

Analysis of a Semi-trailer for Transportation of Vertically Positioned Hydrogen Cylinders: Safety Against Rollover Phenomenon

L. Tello, H. Malon, C. Martin

Abstract—The use of hydrogen as an alternative fuel is generating requirements for its storage and transport. Hydrogen is a highly flammable gas that is transported compressed and therefore precautions for safety should be taken.

The object of analysis in this paper is a semi-trailer vehicle that transports set of cylinders in vertical position.

The structural characteristics of the set will be analyzed by means of numerical methods in order to satisfy the required safety conditions during its transport by road.

Index terms—Semi-trailer, rollover, hydrogen, set of cylinders, cylinders.

I. INTRODUCTION

The numerical analysis with computer tools by means of the finite element method [1] has allowed a great advance in the area of calculation and optimization of semi-trailer structures, contributing to reduce costs relative to experimental tests to check the behavior of a vehicle in case of impact.

Nowadays in Europe, ADR [2] regulation establishes a series of load cases to verify the structural behavior of vehicles transporting dangerous substances.

With regard to a hypothetical rollover of the vehicle, this regulation only considers that the vehicle is submitted to an acceleration of once the gravity in vertical direction bottom up. Hydrogen is a very inflammable gas and this regulation turns out to be insufficient to guarantee the safety in the valves of the cylinders in the case of rollover of the semi-trailer. After checking the existing safety regulations relative to vehicle rollover, the bus rollover test defined in UNECE regulation 66 of Geneva [3] has been specifically adapted to the semi-trailer. This European regulation

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L. Tello is a researcher in the staff of the Mechanical Department of the University of Zaragoza, Spain (phone: +34/976761888; fax: +34/9762670; e-mail: ltello@unizar.es).

H. Malon is a Professor in the Mechanical Engineering Department of the University of Zaragoza, and is a researcher in the staff of the Mechanical Department of the University of Zaragoza, Spain (phone: +34/976761888; fax: +34/9762670; e-mail: hml@unizar.es)

Carlos Martin graduated in 1991 with a degree in mechanical engineering from the University of Zaragoza, Spain. Since 1995, Mr Martin has been Operation Director in Lecitrailer, Zaragoza. From 1992 to 1995 he worked in Lecienda, a semitrailer builder, in Zaragoza, and from 1991 to 1992 he worked for Neumin, a Spanish brakes builder. He has obtained the APICS Master (American Production Inventories Construction Systems) and EWE Master (European Welding Engineer) qualifications. (phone: +34/976462121; e-mail: martin@lecitrailer.es)

guarantees a minimal strength for the superstructure of large passenger vehicles in the case of rollover.

II. CONFIGURATION OF THE VEHICLE

A new semi-trailer vehicle has been designed for the transport of several sets of hydrogen cylinders. This vehicle will be capable of carrying 287 cylinders (in 7 sets of 41 cylinders) representing a total load of 28,400 kg

The calculation of the vehicle and its components by means of the finite element method has been carried out by the commercial software ABAQUS [4]. It has been used the module ABAQUS Explicit which is specific for dynamic calculations.

The cylinders are connected by a system of valves. The system must be adequately protected by the chassis of the cells to prevent a gas leak to occur in the case of rollover.



Figure 1. Cylinders valves detail.

There have been used conventional steels (S275JR and S355JR) as well as high strength steel (Domex 500), both in the chassis and in the cells, in order to obtain the best behavior of the structure in a situation of rollover without compromising the weight of the vehicle.

III. DEFINITION OF THE PROBLEM

It has been developed a finite element model simulating the semi-trailer and the cylinder cells for the analysis of the vehicle.

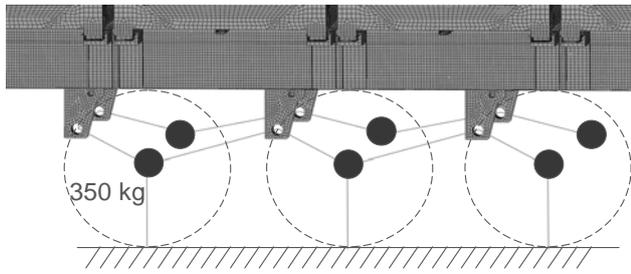


Figure 2. Axles modelling.

All the parts that comprise the chassis, the cells and the cylinders have been modelled by means of shell elements. The semi-trailer axles have been modelled using mass point elements connected to the structure by rigid beam element. It has been considered a total weight of 700 kg per axle which has been assigned to two mass elements.

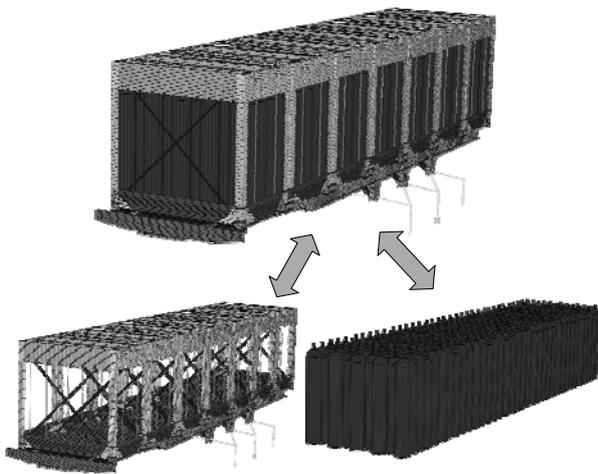


Figure 3. Finite element model.

IV. BOUNDARY CONDITIONS: ROLLOVER TEST SIMULATION AS DEFINED IN ANNEX 5 OF REGULATION NO 66 OF GENEVA

The behavior of the semitrailer in the case of lateral rollover has been analyzed according to the test described in the regulation R66 of Geneva [5]. This test specifies the following considerations:

- Step of 0.8 m high
- Axle of rotation "O" defined by the most external point of the tires of the vehicle in contact with the ground.
- The model is placed in the instant previous to the impact (as showed in figure 4), and is rotating about a longitudinal axle "O" with an initial angular velocity calculated by means of the theorem of conservation of the mechanical energy.

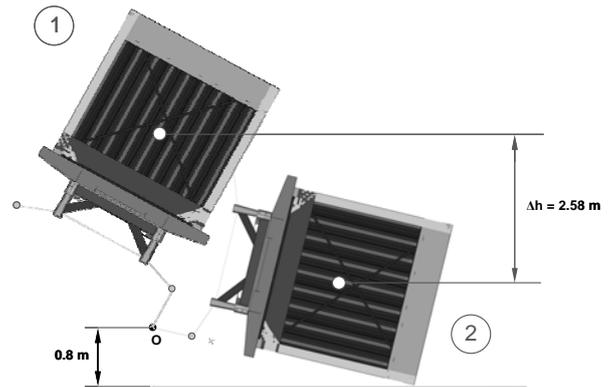


Figure 4. Position of the vehicle at the starting rollover point (1) and at the starting calculation point (2).

$$E_{\text{gravity}_1} = E_{\text{kinetic}_2}$$

$$\omega_2 = \sqrt{\frac{2 \cdot M \cdot g \cdot \Delta h}{I_0}}$$

$$\text{Total_Mass} = 32667 \text{ Kg}$$

$$I_0 = 240550 \frac{\text{Kg} \cdot \text{m}^2}{\text{s}}$$

$$\omega_2 = 2.6 \frac{\text{rad}}{\text{s}}$$

$\omega_2 \rightarrow$ Angular velocity at instant 2.

$I_0 \rightarrow$ Moment of inertia of the model with respect to the axle of rotation.

$\Delta h \rightarrow$ Vertical distance from the centre of mass position at instant 1 to the centre of mass position at instant 2.

V. OBTAINED RESULTS

Firstly, there have been obtained the curves of energy of the model simulated in order to verify that the energy remains and transforms adequately.

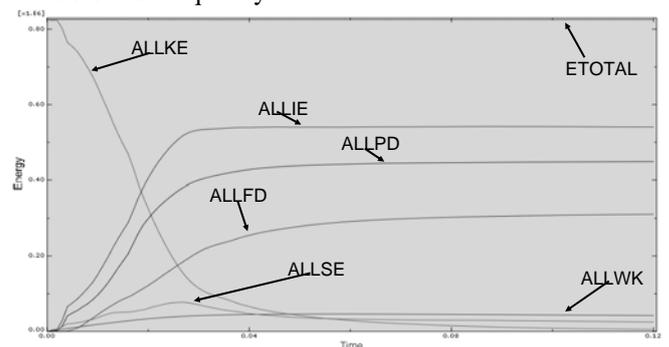


Figure 5. "Energy(J)-Time(s)" graphs of the rollover test simulation.

Where,

ALLWK = External work.

ALLFD = Frictional dissipation.

ALLIE = Internal energy.

ALLKE = Kinetic energy.

ALLPD = Plastic dissipation.

ALLSE = Strain energy.

ETOTAL = Total energy.

From the analysis of these curves it is concluded that the simulation behaves correctly: the total energy of the system is kept constant, diminishing the kinetic energy of the model. At the same time, the plastic dissipation and the internal energy increase progressively until reaching a constant value.

The maximum value for the internal energy is reached between 0.02 s. and 0.03 s. That means this is the instant at which the model reaches its maximum strain.

During all the time the total energy is the sum of the all energies.

Next pictures show Von Mises stress values for different instants and the evolution of the strain in the model.

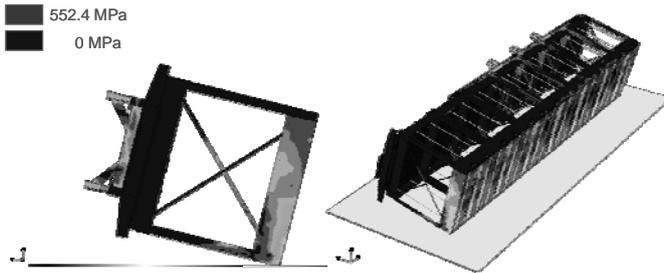


Figure 6. Von Mises stress at $t=0.003$ s.

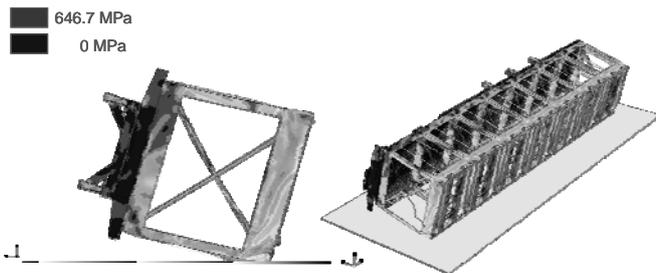


Figure 7. Von Mises stress at $t=0.028$ s.

The instant at which the maximum strain is reached is $t=0.028$ s. Then the vehicle starts bouncing.

During all the simulation the cylinders kept inside the cells, this is a very important safety factor.

The highest strain is taking place on the top of the cells. Figure 7 shows Von Mises stress and the strain at the end of the calculation (instant $t=0.12$ s.)[6].

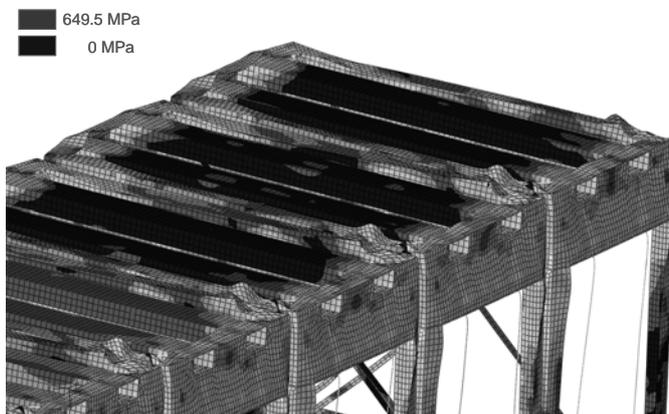


Figure 8. Von Mises stress for $t=0.12$ s.

VI. ANALYSIS OF THE ROLLOVER SAFETY CRITERION

So as to satisfy a minimal safety conditions it is necessary to protect the valves that connect the cylinders [7]. This is necessary to avoid possible hydrogen leaks.

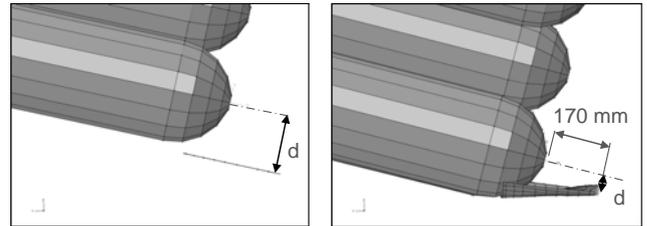


Figure 9. Safety distance in the cylinder coils before and after the impact.

At the initial instant of the calculation, the distance from the center of the cylinders (placed in the side of impact) to the steel sheet of the cell is 156.87 mm. This distance is measured at a height of 170 mm, from the end of the cylinders (as showed in figure 9) to the position where valve coils are located (figure 11).

The displacement-time graph obtained in these points in the side sheets of the cells can be represented for those cylinders located more externally.

Fig. 10 below shows the most critical displacement obtained.

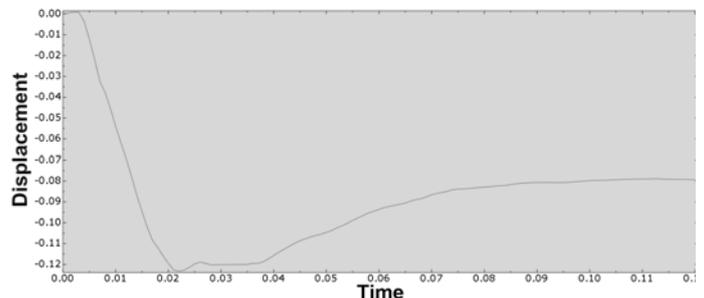


Figure 10. "Displacement(m)- Time(s)" in the most critical side sheet of the cells

The next table shows the values of the minimum distances obtained between the cylinder coils and the lateral sheet of the cells.

Table 1. Available distances between cylinder coils and cells.

| CELL n° | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|-------------------------|-------|-------|-------|-------|-------|-------|-------|
| Available distance (mm) | 34.57 | 34.49 | 34.57 | 33.90 | 33.57 | 33.76 | 34.77 |

The maximum displacement value obtained is 123.294 mm, so the distance (d) to the center of the cylinders that remains available is $156.87-123.294 = 33.57$ mm.

The cylinder coils have a mean diameter of 120 mm, so in order to guarantee the safety of these components it would be necessary at least a minimum safety distance of 60 mm.

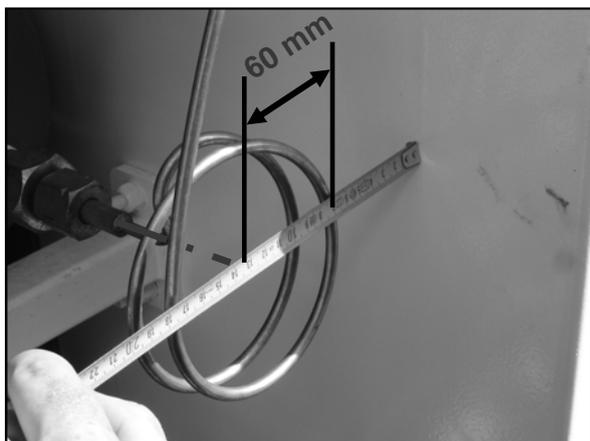


Figure 11 Radius of the cylinder coils.

With the current configuration in the coils an impact will take place between the lateral sheet of the cells and the cylinder coils. To solve this problem it will be necessary to place off-centre the coils of the cylinders. A minimum displacement of 27 mm will be necessary for that coils of the cylinders that are susceptible to contact with the cells in the case of rollover. With this safety measure the lateral sheet of the cells is prevented from contacting with the coil and the risk of hydrogen leak is eliminated.

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