Application of dimensional analysis in the study of impact behaviour on tank truck structures

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Abstract. Nowadays, the analyses of impact of metallic structural elements of big dimensions are very expensive and dangerous due to the fact that the tests are destructive in nature and involve impact forces of the order of Meganewtons. That is the reason why searching for new alternatives that make these analyses easier and cheaper and that ensure the safety for those carrying the tests is necessary. No significative differences in the stress and strain of impact results were observed in a small scale from those obtained at full scale, if the laws for modeling of dimensional analysis are observed, in fact result differences were around 1%. We concluded that dimensional analysis can be applied when studying impacts of tank trucks because it made the analysis easier by reducing the number of factors to be considered and at the same time produced satisfactory results using scaling prototypes.

1. Introduction
Actually, there are many destructive methods to determine whether a mechanical piece can withstand different types of stresses that it can be subject to, whether tension, compression and/or shear. Exist standard tests, such as the Charpy V-notch test [1], axial tension [2] and Rockwell hardness [3] among others for characterizing materials by testing its mechanical properties when used in their specific application. Another method for validating a material entails making the analysis in real conditions, but there are many applications in which carry them out will be very expensive due to the sizes or the materials involved –that’s the case of dams, airplane fins, submarines or eolic generator blades among others.

Dimensional analysis (DA) is a mathematical tool [4-6] for solving complex engineering problems. The work of Yu and Yeong [7] is an example of impact stresses and the plastic deformation sustained by the material into the impact zone. For developing a scaled model similar to the real one geometric,
cinematic and dynamic similarities were taken into account. For the geometric similarity, the model must be equal to that of the prototype but scaled down [8]. According to the scale factor, in the cinematic one, the velocity in any point of the flow field in the model must be proportional to the velocity of the corresponding point in flow field of the prototype, as well as, at the dynamic similarity, every applied force in the scaled model matches the forces developed in the prototype.

In this research, conditions experienced by a tank truck by an elastic impact were used in order to simulate a shock phenomenon in two different size plates considering them, as the critical impact zone of tank. The latter, is a part of a bigger study, firstly we attempt to demonstrate that scaling a model gives acceptable stresses results in simulation, using only elastic relationships. Secondly, we developed a methodology that implies real experiments and elasto-plastic simulation in order to compare to the real fracture conditions and fracture simulations. Finally, an iterative procedure had carried out for the re-design of the tank truck.

2. Procedure

Truck crashes not only interrupt traffic flow, but also cause economic loss. Moreover, truck crashes contribute to a large number of injuries and fatalities due to additional risks, such as larger vehicle size, heavier weight and possible hazardous material release (truck crash injury)[9a]. In Mexico, pressurized tank truck must abide by the terms and conditions established in the standard NOM-057-SCT/2003 [9]. According to federal road traffic regulations [10] vehicles carrying hazardous materials must not exceed 80 km/h (22.2 m/s) however truck crash data, in this country lead to almost 60%, the excessive velocity as the principal factor of accidents [11]. Therefore, the tank truck was subjected to the experimental conditions shown in table 1.

| Material                        | Value                          |
|---------------------------------|--------------------------------|
| Material thickness (sheet)      | 4.762 mm minimum               |
| Internal pressure               | 1.72 MPa                       |
| Impact velocity                 | 22.2 m/s                       |
| Impact time                     | 0.1 s                          |
| Impact angle                    | 90° (relative to tank surface) |
| Chemical composition of medium  | 0.25%C, 1.0-1.5%Mn, 0.15-0.50%Si|
| carbon steel SA 612             | [12].                          |

An iterative procedure was carried out for the re-design of the tank truck. The first step with the original tank parameters involved a computational model subjected to an impact simulation using COMSOL Multiphysics 5.1 [13]. The tank truck was re-designed with the new parameters and again a simulated impact test was performed. Dimensional analysis had used for develop a better small scale computational model to be subject to a new impact force.

3. Analysis of results

3.1 Modelling

The deformation and/or fracture produced by impact on tanker trucks is a problem related to the linearized theory of elasticity that requires finding the solution of a set of coupled partial differential equations known as field equations. The present analysis considered the assumption that the strains are calculated in an infinitesimal way, where the materials are isotropic, elastically linear and homogeneous. In general, the unknowns that must be solved in a linearized elasticity problem are the displacement, strain and stress fields. An initial known parameter was the value of the magnitude of
There are three tensor partial differential equations, which were associated with the equilibrium of the linear momentum and six infinitesimal deformation-displacement relationships that govern the linear elastic limit value problem. The system of differential equations was completed with a set of linear algebraic constitutive relationships that can be written using tensor notation [1]. Firstly, the equation 1 of motion, which is an expression of Newton’s second law: (The bold letters are vectors)

$$ \nabla \sigma + F = \rho \ddot{u} \quad (1) $$

and strain-displacement equation 2:

$$ \varepsilon = \frac{1}{2} [\nabla u + (\nabla u)^T] \quad (2) $$

For elastic materials, the general equation 3 for Hooke's law represents the material behavior and relates the unknown stresses and strains:

$$ \sigma = \sigma_{res} + C : \varepsilon \quad (3) $$

where $\nabla$ represents the nabla operator, $\sigma$ is the Cauchy stress tensor, $\varepsilon$ is the infinitesimal strain tensor, $F$ is the body force per unit volume, $\rho$ is the mass density, $u$ is the displacement vector, $(\cdots)^T$ represents a transpose, $\sigma_{res}$ represent residual stresses, $C$ is the fourth-order stiffness tensor, $(\ddot{u})$ represents the second derivative with respect to time and $A:B = A_{ij} B_{ij}$ is the inner product of two second-order tensors (summation over repeated indices is implied).

Using the related equations, a scale model was constructed in COMSOL Multiphysics 5.1 considering material tank properties (table 2), and an impact force as data entry. The scale model is representing a plate of 19.74 mm thickness, subjected to a 39,738.88 N of force are the principal parameters introduced to the scale model. In order to define the impact surface, we had a scale model impact surface reduced four times smaller than that reported by Yu and Jeong [7].

![Figure 1](image_url)

**Figure 1.** Plate showing a specific area of 1 m$^2$ x 19.74 mm of thickness. The center is the impact surface which measure 152 mm x 152 mm.

Accord to the experimental tank fractured, shown in figure 2, it is necessary just a quadrangular zone to be simulated. This is because the square drawn limits the deformed zone in a perfectly way, the simulated plate was made of medium carbon steel SA612, with 1 m$^2$ in area and 19.74 mm thick.
A 39,738.88 N impact force was applied for 0.1 s at an impact zone of 231.04 cm² in area at the center of the plate model as shown in figure 1. The simulation results of the impact on the plate are shown in figure 3. The color patterns in the images quantified the strains and stresses according to the bar at the right side. The level curves in figure 3a) shows in detail the magnitude of displacement ($1.9 \times 10^{-4}$ m) in the impact zone and its surroundings. Figures 3b) and 3c) exhibit a profile of stresses and strains after 0.1s of impact time.

Figure 2. Real tank impacted by an impactor of defined area of 152x152 mm

3.2 Dimensional analysis and impact test simulation
The von Mises stress caused by the impact force is shown in figure 3b, having a maximum magnitude of 60 MPa and is represented by a color scale, red being the most intense level. The plate shows more residual stress in the impact zone, however farther away from the impact zone then lesser stress magnitude appeared. The impact affectation in a metallic structure is distributed throughout it. That is why the study of the impact must be focused where the strongest stresses occur, since it’s here where cracking can occur in the structure.
By implementing properly the rules of DA modelling using a 1:2 scale, the results were very similar to those obtained by simulating the impact in full scale. Figure 4 shows images of the simulation of the impact on the plate using a 1:2 scale, taking into account the same scale factor in plate dimensions, area and impact forces, retaining in this way the geometric, cinematic and dynamic similarities. The figure 4a) shows that the maximum displacement had a magnitude of 1.36x10^{-4} m, while the von Mises stresses of 60 MPa are illustrated in figure 4b).

**Figure 3.** Images of the Displacement and Stress obtained from the impact simulation on the steel sheet: a) Stress level curves, b) Superior side displacement and c) Lateral side displacement.

**Figure 4.** Simulation results for scale 1:2 having a 0.1 s impact time: a) Maximum displacement reached 1.36x10^{-4} m value, and b) von Misses Stress exhibited 60 MPa maximum value.

**Table 2.** Dimensions and results of the computational simulations.

|                          | Scale 1:1 | Scale 1:2 |
|--------------------------|-----------|-----------|
| Area (m^2)               | 1         | 0.5       |
| Thickness (mm)           | 19.74     | 9.87      |
| Area of impact (cm^2)    | 231.04    | 115.52    |
| Impact force (N)         | 39738.88  | 19869.44  |
| Impact time (s)          | 0.1       | 0.1       |
| Maximum drift (mm)       | 0.19      | 0.136     |
| Maximum stress (MPa)     | 60        | 60        |
The results of the magnitude of the displacement and stress can be seen in table 2, where the results of both simulations are compared. The displacement in the plate, with a scale factor of 1:2 showed that the contour lines had a similar pattern to that which corresponded to the real plate shown in figure 3, the real tank in figure 2, presents a bigger deformation, this is because the force utilized in this simulation even though for the three plates is still small and is localized into the elastic deformation zone.

The structure presented stresses with average magnitude of 20 MPa, which were less than those corresponding to the edges of the plate. However, the maximum stress, which occurs in the impact zone, had the same magnitude as the 1 m² plate. Therefore, it was demonstrated that the application of the theory of dimensional analysis simultaneously with computational simulation tools produced acceptable results.

4. Conclusions
It was interesting to note that the magnitude of the force using dimensional analysis in the simulation to scale was half of the value corresponding to the simulation applied to real scale, maintaining a similar impact load in both cases, this corresponded to the same proportion defined for the area of the plate, resulting in identical plane stresses of 60 MPa. This point was important to demonstrate because was the first step in a complete study of pressurized tank trucks simulation which will be published in posterior works in order to improve real tank design respect impact behavior, having as a principal scope, impact simulations that simplifies the calculation work and implies important costs reduction avoiding repetitive real tank impact tests.

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