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Investigations on lateral vehicle impact on moulded wooden tubes made of beech (*Fagus sylvatica* L.)

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HIGHLIGHTS

- Vehicle impact tests with a speed up to 100 km/h were performed with wooden tubes.
- The tests showed high frangibility and low energy dissipation of the wooden tubes.
- Confinement by fibre reinforcement effectively supresses spreading of wood debris.
- Moulded wooden tubes are a candidate for structures of infrastructure equipment.
- LS-DYNA and its MAT143 are suitable to model the failure behaviour of the tubes.

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ABSTRACT

Lateral vehicle impact tests on moulded wooden tubes were performed to estimate the suitability for infrastructure equipment like lighting poles. Initial speeds of the impacting vehicle of 35, 50 and 100 km/h were tested. Both the tested unreinforced tubes and a glass fibre reinforced tube were classified in energy absorption category NE according to EN 12767. A numerical model was developed in the finite element software LS-DYNA to establish a simulation tool for infrastructure equipment made of moulded wooden tubes. The simulations confirmed the experimental results regarding the failure behaviour and the quantitative deceleration of the vehicle during the crash.

1. Introduction

In 2015, 1427 persons died in the USA due to a street vehicle crash with a pole or a post, which were 4.4% of all fatalities related to motor vehicle crashes [1]. Another 49,000 persons were injured, which were 2.9% of all persons injured in crashes. Although the trend is decreasing, supposedly due to improvements in traffic and vehicle safety, there are still almost four persons dying in the average every day due to a crash with a pole in the USA. For Europe, a common data collection about crashes does not exist [2] but it can be assumed that there is a similar percentage of fatalities due to crashes of street vehicles with poles. Furthermore, it was shown based on European data that car to pole crashes have a high ratio of severe passenger injuries as [3] reveals.

The severity of the injury depends on both the design of the vehicle and the pole. This study is focussed on the contribution of the pole. An important property of the pole in this regard is the energy absorption rate during the crash. A high energy absorption rate involves a strong deceleration of the vehicle and parts fixed to it. Parts and bodies not tightly fixed, like baggage or the head of passengers, will continue moving due to inertia and act either like a projectile or experience high stresses in their attachment to the fixed part, which is the neck in case of the head.

From a mechanical point of view, more compact cross sections and materials with ductile, plastic failure behaviour will have a higher energy absorption rate than thin-walled cross sections and materials with brittle failure behaviour. Thus, reinforced concrete poles are unfavourable in terms of passenger safety because of the compact cross section and the ductile failure behaviour due to the reinforcement. Solid wood poles show brittle failure behaviour but the compactness of the cross section leads to a high energy absorption rate. Steel poles can be constructed with small

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wall thickness, which allows for a small energy absorption rate leading to a favourable solution. Poles of fibre reinforced composites (FRC) might have both small wall thickness and brittle failure behaviour and, thus, are advantageous for passenger safety.

The previous discussion based on mechanical properties revealed the applicability of profiles of steel and FRC in terms of energy absorption rate. However, equipment for infrastructure has to fulfil more requirements. Besides structural resistance under service loads, which is assumed to be achievable with all of the mentioned materials, requirements like high corrosion resistance, cost-effectiveness and, with increasing importance, also eco-friendliness have to be fulfilled. While steel solutions are, in general, prone to problems with corrosion resistance and eco-friendliness, FRC is often not cost-effective.

This led to the idea to use hollow wooden profiles, which fail brittle and have small wall thickness, for pole construction. Wood is usually considered as cost-effective and eco-friendly since it is a renewable material storing carbon dioxide. The corrosion resistance or durability might be challenging to be achieved over the entire lifespan but there exist preservation techniques from other outdoor applications of wood.

The objective of the presented study was to evaluate the potential of using hollow wooden profiles for infrastructure equipment. Therefore, remaining samples of a previous experimental study [4] were used to perform crash tests in order to develop and calibrate a numerical model based on the finite element method (FEM) for further development of wooden pole structures.

2. Materials and methods

2.1. Wood moulding technology

Wood moulding is a novel technology to produce structural elements of timber by means of plastic deformation [5–7]. Principles of wood moulding were recently presented in [4] by means of a mathematical description and the application to beech wood.

The prerequisite for the plastic deformability is the imposition of a compression set by means of densification transverse to the grain. Usually the densification is carried out in a hot-press at a temperature between 80 °C and 120 °C in order to soften the lignin, which is the matrix material in the cell walls connecting the cellulose and hemicelluloses. The densification of wood transverse to the grain is an established process in industry.

The compressed timber is processed to edge-glued solid timber boards with the densification direction in the plane of the board. For gluing, phenol-resorcin resin is suitable. By means of recovery of the compression set, the boards can be moulded and technical profiles like tubes can be produced. In order to enable the recovery, a hot steam treatment at a temperature above 100 °C is applied.

Based on this technology, circular hollow wooden tubes with a length of 3 m, a diameter of 0.3 m and wall thickness of 0.02 m were produced [4]. One of the tubes was reinforced with an outer layer of a glass fibre reinforced composite. The glass fibres were applied as a unidirectional fabric where the fibres were oriented in circumferential direction of the tube acting as a confinement. A polyester resin was used as matrix.

2.2. Properties of moulded wood

Beech wood (*Fagus sylvatica* L.) was applied, which was harvested in the Saxon Ore Mountains. After processing, the material in the tubes had a mean density of about 900 kg/m^3 at a moisture content of 6–8%. The mean Young's modulus was 17,000 N/mm^2. The compressive strength in longitudinal direction of the wood was 59 N/mm^2. More information about the properties of the applied wood is given in [4].

2.3. Properties of FRC

The FRC was composed of a polyester matrix (resin DISTITRON 429 BSXQ) and a unidirectional E-glass fiber fabric. The resin has a tensile modulus of 4000 N/mm^2 and a tensile strength of 50 N/mm^2 [8]. The glass fibers have a tensile modulus of 73,000 N/mm^2 and a tensile strength of 2600 N/mm^2 [9]. Two layers of fabric were wrapped as confinement of the tube at an angle of 90° to the axis of the tube leading to a fibre weight per unit area of 1200 g/m^2.

3. Experimental investigations

3.1. Brief literature review

Crash tests are associated with relatively large effort for preparation and expenses. Thus, the available published database is, especially regarding wooden poles, quite rare.

In the former century, several experimental studies about vehicle crashes at wooden poles were performed and also improved frangibility and energy absorption rate was attempted. In [10], tests of poles with horizontal holes drilled at the supposed impact position short above the street level are documented. Since the drill holes did not improve the frangibility of the pole sufficiently, experiments with thin-walled boxes of laminated veneer lumber were developed [11], which have properties comparable with the investigated moulded wooden tubes. In recent years, publications about crash tests with wooden poles are rare, supposedly due to the domination of steel and concrete in this field of application.

The behaviour of wooden guardrail posts where the poles are expected to withstand the impacting vehicle, is, e.g., investigated in [12–14].

3.2. Test setup

Four crash tests, three with an unreinforced tube and one with a reinforced tube were performed with impact velocities of 35, 50 and 100 km/h. Table 1 gives an overview of selected properties for each test. The tests were carried out according to EN 12767 [15], which defines the requirements for crash tests of support structures of road equipment. The moulded wooden tubes used for the test had the following approximate dimensions: 0.3 m of external diameter, 0.02 m of wall thickness and 3.0 m of length. The mean density of the wood was about 900 kg/m^3.

The pole was positioned vertically at the end of a paved runway in a pit excavated for about 1 m in the ground. In order to avoid the tube to be pulled out during the impact in tests with a velocity of 100 km/h, steel rebars with a length of 1 m and a diameter of 12 mm were inserted in the bottom part of the moulded wooden tube with an end distance of the holes in the wood of about 0.2 m. Then the pit was filled with standard soil and compacted, following the prescriptions of [15]. Hence, about 2 m of the pole were remaining above the ground, see Fig. 1a.

On the opposite end of the runway, the paved area continued for more than 12 m followed by a deceleration area filled with non-compacted gravel. The adopted vehicle for the tests with a velocity of 100 km/h was a surrogate for a series-production vehicle according to [15]. The frontal impactor of this bogie vehicle was constructed from a spot-welded grid of standard steel tubes possessing a diameter of 100 mm and wall thickness of 1.5 mm and 2.0 mm; see Figs. 1 and 6. The bogie vehicle was tested to comply with the requirements for test vehicles according to [15]. On the front tube of the impactor, a pressure sensor was applied serving as a trigger to identify the time of impact in the measured data. In the tests with 35 and 50 km/h production vehicles were used.

The vehicle was accelerated on the runway by a cable system up to the desired velocity and released a few metres before the impact point, see Fig. 1a. This system simulates an impact with a specific velocity letting the car freely move in any direction after the impact.

A triaxial measurement device for determining accelerations $a_x(t)$, $a_y(t)$, $a_z(t)$, a device to measure the rate of yaw $\dot{\psi}(t)$ and a GPS receiver were attached to the vehicle to continuously determine accelerations and velocities. Moreover, two high speed cameras were positioned at the lateral side of the test site to observe the failure behaviour.