ON THE CRACK PATH IN A STRUCTURE OF NON UNIFORM STIFFNESS

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ABSTRACT. The analysis of the formation of a crack in a structure impacting a body of given shape, stiffness and strength is very useful for studying the safety measures able to prevent the recurrence of the event. Numerical simulation of the phenomenon is very hard, due to the difficulties related to the role played by the time, the constraints, the geometry and the direction of relative motion of the two impacting bodies on the extent of the impact damage and on its evolution with time, in respect to that of the material having the utmost importance. The problem of the impact between two bodies having very different stiffness and shape, similar respectively to those of a tank wagon and a fixed prismatic deformable obstacle, has been faced. The achieved results significantly highlight the influence of the different parameters adopted in the study on both the tank wall punctuation phenomenon and the path followed by the crack in the wall.

INTRODUCTION

The design of the passenger rolling stock requires, among the other things, also the analysis of the crashworthiness behaviour of those structures directly involved in any impacts that might occur in service. This design phase can be supported by results of both full-scale testing on single structure or components, and very often, virtual testing by means of FEM approach on 3D models of the same prototypes, to significantly reduce time and cost of the design.

The current Standard (EN15227) indeed prescribes the use of suitable solutions to mitigate the consequences of collisions on passengers and staff, in case of assigned impact scenarios and of other scenarios considered remarkable by the designer. Surprisingly, this Standard has no reference to tank wagons, whatever the nature of the carrying good is. Nevertheless, it is well known what is the risk related to the shipping of hazardous and flammable materials and that most of these materials are shipped by rail. Therefore, it would be desirable and urgent that the great deal of results produced by the scientific community on this topic are translated in Recommendation or Standards in order to provide the designer with guidelines to manage the appropriate actions to avoid the disaster, when possible, or to minimize its consequences, being totally insufficient to this aim the prescription of both the EN 14025 and EN 12972 Standards.

The critical event turning into a disaster the "common" accident derailment of a tank wagon, in full load condition, is the puncture of the cylindrical shell or of the head, since it is responsible of the loss of tons of toxic or flammable liquid. Although the failure of valves, fittings or other similar devices takes place with frequencies comparable to those of catastrophic structural failure, very often it occurs without the loss of fluid [1].
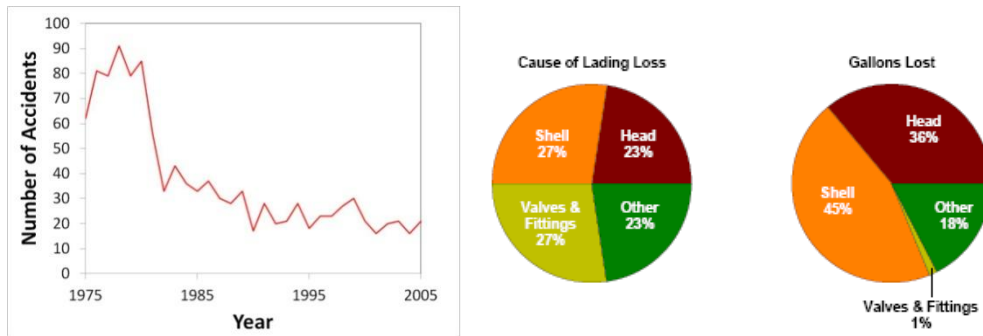

Figure 1 – Accidents reported in US [1 - 2].

On the totality of 252 accidents reported in the US (fig. 1) [1 - 2], in 176 cases the release of hazardous materials occurred. Failures of head and shell occurred in less than half of them with release of liquid that account for the 85% of total loss. Fittings and valves, although involved in about one-third of the total accidents, have been responsible of the loss of less than 5% of the total of lost lading (see fig. 1). Ultimately, the areas with the highest probability of failure during an accident are those close to the bottom and closer to the underframe structure of the tank.

For this reason, protective elements, namely the shield for the head and an external jacket for the shell, have been adopted in order to reduce the possibility to puncture the tank [2].

To face the problem systematically and define solution technically sound, a preliminary analysis of the effects of both loading and geometric parameters, defining the impact scenario, on the phenomenon has to be carried out. That is, in the first phase, the conditions under which, for a given material, the localized failure of the tank occurs, have to be identified and then how wall failure evolves as function of impact parameters has to be analyzed.

It is our purpose, in the present paper, to present some numerical results, obtained by the FE method, that may improve the phenomenon interpretation that the large scientific community has given to the phenomenon until now.

For this purpose, the impact between two bodies having stiffness and shape different and similar to those of a railway tank wagon and a deformable prismatic obstacle has been analyzed. In particular, a railway tank wagon with three different configurations of the head impacting an obstacle, positioned in different ways in respect to the vertical meridian plane of the tank, has been simulated.

ANALYSIS METHODS

The progressive damage process (Dynamic Fracture) that caracterizes the growth of the crack produced in tank wall by the puncturing phenomenon can be described by a series of states induced by the impulsive load, acting on the body, or as sudden growth of the crack front under unstable condition of the flaw. In the first case the crack grows according to the law of *impact fracture mechanics*, in the last the phenomenon evolves according to the *fast fracture mechanics*. In both cases, the time scale of the phenomenon is very short and its analysis by an experimental approach is very difficult, since it is very hard to carry out direct measurements of the physical quantities involved, as the dynamic stress field close to the crack tip or instantaneous dynamic energy release rate. These difficulties do not arise to the same extent in the numerical approach, which therefore seems to have the potential to provide a detailed description of most physical quantities involved [3].

For this reason to face the problem the numerical approach has been adopted. But this analysis method has imposes, in turn, the choice of a material fracture criterion. Several fracture models have been proposed until now, inspired both by Fracture Mechanics or by Continuous Damage Mechanics. However, any criterion derived from the fracture mechanics has significant limitations in both complex loading conditions and significant crack growth. To avoid running into this problem, a model based on the continuous damage mechanics, which does not have those limitations as it uses a local approach, has been chosen [4].

It is based on the idea that the degradation of the material stress bearing capacity, due to void initiation, growth and coalescence depends on the simultaneous (local) effects of both plastic strain and hydrostatic stress component. Most of the developed methods do not include any coupling between the constitutive behavior and the material damage law until material fracture condition is met and the stress is zeroed instantaneously. In this context, the main parameters that describe the damage phenomenon are the effective plastic strain to failure and the stress tri-axiality, defined as the hydrostatic stress component over the equivalent Von Mises stress. Furthermore, if isotropic damage is assumed, material damage is defined by a single scalar variable, *D,* that depends on both the effective plastic strain and the stress tri-axiality ratio.

Two Numerical strategies are usually adopted to implement a fracture criterion ispired on Damage Mechanics in an FE simulation environment: Tied Node With Failure (TNWF) and Element Erosion Method (EE).

The Element Erosion Method, which adopts the standard discretization practice, has been preferred by us due to its quick and easy implementation that does not affect its capability to reproduce correctly the phenomenon. However, this method suffers limitations, which are common to the TNWF, since the element sizes, the mesh orientation and the element disposition affect the numerical crack failure/path. For this reason, an initial tuning of the model is needed to identify the optimal mesh parameters for the numerical solution of the examined problem [5].

IMPACT SCENARIOS

In order to study the behaviour of a wagon tank impacting a deformable prismatic obstacle by means of the aforementioned numerical approach, it is necessary to make reference to a limited and significant number of scenarios, being too onerous and useless take into account all possible scenarios, by varying systematically in a predetermined range, all parameters characterizing the generic scenario.

For this reason, in all examined scenarios, a single geometry for both the obstacle and the cylindrical shell has been adopted. The obstacle is prismatic and has height, thickness and length respectively equal to 100 mm, 20 mm and 900 mm. The diameter of the shell is 2 m, with wall thickness equal to 12 mm and length of 6 m. The other geometric parameters have been varied; they are: - tank head geometry; - eccentricity of the obstacle in respect to the vertical meridian plane of the tank; - angular position of the obstacle in respect to the direction of motion. In details, the chosen geometries of the head are: - torospherical, having radius of the toric part equal to 400 mm and radius of the spherical part equal to 2000 mm; - hemispherical, having radius equal to 1000 mm; - conical, having apex angle equal to 50°, height equal to 500 mm and the spherical end with radius equal to 2500 mm. The thickness of the all heads has been chosen equal to the thickness of the shell.

For each type of head, three different values of the obstacle eccentricity have been chosen: 0 mm; 100 mm and 200 mm. Furthermore, for each value of the obstacle eccentricity, three different angular positions of the obstacle in respect to the direction of tank wagon motion have been defined: 0°; 5°; 10°.

In order to identify the influence of the weight of the tank on the path of the crack caused by the obstacle, all twenty-seven aforementioned scenarios have been analyzed with a total mass of the tank equal to 10 tonnes. Subsequently, only n.6 scenarios that on the basis of the obtained results have been considered more significant have been newly analyzed with an increased total mass of the tank equal to 80 tonnes.

FE MODELLING

The tank wagon, in all the considered configurations, has been discretized using Belytschko-Tsay shell elements with reduced integration formulation and 5 integration points through the thickness. The obstacle has been discretized with constant stress solid element. All models have n. 100968 shell elements and n. 6700 solid elements.
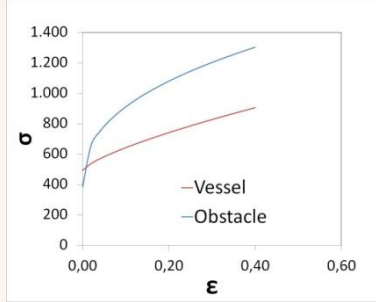
The use of the elements with reduced integration has required the activation of the hourglass control to avoid the activation of the zero-energy deformation mode. Flanagan-Belytschko viscous form and Flanagan-Belytschko stiffness form of the hourglass control, with exact volume integration and Hourglass coefficient equal to 0.03, have been used respectively for shell and solid elements.

An elasto-plastic model with an arbitrary stress versus strain curve and an arbitrary strain rate dependency, implemented in LS-DYNA as MAT24 Piecewise Linear Plasticity, has been used for the material of the tank car and the obstacle. Also, an

effective plastic strain to failure equal to 0.9 has been assigned to the tank wagon in order to activate the element erosion. In tab. 1 material parameters values and σ(true stress)-ε(true strain) curves are reported.

Table 1. Mechanical material properties.

		ρ [kg/mm³]	E [MPa]	ν	Y [MPa]	ε_f	
Rail Tank	Head 1	1.781e-5 (10 ton)	200000	0.29	490	0.9	
		1.425e-4 (80 ton)					
	Head 2	1.659e-5 (10 ton)	200000	0.29	490	0.9	
		1.327e-4 (80 ton)					
	Head 3	1.751e-5 (10 ton)	200000	0.29	490	0.9	
		1.401e-4 (80 ton)					
Obstacle		7.85e-6	206000	0.29	380		

In order to model contact between obstacle and tank wagon, the ERODING SURFACE TO SURFACE contact algorithm [6], with pinball based contact, warped segment checking and search depth set to 5 times the sizes of the elements in contact, has been adopted. Also, to improve the contact performance, the frequency of the contact search has been scaled down so that the code performs the penetration check for each calculation cycle.

The main difficulty, common to overall penalty based contact algorithms, is the definition of the penalty stiffness value, since this parameter affects the accuracy and the stability of the numerical simulation. The optimum value has been determined, for each head type, acting on the SFSFAC parameters and verifying that penetration and irregular behaviour of both contact energy and force did not occur.

In order to simplify the modelling phase, the chosen values of the total mass (10 t or 80 t) have been assigned by means of a fictitious density, computed on the basis of the volume occupied by the wall tank.

RESULTS

The impact forces versus penetration curves, obtained with the weight of the tank wagon equal to 10 t and for the three types of head, have been reported in the diagrams of fig. 2. In each diagram, the curves obtained with the same eccentricity value have been reported in order to show immediately the effect of both the tilt angle of the obstacle and the type of head on the magnitude and trend of the impact force. It is evident that the different stiffness of the heads modifies the slope of the initial part of all curves, while the head geometry which affects the initial position of the contact region, together with the tilt angle of the obstacle, and affect the magnitude of the penetration force. Also, when the crack reaches the cylindrical shell, the obstacle is located, in all scenarios, in positions with respect to the shell not very different each other, as a

conseguence the force necessary to sustain the growth is approximately the same and the curves tend to overlap.
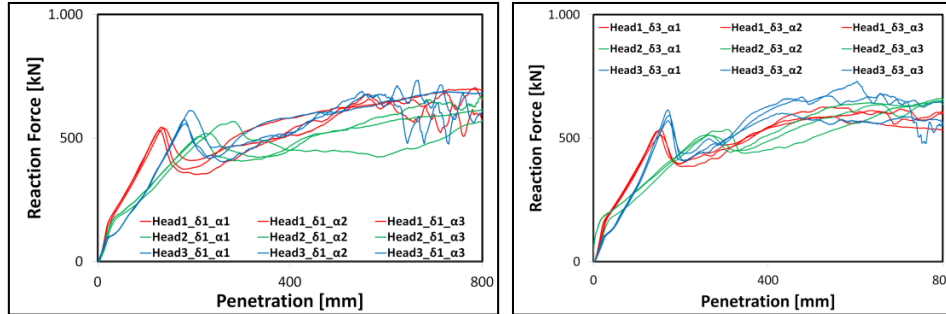

Figure 2. Force vs. penetration (10 tonnes) (δ = 0 on the left and δ = 200 on the right).

The phenomenon of interaction of the head with an obstacle having a sharp shape and dimensions much smaller than the tank wagon evolves in three distinct phases, similarly as reported by Lupker [7]. In the first phase, the interaction between the two bodies causes in the tank severe plastic deformation localized near the contact area, which modify the geometry of both the head and the obstacle, decrease their stiffness, and consequently reduce the slope of the load-penetration curve.

When the effective plastic strain to failure is reached, the formation of the tearing occurs, with the intrusion of the obstacle in the tank and a corresponding drop of the reaction force. In the last phase, the growth of the crack is sustained by the interaction of the frontal region of the obstacle with the tank wall, with high plastic flow on the crack edge.

When the symmetry plane of the obstacle has a non-zero angle with the vertical meridian plane of the tank, the flank of the obstacle interacts with the tank wall altering the impact dynamic and causing a rotation of the tank that affects the crack path (fig. 3). As a matter of fact, in the first phase of the growth, the crack remains nearly straight until the rotation of the tank diverts the crack of an angle close to the tilt angle of the obstacle. Moreover, when the crack is straight, the edges of the crack assume a symmetric configuration in respect to the axes of the crack, when the tilt angle of the obstacle is non-zero, the interaction with the obstacle flank pushes the wall tank inwards with a wall deformation essentially elastic.
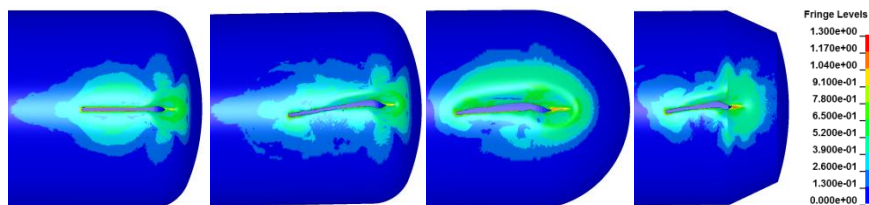

Figure 3. Crack paths for some selected scenarios (10 tonnes).

In the initial phase, the interaction force causes extensive plastic deformation in the obstacle, with appreciable out of plane displacements when the tilt angle is non-zero, and changes of the contact surfaces of the two bodies. The variation of the geometry of the two bodies affects the configuration of the crack with separation of the edges, which are more pronounced as greater the tilt angle of the obstacle is (fig. 4).
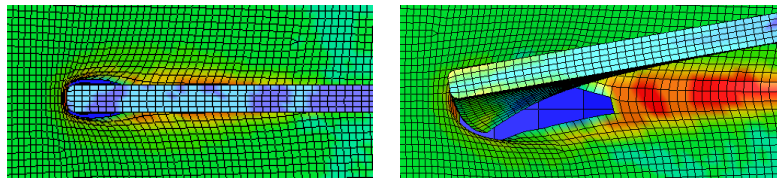

Figure 4. Different shape of the puncture for zero and non-zero tilt angle.
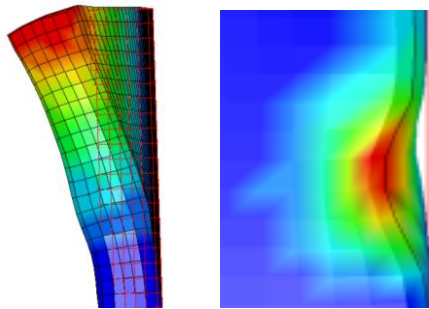

Figure 5. Example of final deformed configuration of the obstacle.

After the puncture, the contact region on the obstacle moves slowly downward until the crack reaches the shell and the contact force produces a deformation localized on the frontal face of the obstacle (throat) (fig. 5).

Also, the increment of the tank weight produces an evident change of the crack path, since the small tank rotation, due to the greater inertia, limits the separation of the crack path from the straight trajectory (fig. 6).
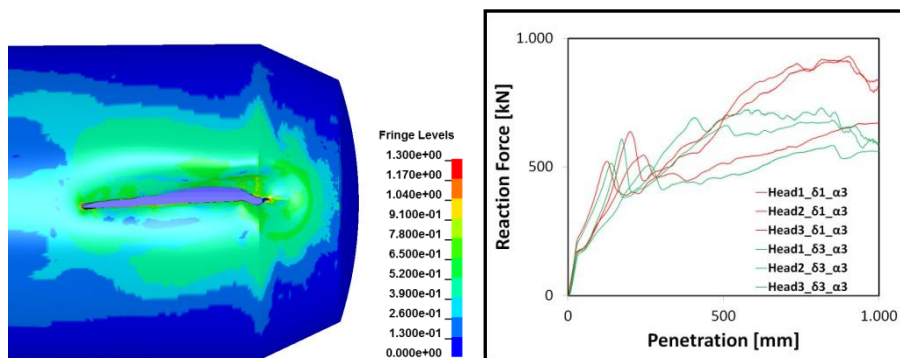

Figure 6. Numerical results with the total mass of the tank equal to 80 tonnes.

CONCLUSIONS

In this paper, the behaviour of a metallic structure, similar to a tank wagon, impacting a deformable obstacle having small size and fixed on the ground have been analyzed. The study has been carried out using a nonlinear, explicit, three-dimensional Finite Element code, modelling the structure free from the means of transport and empty, in order to evaluate the only effect of some geometric and physic parameters on the morphology and evolution of the damage of the tank. The numerical results, presented by diagrams and images of the damaged structure, highlight a strong influence of the impact angle on the final deformed configuration of the crack edges and the path followed by the crack tip during the impact. Quite similar effects have been reported as the geometry of the head, the eccentricity of the impact point in respect to the vertical meridian plane and the mass of the tank change. Also, the deformed configuration of the area surrounding the impact point is strongly affected by the considered parameters, of which the most important seems to be the initial geometry of the head.

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