most of the researches implement a popular Mooney–Rivlin [20,21] constitutive material model for rubber parts [8,15,16,22]. However, other hyper-elastic models are also adopted, i.e. Yeoh model [20,21].

The genesis of the paper is related to the recent events including many world military operations, where IEDs are commonly used in the battlefield and their explosions can destroy wheels or even the suspension system [4,23]. Their destructive effect results in tyre tearing followed by large deformation of other elements of the suspension system. Such problems are also simulated using numerical methods [24,25]. However, the authors found that there is lack of material data of tyre rubber with a wide range of the stress–strain curves within a number of strain rates, especially in terms of numerical simulations of a tyre under dynamic loading. In the presented tyre modelling concept, the Simplified Rubber Model [26] was chosen with the implemented family of stress–strain curves for different strain rates obtained from quasi-static and dynamic tests performed using universal strength machines and split Hopkinson pressure bar (SHPB) with aluminium and polyacrylate (PMMA) bars [27]. Such a material model with proper and validated stress–strain curves is universal for various problems considering rubber modelling not only under the dynamic conditions, but also in problems of the quasi-static nature.

During the very first stages of the development process of the tyre numerical model, its geometry was achieved with the use of the reverse engineering technology. Moreover, both the tyre cords size and their arrangement were verified with the use of the computed tomography (CT) scan. Finally, a detailed FE model of the tyre was developed and validated with the actual one. The tyre structure was loaded with a blast wave, therefore, the rubber itself was investigated with high-strain rates taking into account. The tyre structure destruction characteristic was compared from experiments and finite element analyses (FEA). Such characteristics as tyre internal energy, pressure distribution, flow-around effect were also discussed.

## 2. Experimental and numerical tyre testing

### 2.1. Tyre numerical modelling

In the paper, the Michelin 315/70 R22.5 tyre with rim was tested experimentally as well as modelled numerically. As it was mentioned, the tyre geometry was achieved with the use of the reverse engineering technology. For the scanning process, a 3D laser scanner was used and the point cloud was obtained, which was represented by the polygon mesh. Based on it, characteristic edges and cross-sectional curves were generated. They were used to develop a CAD model and, consequently a discrete model of the tyre with the rim.

The rim was modelled using Belytschko-Tsay (BT) shell elements [26]. Such choice was dictated by the fact that these shell elements have five integration points through the thickness requiring only 725 mathematical operations compared to 4050 under integrated Hughes-Liu element (35,350 in selectively reduced element) [26]. The thickness of rim corresponded to the actual one which was 8 mm besides the central hole with 15 mm thickness.

Before developing the discrete model, both the tyre cords size and their arrangement were verified with the use of a microscope and a CT scanning technique. It can be noticed in Fig. 1 that a single cord consists of 9 smaller wires, with a total average diameter of ~1.20 mm. It can be observed that steel cords are arranged radially inside the tyre sidewall (Fig. 1a), whereas within the tread area, 4 layers are placed circumferentially under different angles (Fig. 1b).

For modelling of the tyre, brick elements with one integration point, which are recommended for large deformation analyses, were adopted (constant stress solid elements) [26]. Such solid formulation is default in explicit numerical codes. It is efficient and accurate, however, hourglass control is required in almost every case.

Steel cords were modelled using truss (cable) elements which have three degrees of freedom at each node and transfer only axial force [26]. The diameter of 1.20 mm measured from the microscopic photo was used. The nodes of the truss elements were constrained to remain in the same parametric positions within the solid elements using the special feature [26,28] based on the penalty method. The method is dedicated to simulate coupling between gaseous medium and solids, however can modified to couple beams in brick elements. The main advantage of such an approach is that the meshes of the cords and tyre rubber do not have to coincide and can separate from each other. The method proposed by the authors seems to be original and different than those presented by others, where orthotropic material properties with direction angles were adopted [10] or the beams nodes were

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