Safety Science 101 (2018) 98–107

Contents lists available at ScienceDirect

Safety Science

journal homepage: www.elsevier.com/locate/ssci

Numerical analysis of passive safety systems in forklift trucks

Marcin Milanowicz *, Paweł Budziszewski, Krzysztof Kędzior

Central Institute for Labour Protection – National Research Institute, Poland

ARTICLE INFO

Article history:
Received 20 December 2016
Received in revised form 7 July 2017
Accepted 13 July 2017

Keywords:
Passive safety
Numerical simulation
Injuries criteria
MADYMO
Accident analysis
Multibody dynamics
Numerical human body model

ABSTRACT

90 accidents involving forklift trucks occur each year in Poland, resulting in nearly 100 injured persons including 10–15 fatalities. The most frequent and most dangerous accidents include those caused by the loss of stability of a forklift truck with the operator inside, resulting in its tip-over. More than a half of this type of incidents have a fatal outcome. The paper describes results of tests aimed at verifying the effectiveness of passive safety systems used to protect the operator against the effects of the truck tip-over. The tests were performed with the use of numerical simulation. The authors selected 12 configurations taking into account the forklift's velocity, position of the steering wheel and seat and the operator's reaction, in terms of which selected passive safety systems were tested. In order to conduct the effectiveness tests of these systems, a simulation model was developed, consisting of numerical models of: a forklift truck, human body, ground and tested passive safety systems. This was followed by a series of simulations of the forklift tip-over with the operator inside, with the use of different passive safety systems. More than 170 simulations of possible cases were performed in total. Results, in the form of recorded resultant acceleration of the head, were used to estimate the severity of injuries for each case considered. This was used as a basis to determine the effectiveness of the passive safety systems.

1. Introduction

Nearly 100,000 forklift trucks are registered in Poland. According to statistical data of the National Labour Inspectorate, on average 90 accidents involving forklift trucks occur every year. The accidents result in nearly 100 injuries, with 10–15 of those turning into fatalities. The most dangerous accidents involving forklift trucks are those caused by the loss of stability of a truck with the operator inside, resulting in its tip-over. This type of accidents makes up nearly 45% of serious and fatal accidents involving forklift trucks. A similar situation is observed in other European countries. For example, according to the data of the French National Institute of Research and Safety (INRS), year by year 63% of fatal accidents involving forklift trucks are caused by their tip-over, however in the majority of cases the operators do not have their safety belts fastened (Rebelle et al., 2009). Causes of this type of accidents include excessive velocity, taking sharp bends, hitting an obstacle or transport of a load lifted too high.

In Poland, every forklift truck must be fitted with passive safety systems reducing the risk of tip-over consequences. Statistics show that in spite of mandatory passive safety systems the problem of serious and fatal accidents remains significant. The question here may be either failure to use passive safety systems by the operator, or their poor effectiveness. The subject of effectiveness tests of the forklift passive safety systems is examined by few research centres or few of them publish their research findings. One of the first teams to focus on this issue comes from the University of Michigan (Alem, 1985). They examined the application of 2-point (lap) belts and a structure helping to keep the operator in the seat, so called Seat Wings. The test stand was composed of a forklift, a system of actuators turning the forklift over and a dummy used in crash tests. Using the dummy helped to estimate the injuries. Presently INRS researchers have developed a test bench consisting of a forklift cabin moving on a bending track. A Hybrid III dummy is placed inside the cabin, which is then accelerated up to the velocity causing a lateral tip-over during the turn. This method is used to test passive safety systems available in the market (e.g. safety belts, door-bar systems, etc.) (Rebelle, 2015). The test bench developed by the INRS is also used in works on new operator protection designs. For example, the researchers developed air bags protecting the operator against ejection and the head shocks (Rebelle, 2012). However, application of the above-described test setup has certain limitations. Solutions of this type require a laboratory and space, while construction of a laboratory and purchase of a dummy with a relevant operation system are all very costly. Additionally, testing many passive safety systems is also very expensive and time-consuming.

* Corresponding author.
E-mail addresses: marmi@ciop.pl (M. Milanowicz), pabud@ciop.pl (P. Budziszewski), krked@ciop.pl (K. Kędzior).

http://dx.doi.org/10.1016/j.ssci.2017.07.006
0925-7535/

Development of numerical methods made it possible to perform similar highly accurate experiments based on simulation. For several years now, this type of tests have been conducted in the automotive industry. Almost every car manufacturer tests its new structures using virtual crash tests. This is done by using specialised computer applications. For this sort of tests, it is necessary to apply a human body model which enables to carry out reliable simulation of a real accident. Therefore, the aforementioned programs contain libraries of advanced numerical models of human bodies and dummies. The models represent human behaviour with high accuracy and allow assessing the injuries which would be sustained by a person subject to a specific external force. This is a direction towards which INRS advances its works. The institute has developed a numerical model of a test bench for testing passive safety systems (Rebelle et al., 2009). Another example is a team which uses MADYMO software to evaluate injuries resulting from the tipping-over of forklifts with operators standing during their operation (Meyer et al., 2009). The team used a numerical human body model available at the MADYMO software library to assess head and neck injuries for 7 configurations of accidents.

Although centres around the world are already dealing with issues related to forklift passive safety systems protecting against consequences of a tip-over, in Poland information on their effectiveness and proper use is still scarce. The same applies to the solutions to be used to minimise the risk of occurrence of serious and fatal injuries resulting from forklift truck tip-over. The Central Institute for Labour Protection – National Research Institute (CIOP-PIB) research team performed tests with the use of numerical simulation aiming at verifying the effectiveness of passive safety systems protecting operators against consequences of the forklift tip-over.

2. Method

Simulations (reconstructions) of accidents of this type in different configurations were conducted to investigate effectiveness of the passive safety systems designed to protect the operator against the effects of forklift truck tip-over. Three groups of configurations were distinguished. The first group took into account the truck's velocity:

- Tip-over of a non-moving forklift with the operator inside.
- Tip-over of a forklift moving at the velocity of 13.5 km/h with the operator inside.
- Tip-over of a forklift moving at the velocity of 23 km/h with the operator inside.

The second group took into account the operator's position in the cabin:

- Steering wheel and seat are in the middle of the forklift (Fig. 1, left);
- Steering wheel and seat are located closer to the side to which the forklift tipped-over (Fig. 1, right).

The third group took into account the operator's reaction when the forklift tipped-over:

- Passive human body model – the model is affected by external forces, no reaction of the model resulting from the tension of human muscles (Fig. 2, left);
- Active human body model – during the tip-over, the model represents the human reaction (assumes the position recommended by forklift manufacturers and reacts to the external forces acting on it) (Fig. 2, right).

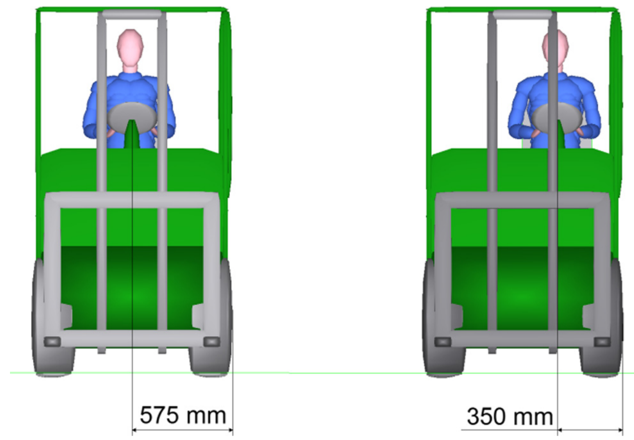

Fig. 1. Configurations of the operator's position in the forklift cabin.

Forklift manufacturers and operator training centres have developed a number of instructions and manuals for operators relating to the method of reacting to situations leading to the forklift tip-over (hereinafter: recommended position). These instructions are usually consistent and some of them differ only in immaterial detail. The operator should take the following steps:

- o lean in the opposite direction of the forklift tip-over,
- o hold tight to the steering wheel or, preferably, to the hand grips inside the cabin,
- o press the feet tight against the floor so that the back is forced into the seat (Mitsubishi, 2016).

The following configurations of passive safety systems were tested for each of the aforementioned configurations:

- Forklift with 2-/3-/4-point safety belt.
- Forklift equipped with a structure protecting the operator against falling out of the cabin in the form of an additional door (so called door-bar system, variant with and without the safety belt fastened).
- Forklift equipped with a structure helping to keep the operator in the seat – 4 different designs of this type of structure were tested (variant with and without the safety belt fastened).

To simulate the accidents, the authors used MADYMO software (TASS International, 2013b), which allows for modelling kinematics and dynamics of the forklift and human body models using two numerical methods: multibody systems (MB) and finite element (FE). The simulation resulted, inter alia, in determining parameters which allow to evaluate severity of injuries which would be sustained by the operator if a real accident occurred, and developing animation of the accident simulation. Evaluation of the passive safety systems effectiveness was performed by estimating severity of head injuries, since it is the head which is most exposed to injuries. The more effectively a passive safety system protects the operator, the less severe the injuries are. Biomechanical resistance criteria were applied when evaluating injuries, which allowed for connecting the recorded physical values with the probability of injuries of a body part subjected to the same loads. Head injuries were evaluated according to the criterion of head biomechanical resistance to impact loads – HIC 15 ms (Head Injury Criterion) (TASS International, 2013b, p. 290) determined based on the measurement of total acceleration of the head centre of mass. However, injury criteria do not provide detailed information on injuries but they do provide the probability of the injury according to a predefined scale. Abbreviated Injury Scale (AIS) (Association for the Advancement of Automotive Medicine, 2008)