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Numerical and Experimental Analyses of a Lighting Pole in Terms of Passive Safety of 100HE3 class

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Abstract

Nowadays trends related to the road safety make the lighting poles producers meet rigorous requirements that decrease the risk of death and injury of vehicle drivers in case of the impact. New requirements are in force from 1 January 2015, when Road and Bridge Research Institute informed that each pole liable to a direct vehicle impact has to meet Standard PN-EN 12767. The article presents the design of a novel, safe lighting pole. The novelty lies in the pole simplicity, which results in the manufacturing technology the cost of which is comparable to that of the conventional pole. Compared to the conventional poles of thickness 3 mm and greater, this one is made of thin-walled steel sheet of increased strength parameters and specially designed sleeve that is fixed to the base plate. The crash tests carried out on the track for the impact experiments proved that the requirements of the standards in the driver highest safety class and in the high vehicle kinetic energy absorption were satisfied both for the speed impact 35 km/h and 100 km/h. The numerical model for simulations of the vehicle behaviour during and after the impact was implemented in software Ansys LS-Dyna. The simplifications of some elements were of negligible influence on the analysed phenomena. The comparative parameters were ASI, THIV and exit velocity of the vehicle. The numerical results were close to the empirical ones, therefore they confirmed that finite element analysis can be successfully applied at the stage of elaborating of the initial concepts of the road lightning poles. It follows that the number of expensive crash tests can be reduced.

Keywords: Passive safety, crash test, EN 12767, finite element method, Ansys LS-DYNA

1. Introduction

Nowadays trends in road infrastructure manufacturing cause that constant efforts are focused on increasing the safety on the roads. As a result of such an approach, new lighting pole designs have to be tested on account of the safety in terms of European Standard EN 12767. Such requirements make the implementation of this product time-consuming and expensive. The usage of the FEM-based software could significantly shorten the implementation time and reduce its costs.

The article presents the design of an innovative lighting pole that meets conditions of the passive safety. The pole had been tested according to the standard [2] and the empirical results were set together with the results of the numerical simulation. The researches were devoted to working out the design that may cause maximally a 10 percent increase in manufacturing costs in comparison with the conventional pole of the same size and strength parameters. The article constitutes the continuation of the achievements described in [12]. The paper [12] deals with the pole that is fixed to the ground base by means of a different technique than the one used in the present work. As a result of the structure modification, by adding two especially designed half-sleeves, the fracture of the pole during car crash is avoided, and consequently a higher amount of the kinetic energy can be absorbed by the pole.

More and more number of the road poles producers follow the nowadays trends and offer products meeting passive safety standards, but because of the trade secret the literature is short of the descriptions of the pole designs. This is why the significant part of the state of the knowledge on the available structures comes from patent documents.
By analysing this structures, one can conclude that mostly the pole columns are designed to absorb energy of the car. The structure of the conventional poles is characterized by high stiffness that allows for transmitting forces caused by the wind pressure and forces caused by the weight of the pole with bracket and luminaire. Such poles absorb an extensive amount of car energy, which brings about too big risk of injury of the car driver. Various modifications were made to weaken the pole, e.g. the pole column was longitudinally cut [4] or the welded connection was replaced with the riveted one [5]. The paper [6] presents the application of the thin-walled material with the pipes and flat bars mounted inside the column to compensate the excessive loss of the loading capacity and stiffness. Another approach for absorbing car energy is described in [7] where the special connector at the ground level and the rope inside the column are used. For relatively small shear forces, it is expected that the connector breaks the connection between the column and the ground base plate at the instant of collision. Such a structure behaves like a non-absorbing energy pole, the only difference is that the additional rope decelerates the car in a controlled way.

The review of the literature focuses on the thematically closest articles [8-11]. The poles described there differ in manufacturing technology: structures reinforced with laminate [8] or beech wood as well as wood reinforced with laminate [9]. Another difference with the poles considered in this paper is that the poles presented in the literature do not absorb energy [10] and moreover they are not assigned to the category of passive safety [9, 10] defined in the standard [2]. The FEM LS-Dyna was utilised in [8] to numerically analyse the impact of a car into the pole. The progress of the deceleration showed a good correlation with the experimental results. The maximum deviation of the relative decelerations recorded during the experiment and obtained from the simulation was about 14 percent. The results proved that numerical analyses give satisfactory and reliable results. The studies presented in [11] and the ones discussed in this article were performed with the same machinery and on the same track for impact experiments, and the first author of this paper took active part in those studies. The numerical analysis were also carried out, and the results proved the usefulness of the LS-Dyna software in simulating impact tests with both reinforced and non-reinforced wooden pipes.

2. Crash track equipment, requirements and test methods

Before the crash tests were carried out, the pole had been tested by means of the company Eurpoles proprietary software for strength calculations. The software enables static analysis of a pole subjected to the wind pressure and weight of masses hung on it. The track for the crash test, designated for passive safety studies, is a specifically designed truck that can be used instead of a conventional vehicle. Nonetheless, the tests results for the truck are characterized by a higher repeatability because of a lower number of variables. The measuring equipment was mounted on the truck. During the experiment, there were measured the accelerations in three axes in the range ±600*g* and angular velocity up to 3000 rad/s. All data were recorded into a computer with a sampling rate of 10000 Hz. The area of 6 m before and 12 m behind the point of the impact was recorded by two high-speed cameras. The parameters of the camera are as follows: a frame rate of 500 fps and a resolution of 800×600 pixels. All the data recording was triggered by two contact sensors placed on the bumper of the truck and on the column of the pole. All the tests were carried out according to the recommendations for passively safe support structures for road equipment included in the standard EN 12676 "Passive Safety of Support for Road Equipment Requirements and Test Methods".

Table 1. Categories of energy absorption (own elaboration on the basis of [2])

Energy absorption category	Exit velocity v_e [km/h]		
	50	70	100
HE – energy absorption in the high degree	0	$0< v_e \leq 5$	$0< v_e \leq 50$
LE – energy absorption in the low degree	$0<v_e\leq5$	$5< v_e \leq 30$	$50< v_e \leq 70$
NE - non energy absorption	$5< v_e\leq50$	$30< v_e \leq 70$	$70< v_e \leq 100$
„0” – no requirements	-	-	-

Table 2. Safety classes (own elaboration on the basis of [2])

Category of energy absorption	Driver safety class	Test mandatory at low speed of 35 km/h		Test for velocity class of 50, 70 and 100 km/h	
		ASI	THIV [km/h]	ASI	THIV [km/h]
HE	1	1,0	27	1,4	44
HE	2	1,0	27	1,2	33
HE	3	1,0	27	1,0	27
LE	1	1,0	27	1,4	44
LE	2	1,0	27	1,2	33
LE	3	1,0	27	1,0	27
NE	1	1,0	27	1,2	33
NE	2	1,0	27	1,0	27
NE	3	1,0	11	0,8	11
NE	4	-	-	-	3

The aforementioned standard specifies the conditions that have to be met to reduce the injury risks to vehicle occupants in case of the crash into a pole. Poles can be classified at a particular speed or speeds dependent upon the speed at which they are tested and the observed collapse mode. As shown in Table 1, there are three energy absorption categories. Each category specifies the safety of car occupants. The lowest class 1 is assigned to HE supports that provide the highest risk of injury to vehicle occupants, and the highest class 4 is assigned to NE supports that provide the lowest risk (Table 2). Category LE and HE supports reduce the risk of secondary incidents and collisions with non-motorized users, as the vehicle exit speed is lower, and thus can have advantages on built-up roads where there is a significant volume of such users. The safety classes are dependent on Acceleration Severity Index (ASI) and Theoretical Head Impact Velocity (THIV). Both severity indices are calculated according to the standard [3]. ASI is dependent on the acceleration in all three axes and computed from the formula:

$$ASI(t)=\left(\left({a_x}/{12}\right)^2+\left({a_y}/{9}\right)^2+\left({a_z}/{10}\right)^2\right)^{1/2} \qquad (1)$$

THIV is a theoretical velocity of the head impact into the steering wheel, and is computed from the negative overloading and angular velocity of the vehicle. The value of the angular velocity is computed after the head has displaced 0.6 m along the longitudinal vehicle axes and 0.3 m along the transversal vehicle axis. Notwithstanding the pole category (NE, LE and HE) and velocity class (50, 70 and 100 km/h), the tests are carried out at the vehicle velocity of 35 km/h and at the declared velocity (50, 70 and 100 km/h), e.g. if the pole is assigned to the velocity class 100 km/h, the tests are carried out for vehicle velocities 35 km/h and 100 km/h. The impact angle is characteristic to the vehicle driving off the road at an angle of 20 degrees.

3. The project of the novel, safe lighting pole

The project of the pole is a trade secret, therefore the external elements are described, whereas the details are not revealed in this work. The novel structure of the lighting pole is attached to a prefabricated concrete foundation of height 1.2 m. The foundation is installed on firm soil, beat mechanically in the layers of height less than 300 mm.

The base plate 400×400×25 mm along with a specifically designed half-sleeve is mounted to the pole column with fillet weld using the MAG method. The total height of the pole is 12 m, the components of the pole are the 10.2 m high column and the 1.8 m high bracket mounted by means of 8 screws. A peak diameter equals to 76 mm, the taper is of 14 mm/m.

The steel used to fabricate the pole has increased strength parameters S355 and thickness of 2 mm. The pole column is shaped on an edge press and longitudinally welded. The steel batch employed to manufacture the pole had been subjected to static tensile tests. The strength parameters obtained in this test are gathered in Table 3. Two samples were taken from various parts of the steel batch in order to observe the distribution of the mechanical properties along the whole length of the batch. The tests did not revealed any significant changes in the mechanical parameters, moreover they are close to those characteristic of the steel grade.

The pole is designed in order to absorb the energy in a controlled way, i.e. in the way that guarantees a reduction of the vehicle speed from 100 km/h at the impact instant to 50 km/h at the instant when the vehicle has travelled 12 m from the pole. To meet this performance, the pole cannot loose the connection with the ground, and simultaneously energy absorption should be made on the distance as long as possible, without causing any excessive overloads in the vehicle.

Table 3. Strength parameters of steel taken from tensile test (own elaboration)

Sample	Area [mm^2]	Yield strength [MPa]	Tensile strength [MPa]	Elongation [%]
BD-09-2013-001	76.03	378.75	467.15	33
BD-09-2013-003	76.13	380.77	462.51	33

4. Experimental studies

Experimental study of the innovative pole had been preceded by the calibration of a test truck. In the calibration test the truck impacts into the steel pipe with 290 mm in diameter and 1.1 m in height (measured from the ground) at the speed of 35.77 km/h. During the test, the displacement of the steel pipe after the impact cannot exceed 10 mm. As a result of the calibration, Seat Ibiza car was authorised. The total mass of the car along with the measuring equipment and ballast manikin was 930 kg.

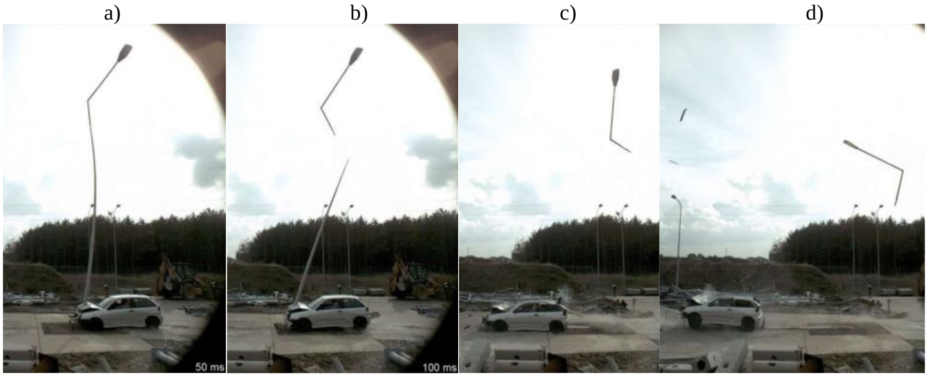

Figure 1. Camera pictures taken:
a) 50 ms, b) 100 ms, c) 300 ms, d) 600 ms after the impact

The assembly of the pole in the ground was made according to standard EN 12767. The soil meets the requirements, if it consists of stone and gravel of precisely defined proportions and granular size. The area of backfill was flat and concentrated in 30 cm thick layers by means of the beater of 150 kg. The pole point of the impact was located in the centre of the car bumper with a tolerance of ±0.1 m. The impact angle simulated the car driving off the road was equal to 20°±2°. The measured impact velocity was 98.05 km/h. The subsequent instants of the impact are shown in Fig. 1.

The variations of indices ASI and THIV are shown in Fig. 3. The approximate rounded up maximum value of ASI is 1.0. The velocity of the head with respect to the car is shown in Fig. 3b. THIV equals 27, as the head hit the steering wheel with the speed of 27 km/h. The vehicle moved further than 12 m from the impact location, and its exit velocity computed from the values registered by the three-axes accelerometer and the initial velocity given by GSP was 29.4 km/h. On the basis of these parameters, the pole could be classified as a structure absorbing energy in high level and assigned to the highest driver safety class for impact velocity of 100 km/h, i.e. to 100HE3.

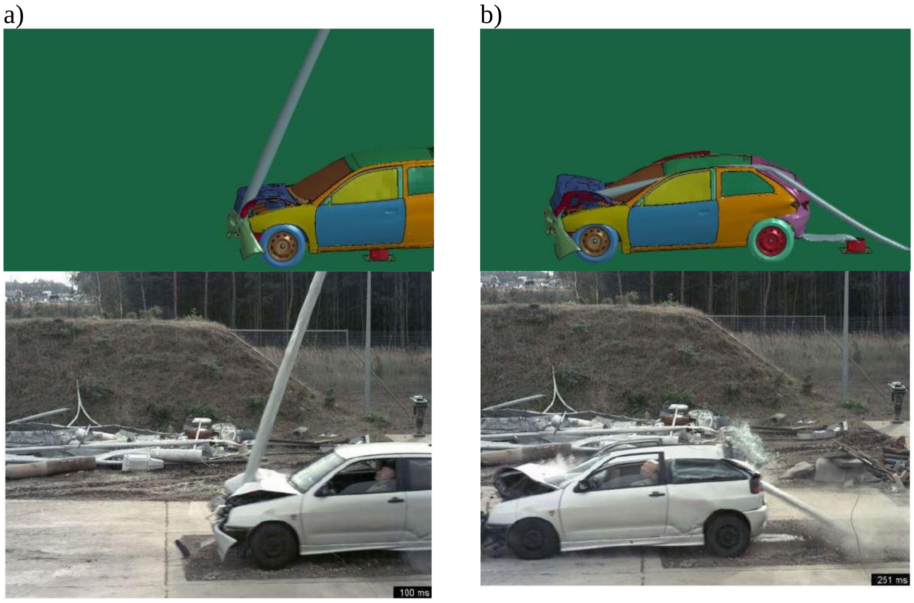

Figure 2. The visualisations taken from the numerical simulation (a) and the camera pictures (b) for two time instants: 100 ms (left) and 251 ms (right) after the impact

5. Numerical simulation

The finite element analysis was performed using LS-Dyna software. The method with an explicit integration of equations of motion ("Explicit Dynamics") was applied to analyse the pole and car behaviour at and after the impact instant. The method is utilised to analyse high-velocity impacts which are accompanied by large loads causing large material deformations [13]. The numerical computations were conducted using the preprocessor LS-Prepost, in which physical phenomena were defined, the mechanical system was discretized, and results visualisation and analysis were carried out. Ansys SpeClaim software conversed the solid model into the shell model. The data read from the virtual accelerometer located in the car allowed for computing values of the severity indices: ASI and THIV.

The numerical model of the pole was built entirely of shell elements. The discretization of the pole model was realized with the option of reduced integration due to large plastic deformations. For the car, which did not deform in such an extent, and for which computation accuracy is essential, the full integration option was applied. The inner parts of the car were welded to each other. The model consisted of 242 000 elements, and the mesh size was about 10 mm. In order to prevent from mutual penetration of the pole walls, the contact the option *automatic single surface* was set up. On the contrary, the allowed contact surfaces between the pole and car were defined using the option *automatic surface to surface*. The base plate of the pole was fixed by taking away all the degrees of freedom. Ford Geo Metro car model was used in the simulation, and the only modification of the car consisted in locating virtual accelerometer in its mass centre. The car was initially set in the same position as during the experiment carried out in the test track. Then, the initial velocity at the impact instant was 98 km/h. The gravity forces were taken into account in the numerical simulation. The multilinear constitutive model of the pole material, composed of eight segments based on the stress-strain curve, was applied. In the presented analysis the strain rate was not taken into account.

The severity indices ASI and THIV were treated as the major criteria of the result evaluation. The way the pole was being deformed was also analysed. The chosen numerical visualisations of the impact and corresponding pictures taken during the experiment are presented in Fig. 2. For the comparative purposes, the severity indices for numerical and empirical tests were presented together in Fig. 3. In the numerical simulation, ASI achieved the maximum value of 0.99 at time $t = 0.072$ s. Similarly, one can observe a high conformity between the numerical and empirical values of THIV, that was of 30 km/h in the simulation (Fig. 3b) and of 27 km/h in the experiment. A higher deviation was observed for the exit velocity, which in the numerical simulation was equal to 11 km/h, whereas in the experiment it was nearly three times greater.

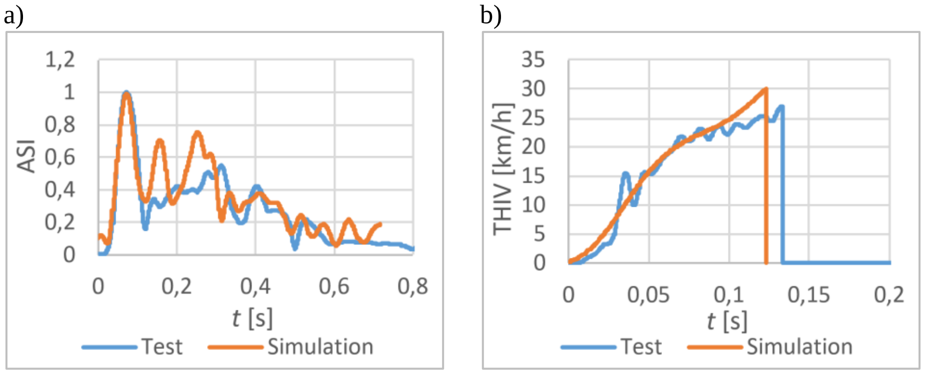

Fig. 3. Results from the numerical simulation and experiment: a) ASI, b) THIV

6. Conclusions

The results of the numerical simulation are close to the ones of the empirical test. The deviation of ASI index is less than 1%. The deviation of THIV index was greater, but still less than 10%. The results differ only in the exit velocity. The new pole, which has been developed, certified by an independent laboratory and introduced to production, will certainly contribute to increasing the safety on the roads. The numerical simulations reflect the real dynamical progress of the analysed phenomena in such a degree that one can state their reliability. The computer software can be implemented at the initial stage of design of subsequent poles. It will significantly reduce the production costs. It should be noticed, though, that the numerical computations are very time consuming, therefore the model and simulation for only one crash test were worked out and performed. A greater number of simulations would offer a much wider perspective on the advantages of computer software usage.

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