Proceedings of the IMProVe 2011
International conference on Innovative Methods in Product Design
June 15th – 17th, 2011, Venice, Italy

Study of the impact of a bomb on the side of a vessel and validation by comparing the original sheet with numerical simulation

G. García [a], A. Álvarez [a], C. Anido [b], B. Álvarez [b]

[a] Departamento de Construcciones Navales, E.U. Politécnica, Universidad de La Coruña. 15404 Ferrol, Spain
[b] Departamento de Economía Financiera y Contabilidad, Universidad de La Coruña. 15072 La Coruña, Spain.

Article Information

Keywords:
Bomb,
Vessel,
Numerical simulation,
Finite element method.

Corresponding author:
Ana Álvarez García
Tel.: 34981337400/Ext.3097
Fax.: 34981337301
e-mail: aalvarez@udc.es
Address: Avda. 19 de febrero s/n, 15405 La Coruña (Spain)

Abstract

The present work shows the comparison between the results of simulating the impact of a bomb in the side of the destroyer "Marqués de la Ensenada" structure and the outcomes obtained by digitalizing the original sheet that suffered the crash.

On the 2nd of October 1981 an explosive device was placed against the dock of the city of Santander very close to the destroyer, which was in the port collaborating on the surveillance of the borderland. The vessel was then towed to the Santander shipyards with the help of four tugs and moved into dry dock to be urgently repaired. However, the final repair took place later on at the National Company Bazan dockyards, in Ferrol.

When the damaged elements were substituted, they were handed over to the Naval Museum of Ferrol for exhibition. This material was used to simulate the explosion by means of the finite element method and compare these results with the digital photograph of the real sheet.

1 Introduction

Numerous works have been performed to analyse the resistance during impact process (*v.gr.* Bishop et al.[1], Backman and Goldsmith [2], Jonas and Zukas [3] and Anderson and Bodner [4]). In 1969 Florence [5] presented the first analytical model to determine the speed at impact of a projectile. However the experimental method is still one of the major means for penetration investigation. The empirical formulae were usually proposed by fitting normalization of large amount of experimental data after different tests with real and reduced scale.

The present paper is intended to show the results of a work carried out with ABAQUS/Explicit [6] to analyse by means of the finite element method the impact of a projectile on the side of an *Oquendo Class* destroyer of the Spanish Navy. The bomb aimed to sink the vessel or put it out of action. The 10kg plastic explosive device was located near the munitions silos in order to cause a great explosion, but in the end it came down to a hole in one of the shell sheet and some damages on the inside.

2 Background

On the second of October 1981, a bomb was planted against the dock of the city of Santander close to the destroyer. The detonation took place abaft on the port side near the boiler room, as shown in fig. 1 and fig. 2.

In order to estimate the damages the vessel was towed to the Santander shipyards with the help of four tugs and moved into dry dock for initial repair operations. Later on it was moved to the National Company Bazan dockyards, in Ferrol, where the final repair took place.

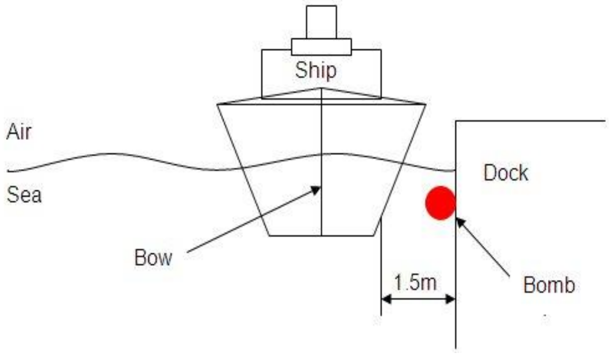

Fig. 1 Sketch of the attack.

The explosion originated in the water line, producing a tear on the port side shell of 2 x1.9 m between frame 111 and 117, a water leak implying the flooding of different compartments and detachment of port wing trim.

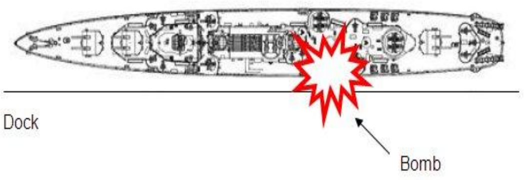

Fig. 2 Position of the explosion on section plan.

The damaged area was replaced and, since then, is exhibited at the Naval Museum of Ferrol together with the ship's bell, such as a historical reference for the Spanish Navy. In the fig. 3 we can see the entrance of the Museum.

Fig. 3 Photograph of the Naval Museum of Ferrol entrance.

The sheet displayed at the Museum, see fig. 4, has been used to carry out the analysis, through numerical simulation, of the distortion due to the explosion.

Fig. 4 Shell sheet of the destroyer "Marqués de la Ensenada".

3 Method

There are diverse techniques to calculate distortions in ship structures, among which:

- Laser/CCD (Charge Coupled Device) method, allowing the obtaining of rigorous and quality data for areas of difficult access..
- Photogrammetric method, described by Wolf and Dewit [7], used for slanted and out of reach surfaces.
- Theodolites method, for measuring angles in the horizontal and vertical planes by means of an optical instrument (*cf.* Casaca *et al*. [8]).

These techniques have a common drawback, as they imply a high cost that makes their implementation difficult. Consequently the present work has followed another method, based on the comparison of the results obtained through numerical simulation and the digital photograph, taking as reference the study executed by Webster [9] en his Doctoral Thesis. The present study is based on Webster's analysis.

Webster analysed the close proximity explosion effects on a ship-like structure in two conditions: AIREX (air explosion) and UNDEX (underwater explosion). For this purpose he exposed a real scale model, see fig. 5, to an explosive charge.

Fig. 5 Real scale model. Source: Webster PhD. Thesis[9].

Subsequently, through LS-DYNA finite element software, he modelled it and replicated the same conditions as in the experimental test. As shown in fig. 6 the results obtained are nearly identical.

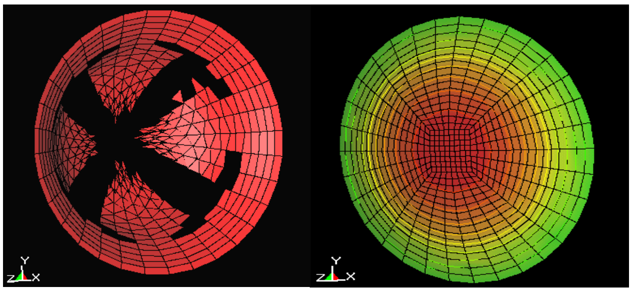

Fig. 6 Schema of the simulated model. Source: Webster PhD. Thesis[9].

4 Numerical Simulation

ABAQUS/Explicit uses an explicit direct-integration procedure. An explicit dynamic analysis is computationally more efficient than an implicit one for large models with relatively short dynamic answer, allowing discontinuous processes or events characterization. Moreover it is possible to define contact conditions, as well as the inelastic behaviour of the material and the structure absorption by introducing dissipation energy in the model.

ABAQUS/Explicit uses the central-difference operator as time integration rule, each time increment is relatively inexpensive, compared to direct integration method, because it is not required to solve a set of simultaneous equations. The explicit operator satisfies the dynamic equilibrium equations at the beginning of each increment.

The allowed input parameters and environment variables depend on the finite element type chosen. Nevertheless, concentrated forces may be applied in the nodes and momentums in the six degrees of freedom, such as distributed pressures over the surface..

4.1 Three-dimensional impact analysis

The impacts on the structures are highly intensive short duration dynamic loads that, due to their nature, may produce important damages or remarkable changes in the structures stability or movement (*v. gr.* Wood [10], Zaera and Sanchez- Galvez [11] and Feli *et al.* [12]).

In most of real-life situations it is necessary to carry out more detailed studies, analysing in greater depth the topics not covered by the impact theory, for example: how does energy loss happen, how does impact force arise through bodies in contact or how do structures degrade and break due to high loads. Generally numerical methods, by means of finite difference or finite element, offering an adequate solution of dynamic equations are required.

Impact studies may refer to the attack, aiming at achieving maximum penetration or damage, or to the defence, seeking accurate protection or armour plating.

The explosives, for projectiles propulsion or dynamic loads located close to the targets, are usually of two kinds: gunpowder and detonated (dynamite or trinitrotoluene).

The speed is maybe the simplest parameter to define the different types of impact. According to the effects caused in materials, the following structure may be considered:

- low speed (v < 50m/s) elastic effects or localised plastic deformation,
- *medium seep* (50m/s < v < 500m/s) widespread plastic deformation,
- *high seep* (500m/s < v < 2000m/s) viscous resistance of the material still not important,
- hypervelocity (2000m/s < v) the material may be considered as a hydrodynamic fluid.

However, it is difficult to absolutely classify the impacts considering an only parameter, since other geometric variables, related to projectile or target properties, have a significant importance. When taking them into account, the impact may produce the following phenomena:

- *Structural dynamics and vibration*. Predominance of structural geometry, of great importance in low speed impacts, being studied through transient implicit or explicit integration methods.
- *Stress and impact waves spreading*. While studying medium and low speed impacts, it is important to analyse in detail the effect of the stress waves, that turn into crash waves for hypervelocity impacts, in general over 2000 m/s.
- *Material nonlinear behaviour*. Plasticity, breaking, dependence on speed of deformation, internal energy or temperature. It occurs to a great extent when increasing the speed impact, although at very high speeds the material behaves almost like a fluid, being its resistance negligible.
- *Great displacements.* Geometry and finite rotations changes, which influence loads and their effects.
- *Great deformations*. Unitary stretching of materials in solid phases may go beyond 100%. At very high pressure the material behaves like a fluid, with great deformations.
- *Contact sand interface phenomena in the boundary.* Contact is a key aspect in any impact model, since impact transmits loads.
- *Penetration and perforation due in the outlines*. Penetration implies that the projectile has not gone through the target, while perforation means that the projectile has pierced it.
- *Local phenomena of breaking such as spalling, scabbing, petalling, plugging*. They refer to the breaking mechanisms of the target, producing the partial or total penetration.

The equations of motion of the body eq. 1 and eq. 2 are integrated by ABAQUS using the explicit central difference integration rule given by

$$\left.\begin{aligned} \dot{\mu}^N_{\left(i+\frac{1}{2}\right)} &= \dot{\mu}^N_{\left(i-\frac{1}{2}\right)} + \frac{\Delta t_{(i+1)} + \Delta t_{(i)}}{2}\ddot{\mu}^N_{(i)}, \qquad (1)\\ \mu^N_{(i+1)} &= \mu^N_{(i)} + \Delta t_{(i+1)}\dot{\mu}^N_{\left(i+\frac{1}{2}\right)}, \qquad (2) \end{aligned}\right\} \text{ for all } \Omega$$

where μ^N is a degree of freedom (rotation displacement or component) and subscript (i) refers to the number of increases in an explicit dynamics step. The central-difference integration operator is explicit in this kinematic state and may be used once the previous increase values are known $\dot{\mu}^N_{\left(i-\frac{1}{2}\right)}$ y $\ddot{\mu}^N_{(i)}$.

The equations of conservation of momentum eq. 3 and energy eq. 4 are used to obtain the displacements of the mesh.

$$\rho\frac{\partial v}{\partial t} = \sigma_{i,j} + \rho u_i \frac{\partial v_i}{\partial x_j}, \qquad (3)$$

$$\rho\frac{\partial e}{\partial t} = \sigma_{ij}\varepsilon_{ij} + \rho u_i \frac{\partial e}{\partial x_j}, \qquad (4)$$

where μ is the mesh speed.

It is extremely complex to represent these phenomena. For this reason, it is sometimes necessary to formulate hypothesis, appropriately based on the basic principles of mechanics, to simplify the model. In the present work, the following simplifications have been considered (*cf.* Webster [9]; Ding and Buijk [13]):

- explosion has not been tested due to difficulty, time and computational requirement; the analysis focused on the impact of a projectile thrown at a certain speed.
- due to computational memory leakage, the model refers to a simple sheet without reinforcement, which has the same mechanical properties than the original vessel see tab. 1,
- since there is vertical and horizontal axis symmetry, the computational domain considers a quarter of the sheet-bomb ensemble, see fig.6.

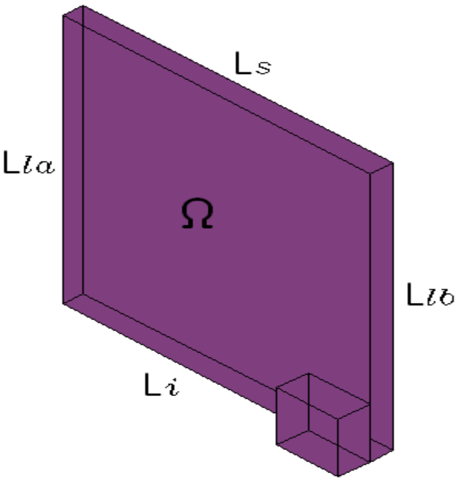

Fig. 7 Computational domain.

The following boundary conditions complete the eq. (1) y eq. (2):

- upper side: fixed PINNED (degree of freedom 1, 2, 3 =0) in L_s ,
- lower side: X- axis symmetry XSYMM (degree of freedom 2, 4, 6 =0) in L_i ,
- left side: fixed PINNED (degree of freedom 1, 2, 3 =0) in L_{la} ,
- right side: Y- axis YSYMM symmetry (degree of freedom 2, 4, 6 =0) in L_{lb} .

Density, Kg/m^3	7800
Area, m^2	6,095
Thickness, m	8x10^{-3}
Mass, kg	380.33
Mass per unit area, kg/m^2	62.4

Tab. 1 Physical data for sheet.

The mesh of the computational domain is formed by 14330 structured elements with cubic geometry, as shown in fig.8.

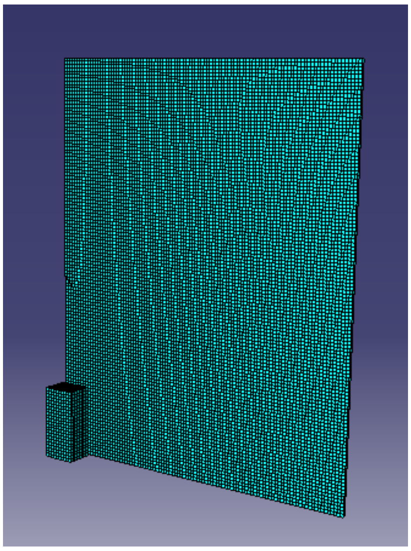

Fig. 8 3D mesh of the sheet-bomb ensemble.

5 Results

Dynamic analysis allows the observation of the moment when deformation attains its greatest amplitude, the direction and intensity of the forces/loads produced by the impact, as well as the sheet behaviour. In fig. 9 the different colours show the Von Misses stresses: red implies major concentration (breaking), green medium efforts and blue no stress.

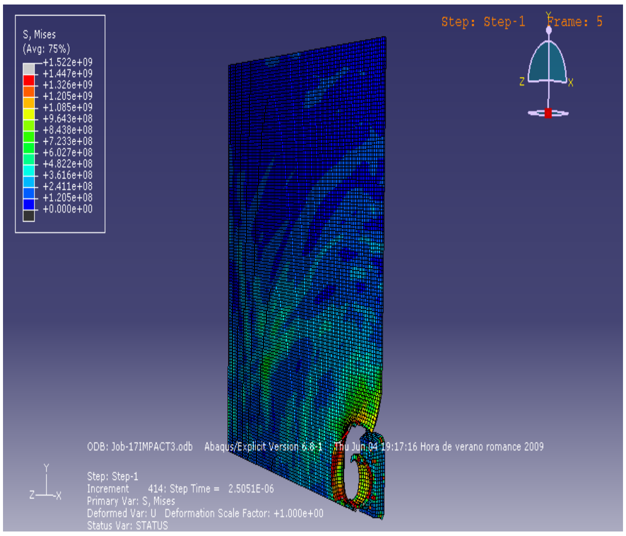

Fig. 9 3D simulation of the impact.

Fig. 10 shows the *petalling* phenomenon, so-called due to the close resemblance of steel breaking or deformation to a petal. It is worth noticing that the projectile has dragged a piece of the sheet, in consequence such impacts produce great breaks and deformations that may reduce or cause the structure to collapse.

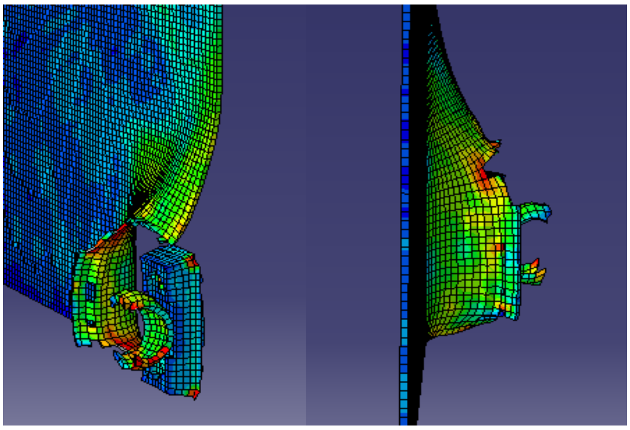

Fig. 10 Detail of the impact.

As shown in fig. 11, when comparing the results of the numerical simulation and the digitalization of the original sheet, deformation and fragmentation are quite similar in both images. Although some factors have not been taken into account like for example: high temperatures due to bomb explosion or forces produced by shock waves that would intensify the damages.

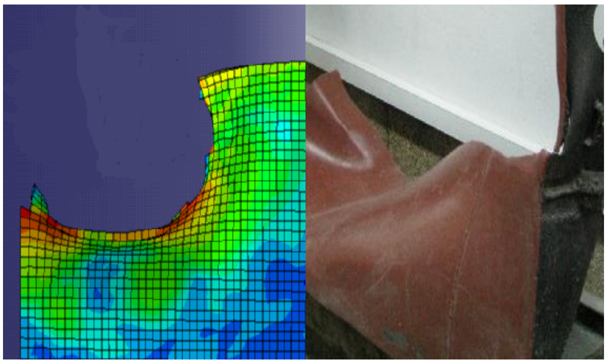

Fig. 11 Comparison between simulation and digital photograph.

6 Conclusions

As the initial study was too extensive, it has required some simplification hypothesis, analysing the impact as coming from a projectile of the same material as the sheet and removing heat transfer, shock wave, reinforcement and fluid, although the explosion took place under water line (*cf*. Webster; Ding and Buijk).

Visual comparison of the images resulting from the use of the software and the digital photograph of the real sheet enables the identification of diverse common effects: *petalling*, which implies breaking and cracking, and plastic deformation around the impact. Visual treatment allowed by this software facilitates the understanding of these effects and shows that the simulation is similar to reality.

The main significant conclusion drawn from the present work is that visual results obtained through ABAQUS simulation match the digital photograph of the sheet damaged by the bomb impact. Then the established equations and conditions are correct. Moreover, these results are corroborated by the ones presented by Webster.

Acknowledgement

A. Álvarez has been supported by PFC770311A093.

References

[1] R. F. Bishop, R. Hill, N. F. Mott. *The Theory of Indentation and Hardness Tests*. Proc Phys Soc. 57, Part 3 (1945) pp.147–59.

[2] M. E. Backman and W. Goldsmith. *The Mechanics of Penetration of Projectiles into Targets*. Int. J. Eng. Sci. 16 (1978) pp. 1–99.

[3] G. H. Jonas and J. A. Zukas. *Mechanics of Penetration: Analysis and Experiment*. Int. J. Engng. Sci. 16(1978) pp. 879-904.

[4] E. C. Jr. Anderson and S. R. Bodner. *Ballistic Impact: The Status of Analytical and Numerical Modeling*. Int. J. Impact Engineering. 7(1988) pp. 9-35.

[5] AL. Florence. Interaction of projectiles and composite armour, part II. California: Standard Research Institute Menlo Park 1969. AMMRC-CR-69-15.

[6] ABAQUS website. http://www.simulia.com/ accessed 9 February 2011.

[7] P. Wolf and B. Dewit. Elements of photogrammetry. New York: McGraw-Hill, 2000.

[8] J. Casaca, J. Matos, M. Baio. Topografia Geral. LIDEL, 2000.

[9] K.G. Webster. Investigation of Close Proximity Underwater Explosion Effects on a Ship-Like Structure Using the Multi-Material Arbitrary Lagrangian Eulerian Finite Element Method. PhD Thesis Virginia Polytechnic Institute in Ocean Engineering, 2007.

[10] S.L. Wood. Cavitation Effects on a Ship-Like Box Structure Subjected to an Underwater Explosion. Naval Postgraduate School: Monterey, CA. 1998.

[11] Zaera R. and Sanchez-Galvez V. *Analytical modeling of normal and oblique ballistic impact on ceramic/metal lightweight armours*. Int J Impact Eng. 21(1998) pp.133–48.

[12] S. Feli, M.E. Aalami, Z. Ahmadi. *A new analytical model of normal penetration of projectiles into the light-weight ceramic–metal targets*. International Journal of Impact Engineering 37 (2010) 561–567.

[13] P. Ding and A. Buijk. Simulation of under water explosion using MSC. Dytran, 2006.