Numerical Reconstruction of the Real-Life Fatal Accident at Work: A Case Study

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Abstract. Every year about 2.8 million people are injured in accidents at work in Europe. The resulting high costs are incurred by the victims themselves, their families, employers, and the society. A numerical simulation can be used to reconstruct accidents and to provide information about the course and cause of those accidents. This knowledge is crucial in developing successful safety systems and safety procedures.

This paper presents a multi-body approach to reconstructing a real-life fatal accident of a forklift that overturned with its operator. A reconstruction took place to find out why forklift overturned. This study consisted of about 700 simulations. Their results were compared to data from the real accident. The path of simulated wheels and the location of the model of a forklift after the accident corresponded to the real tire tracks and the final location of the real machine. The location and position of the computer model of the operator was similar, too. The injury criteria obtained in the simulation exceeded the critical values for the head and neck, which corresponded to the operator's injuries: numerous fractures of the skull and cervical spine fracture with dislocation. Thus, speeding and a sudden turning maneuver caused the accident.

Keywords: accident reconstruction, computer simulation, multi-body, MADYMO, human model.

1 Introduction

In spite of increasing accident prevention the number of accidents at work is still very high. In EU 27[1] in 2009, 2.8 million people were injured in accidents at work [1]. In Poland, 90 000 people per annum are injured as a result of those accidents [2]. In 2002, according to some estimates, the total cost of all accidents at work in Poland incurred by the victims, their families, employers, and the society was approximately 2 200 million PLN (740 million USD). Thus, a reduction in the number of accidents at work can have high social as well as economic benefits. A proper understanding of the course and cause of accidents is a major factor in accident prevention. This knowledge is crucial in developing systems and procedures that are to be successful.

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[1] EU 27 – Twenty seven is the number of member states in the European Union.

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However, it is often hard to identify the precise course of events on the basis of the evidence at the site of an accident. In such cases a numerical simulation can help reconstruct accident-related events. Computer simulations can improve safety; they can also help in establishing responsibility in court.

For years, numerical simulation has been successfully used in reconstructing road accidents. These analyses simulate the dynamics of vehicles, the behavior of their occupants, and their injuries. Advanced simulation software, e.g., PC Crash[2] and MADYMO [3], is used for this purpose. Road accidents can be reconstructed with either of two main numerical simulation methods, the finite element method or the multi-body dynamics method. In addition to accidents involving cars only, collisions of cars and motorcycles [4] or pedestrians [5] are reconstructed, too. The analyses focus then on evaluating injuries. Adapting the methodology of reconstructing road accidents to reconstructing accidents at work is not easy. There are fewer configurations of car accidents, for example. Moreover, the occupants of cars are usually in their seats restrained with safety belts; even the configuration of the cars involved is often typical. On the other hand, each accident at work can be configured differently. Hence, each case requires an individual approach. In spite of those problems, or possibly because of them, researchers work on reconstructing accidents other than car-related. O'Riordain [6] used multi-body modeling software to reconstruct real-life head injury accidents resulting from falls. Their aim was to compare simulation output with sustained injuries. Doorly [7] used the MADYMO Pedestrian model with an adapted finite element brain model to reconstruct real-life accidents with injuries resulting from falls.

The aim of this study was to reconstruct a real-life fatal accident at work on the basis of numerical simulations. The accident involved a forklift that overturned with its operator. The study was carried out at the Central Institute for Labour Protection – National Research Institute (CIOP-PIB).

2 Methods

2.1 Overview

Method of reconstructing accidents at work with numerical simulations can be used to reconstruct accidents related to mechanical hazards: falls, overturns, or impact by objects. The sequence of events that led to an accident is determined with equations describing the mechanical properties of real objects. This task requires computer models of all objects and persons involved in the accident and defined initial conditions. The reconstruction will be accurate if the initial models and conditions are faithful; this is relevant for the quality of data describing an accident and its site. These data are usually incomplete, sometimes inaccurate or even contradictory. In the reconstruction such data must be considered multiple variants of the initial conditions. Simulating each variant leads to identifying the most probable one. This methodology

[2] MEA Forensic Engineers & Scientist. Retrieved January 28, 2013, from: `http://www.pc-crash.com`

is successful for road accidents. For accidents at work it has to be altered. These accidents are very diverse, each one has to be reconstructed individually. Even so, some steps in the procedure of the reconstruction are the same.

2.2 Numerical Simulation and Software

Accidents at work differ from road accidents. There are numerous possible scenarios such as falling, being crushed or being hit with parts of machinery. In these accidents, attention should be focused on the behavior of the human body. Kinematics and dynamics of the human body can be modeled with numerical simulation using multi-body (MB) and finite element (FE) methods. The reconstruction analysis described in this paper was done with MADYMO crash simulation software [3], with the MB method.

MADYMO combines two types of solvers in one simulation program: the MB module for simulating the motion of the body and its systems, and FE methods for simulating the motion of deformable structures. The MB model consists of a chain of rigid bodies connected with joints. Loads, contacts, and restraints (such as friction in joints or spring-dampers) can be defined to simulate real conditions. Differential equations describe motion, they are solved with numerical integration, which results in displacements, velocities, and accelerations of rigid bodies. These data, together with masses and moments of inertia, are used to calculate forces and moments. The FE model is deformable; the deformation depends on the properties of the material. The motion of the body can be defined with initial velocity, a prescribed motion, or an acceleration field. Contact interaction between any surfaces can be defined. In MB, contact between planes, ellipsoids, cylinders, and FE models can be defined. Moreover, physical parameters like damping or friction can be incorporated in contact definitions. For both MB and FE contact forces prevent surfaces from going through each other and if a deformable structure is used, it is deformed in accordance with the properties of the material. Loads and constraints can be applied on every deformable structure [3].

2.3 Injury Evaluation

Numerical simulation can be used to evaluate probable injuries. This is done with so-called injury criteria; they provide correlation between physical quantities such as resultant accelerations, forces, or moments of force measured at the time of impact, and the probability of a body subjected to the same strain sustaining an injury. There are different injury criteria for injuries in different parts of body. Injury criteria are not all-purpose, they are limited by the range of cases for which they were validated. These criteria do not provide detailed information on injuries but they do provide the probable level of the injury according to a predefined scale. Abbreviated injury scale (AIS) describes most injury criteria; it ranges from 1 (minor injuries) and to 6 (virtually unsurvivable) [8].

3 Reconstructing Real Accidents

One real-life example of a fatal accident of a forklift overturning with its operator will illustrate the method of reconstructing accidents at work. Because there were no eyewitnesses, the cause of the accident could only be inferred from tire tracks. The most probable sequence of events that led to the accident and its cause were established on the basis of a reconstruction.

3.1 Description of Accident

The accident happened in front of a warehouse. The operator was driving a forklift around the square and loading pallets onto a delivery truck. All other workers had their lunch break. While they were inside a building, they heard a loud noise. They immediately ran outside, where they saw the overturned forklift. The frame of the forklift crushed the operator; it had pinned his neck to the ground. He died on the spot. He had not fastened his seat belt. There were tire tracks close to the forklift.

Because there were no eyewitnesses, it was crucial to determine the cause of the accident. It was necessary to find out whether a forklift could make a turning maneuver that would result in its overturning. A computer simulation would make it possible to determine the initial speed of the forklift and to describe the turning maneuver.

3.2 Simulation Models

Forklift Model. A computer model of the forklift was created on the basis of the technical specifications of the real forklift. Table 1 lists data that defined the model.

Table 1. Technical specifications of the forklift

Characteristics		
Curb weight	3485	(kg)
Load center	500	(mm)
Width/Height	1150/2110	(mm)
Turning radius	2190	(mm)
Wheel base	1650	(mm)
Front tires diameter/Width	672/192	(mm)
Rear tires diameter/Width	540/160	(mm)

There is no information on the maximum speed of this kind of forklift in the technical specifications. So, for the purpose of this simulation, the maximum speed of the forklift was defined as 25 km/h (such speed can be reached by similar types of forklifts). On the basis of the turning radius, the maximum angle of the wheels was calculated as 40°. The forklift model consisted of rigid bodies with masses and moments of inertia. Ellipsoids described the outer surface. Interaction between the forklift and the ground was simulated with an elastic contact model. In MADYMO, it is possible to define contact interaction between a master surface and a slave surface, and contacting surfaces can penetrate each other. Penetration of the surfaces depends on the elastic contact force. This dependency can be defined as the force-penetration characteristic [3]. The first contact was defined between the ellipsoids describing the wheels and the plane describing the ground. The friction coefficient was a variable parameter. The second contact was defined between the ellipsoids describing the body of the forklift and the ground. The friction coefficient was set to 0.4. In both contacts the force-penetration characteristics were set according to data obtained from the MADYMO model database. The movement of the forklift was simulated with linear velocity set on the forklift and angular velocity set on the wheels. The turning of the forklift was defined with a function that changed the angle of the wheels during the simulation. In four-wheel vehicles the angle of turning for the outside wheel is different from for the inside wheel, and this is so because of the kinematics of such vehicles. The angle of each turning wheel was calculated separately on the basis on this function. The function of the turning of wheels was defined on the basis of two parameters describing this maneuver: the maximal angle of the wheels and the time necessary to reach that angle. The maximal possible angle was set to 47.8° for the inside and 34° for the outside wheel on the curve of the road and the time to reach those angles was set between 0.5 and 2 seconds.

Model of Tire Tracks. Three tire tracks were identified as traces of three wheels of the forklift sliding on the ground. Photogrammetry [9] based on photographs taken at the site of the accident was used. Photogrammetry consists in drawing a grid on the photo that is based on a reference pattern. Any object with known dimensions can be used as a pattern. In this case it was a paving block. The procedure was as follows: the grid was applied onto the photo and matched to the pattern of paving blocks; the image with the grid was turned into an orthogonal projection; the projection was used to create a 3D model of the tires tracks.

Human Model. A computer model of a human is the most critical aspect of reconstructing an accident. We selected one of the many types of dummies and human models in the MADYMO database: the Pedestrian (Fig. 1). The Pedestrian was developed with the MB method; it consisted of 52 rigid bodies with defined mass, center of gravity, and moments of inertia. Ellipsoids described the geometry of the model. Bodies are connected via different types of joints. These joints are restrained by functions describing parameters such as friction and damping in order to simulate human joints. The Pedestrian has 11 contact interactions between the following parts of the body defined by default: head and torso, lower extremities, upper extremities, and thorax and pelvis. These are elastic contact models with force-penetration characteristics and parameters defined on the basis of biomechanical research on the human body [10]. Moreover, for the purpose of the simulation, contact interactions human – forklift and human – ground were defined. The Pedestrian made the following outputs possible: animation with the kinematics of the body, forces that had been recorded, moments of force, displacements, positions, velocities, and accelerations of body segments.

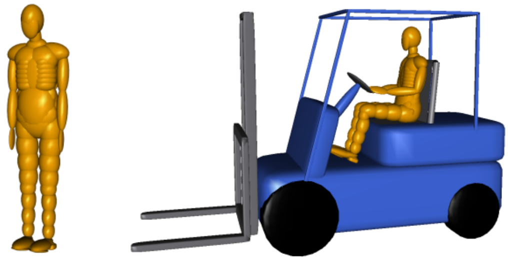

Fig. 1. The Pedestrian from MADYMO database (left) in a standing posture and (right) seated in the forklift

3.3 Simulation Analysis

The simulation focused on finding a set of initial conditions that would make the simulation result as close to the accident result as possible. The comparison focused on the shape of the tire tracks and the place where the forklift was located at the end of the accident. The analysis had two phases. First, the ranges of parameters for which it was possible for the forklift to overturn were determined. Then, those parameters were modified—within those ranges—to match the tire tracks.

Identifying the Initial Conditions Leading to the Accident. Four parameters were considered as variables in this phase: speed at the beginning of the curve, maximal angle of the wheels, time to reach the maximal angle of the wheels, and the coefficient of friction between the road and the tires. The simulations aimed to establish ranges of those parameters for which the forklift could overturn. To do this parameters were changed as follows. Initially the parameters were set to maximal (speed, angle of the wheels, and friction coefficient) or minimal (time to reach the angle of the wheels) values for this type of forklift. The model of the forklift overturned in those initial conditions. Next, the parameters were changed in pre-determined steps until the forklift no longer overturned. Initially, the maximal speed of the forklift was set to 25 km/h, then it decreased by 0.5 km/h. The maximal angle of the wheels was set to 40°. This angle was reduced in one-degree steps. The speed of turning the steering wheel was defined as a function of time. The time to reach the maximal angle was 0.5–2.0 s. The friction coefficient corresponded to friction between rubber and dry concrete. It was changed in the range of 0.25–1 [11]. Table 2 lists the obtained ranges of parameters leading to the forklift overturning.

Table 2. Parameters of the simulation models leading to the forklift overturning

Speed (km/h)	Maximal angle of wheels (°)	Time to reach maximal angle (s)	Coefficient of friction between tire and ground (–)
18	40	0.5–2	1
19	31–40	0.5–2	0.85–1
20–25	31–40	0.5–2	0.85–1

Matching Simulated Wheels Path to the Tire Tracks. This phase determined values of variables in such a way that the path of the simulated wheels would match the tracks from the accident site. The results were considered positive if the simulated wheels moved inside a 180-mm wide corridor around the tracks.

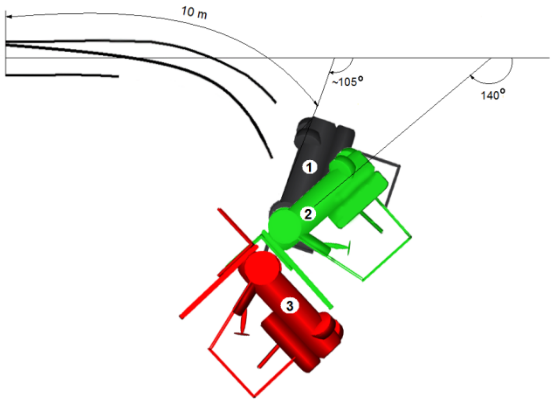

Fig. 2. Rotation of forklift at the end of accident: 1 – rotation of real forklift; 2 – borderline acceptable rotation of simulated forklift (140°); 3 – unacceptable rotation (>140°)

The simulation was successful if speed was set to 22–25 km/h, whereas the angle of the wheels to 38–40° and friction coefficient to 0.9-0.95. Although in these cases the path of simulated wheels was inside the corridors, the final location of the overturned forklift was sometimes drastically different than in the accident. Two problems were identified. Firstly, sometimes the forklift drove much further before it hit the ground. According to the tracks from the site of the accident, the rear left wheel covered 10 m from the beginning of the tracks to the place where they stopped moving. To eliminate this problem, results where this distance was approximately 10 m were considered only. Secondly, the final rotation of the overturned forklift was sometimes much higher than in the accident. In the actual accident it was around 105° (Fig. 2, position 1), whereas in the simulation it sometimes exceeded 180° (Fig. 2, position 3).

This problem, however, strongly depends on the definition of contact between the side of the vehicle and the ground. This contact was difficult to simulate because of insufficient data and the complicated shape of the forklift. So, all results where this angle was not greater than 140° were considered correct (Fig. 2, position 2). The fit of the tire tracks was best with the friction coefficient of 0.9 but in that case the location of the overturned forklift was outside the acceptable area. This could be so because real ground was not smooth; paving blocks covered it and during the slip, a tire could catch on the edge of blocks. To simulate such a situation, the friction coefficient was changed during the slip of the tire from 0.9 to 1.7.

4 Results

4.1 Position of the Forklift and the Operator

After about 700 simulations, a set of parameters was found for which the forklift overturned in an acceptable area. The speed at the beginning of the curve was 23 km/h, the wheels were at 39°, the time necessary to reach that angle was 2 s, and the coefficient of friction between the road and the tire was 0.9, increasing at the end to 1.7. Figure 3 illustrates the position of the forklift.

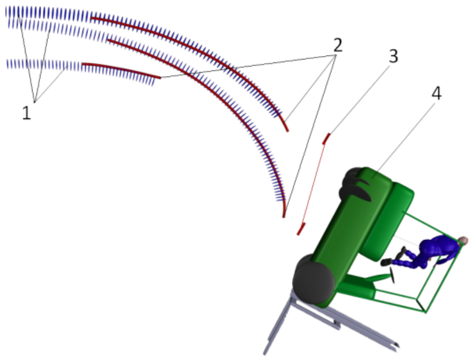

Fig. 3. Position of oveturned forklift with simulated reference tire tracks. 1 – simulated path of wheels; 2 – tire tracks of real forklift; 3 – position of real wheels; 4 – position of simulated forklift.

The results follow:

- The path of the simulated wheels was inside a 180-mm-wide corridor outside the tire tracks.
- The path of the simulated wheels ended before the tire tracks (i.e., before the place where the tires lost contact with the ground). The difference was 0.2–0.3 m.
- The final position of the simulated forklift was about 0.6 m further than real tracks indicated.
- The rotation of the overturned forklift was 118° (as opposed to 105° in the actual accident).
- The driver fell off his seat during the accident. The frame of the forklift hit his neck and pinned him to the ground.

4.2 Injuries

The autopsy report listed serious head (abrasions, bruises, and numerous skull fractures) and neck (cervical spine fracture with dislocation) injuries. That is why the acceleration of the head and forces in the neck were measured during the simulation. Thus it was possible to evaluate the injuries on the basis of the head and neck injury criteria.

Table 3. Values of injury criteria for the head and the neck

Body part	Injury criterion	Value	Critical value	AIS
Head	HIC 15 ms	20 859	>1800 (severe life endangering fracture) [12]	4–5
Neck	For- & rearward shear force Fx (N)	14 285	>3300 (major neck rupture and dislocation) [13]	4–6
	Lateral shear force Fy (N)	7377		
	Axial force Fz (N)	4407		

Notes. AIS – abbreviated injury scale [8], HIC – head injury criterion [14].

Head injuries were evaluated with HIC. This injury criterion was calculated by MADYMO software on the basis of resultant acceleration of the head's center of gravity. Neck injuries were evaluated on the basis of shear and axial forces measured in the neck segment; they were then compared with critical values. The measurement of these forces was possible because the Pedestrian model has virtual load cells implemented in most parts of the body including the neck segment. The results indicated that the injuries for both the head and the neck were critical (Table 3).

5 Conclusion

By changing initial conditions it was possible to match simulated paths of the wheels to the tire tracks from the site of the accident. The simulated wheels moved in a 180-mm-wide corridor, which was comparable to the width of the tires. The operator's injuries estimated with injury criteria matched the autopsy report. Moreover, the final position of the overturned forklift matched tracks in the actual accident. Any differences could have been caused by the simulated contact between the frame of the forklift and the pavement. Real contact was much more complex and should be modeled more precisely. According to the description of the actual accident, after the forklift overturned, the operator was in a sitting position with the frame of the machine pressing his head to the ground. As a result of the simulation, the human model, ejected by the centrifugal force, was pinned to the ground, with the frame of the forklift pressing on its neck. That was exactly how the accident had been described. The configuration of his extremities was different, though. This may have been caused by the operator's movements, which were not simulated. Another conclusion can be drawn, too: the operator's behavior in the last phase of the accident did not have much influence on the overall result. A comparison of the simulation results with the values for the injury criteria of the head and neck shows that both the head and the neck exceeded the critical values, which means life-threatening skull fracture and serious fracture with dislocation of the cervical spine. According to the description of the accident, that is exactly what happened to the operator of the forklift. An analysis of the results shows that speeding and a sudden turning maneuver were the causes of the accident.

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