Pre-test input optimization of high explosive blast effects on steel sheets using finite element analysis

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***Abstract* – The study of the effect of high explosives on structures is important for the design of new protective elements or assessment of existing capacity. In this context, detonation tests of TNT charges will be executed observing the blast effects on structural thin sheets made from A36 steel. Before conducting these tests, it is necessary to predict the blast stand-off distance and steel sheet thickness that will be necessary to optimize the blast effects. To achieve this goal, a series of finite element method (FEM) simulations were performed in Abaqus® software, varying the stand-off distances and thicknesses. The automation of these simulations was performed through a Python macro compatible with the FEM software.**

***Key words* – Blast effect, FEM, dynamic analysis.**

I. INTRODUCTION

A. Contextualization

The use of explosives has become increasingly common in various applications, including in civilian applications, military applications and the aerospace industry [1] [2]. In recent decades, such materials have gained notoriety and raised worldwide concern with the increase in terrorist actions around the world [3] [4]. In addition to its objective applications, its lethal capability is notorious if not used correctly, whether in accidental explosions, terrorist actions or side effects in poorly planned military actions. Due to this, several institutions and researchers, both civil and military, have been studying the destructive effects of explosives, both on the human body and in installations and constructions [5] [6].

Among the possible elements that can suffer the effects of explosives, civil, military and aerospace constructions deserve a significant attention. Such buildings constantly endure military actions, terrorist acts or accidental explosions. Its possible ruin, in addition to generating serious economic losses, will result in human and material losses [6] [7].

Because of this, the study of these effects on buildings becomes important for two reasons: in the design of explosion-resistant installations or, in military actions, in the selection of the most suitable weaponry to hit an enemy target of military value [5] [7].

This research is a follow up of Mendonça *et al.* [7] [8] [9] [10] [11] [12] [13] [14] and Augusto *et al.* [15].

B. Objectives and overview

The research will test a set of blasts with bare TNT charges close to thin sheets made from A36 steel. The objective is determine the blast effects of the explosives over structural steel and compare results with computational methods, like FEM conducting field tests. This pre-test analysis is necessary to predict the best experimental configurations and layout. Without this pre-test analysis, proceeding with the experiments could result in total failure or no deformation response at all.

This paper presents the solution adopted to find the best configuration for the blast test experiment. An explosive charge weighing 320g of TNT was defined, considering safety, costs, and availability of forms for the explosive. For this charge, 48 FEM simulations were carried out, varying two important input parameters: the stand-off distance between the test steel sheet and the center of detonation; and the thickness of the steel sheet. The main output parameter measured was the displacement at the center of the steel sheet.

The software used was Abaqus® explicit module that is suitable for dynamic analysis. The automation of these numerous routines was performed with a Python macro suitable for Abaqus. This macro was capable of changing the layout, running the FEM simulation, reading the important outputs, and exporting charts for each combination of distance and thickness [16] [17].

II. MATERIAL AND METHODS

A. Material constitutive model

Johnson and Cook (JC) [18] is used in this study. JC is a constitutive model developed in 1983 for metals at different temperatures, high torsions and elevated strain rate. This model is suitable for situations where a ductile material experiences large deformations at high speed, such as in explosions. Equation (1) presents the Von Mises stress used in the JC model, which takes into account the strain rate and the effect of temperature on the reduction of the metal's strength [18]. This work will disregard the effect of temperature in the simulation, according to the studies of [19] [20].

$$\sigma_v = (A + B\varepsilon^n)(1 + C\ln\dot{\varepsilon}^*)(1 - (T_m^*)^m) \qquad (1)$$

where:
σ_v – Von Mises stress;
ε – Equivalent plastic strain;
$\dot{\varepsilon}$ – Strain rate;
$\dot{\varepsilon}^*$ – Dimensionless equivalent strain rate equal to $\dot{\varepsilon}/\dot{\varepsilon}_0$;
$\dot{\varepsilon}_0$ – Reference strain in s^{-1};
A, B, C, n e m – Model constants, obtained in tests;
T_m* - Homologous Temperature.

In 1985, following the same theoretical line, JC presented another model [21] that implements metal failure. This model considers an accumulation of material damage over the numerical simulation integration cycles. The equivalent plastic strain for failure is shown in (2).

$$\varepsilon_{fp} = (D_1 + D_2 e^{D_3\sigma^*})(1 + D_4 \ln \dot{\varepsilon}^*)(1 + D_5 T^*) \qquad (2)$$

where:
ε_{fp} – Equivalent plastic strain to fail;
D1 to D5 – Damage constants obtained in tests;
σ^* – Dimensionless stress equal to σ_m / σ_v;
σ_m – Average of the three main stresses.

As the value of ε_{fp} presented in Equation (2) is variable, it is necessary to implement a damage variable (D) that accumulates over the integration cycles, defined in (3). Damage occurs when this variable reaches a value equal to 1.

$$D = \sum \frac{\Delta\varepsilon_p}{\varepsilon_{fp}} \qquad (3)$$

where $\Delta\varepsilon p$ is the plastic strain accumulated in each integration cycle.

B. Full-scale tests

The full-scale tests will be conducted in 2023 on the Instituto de Aeronáutica e Espaço (IAE) blast test arena. Fig.1 shows the proposed test layout. The steel mechanical support will be fixed on a concrete base, and have 900 mm height, that is expected to be rigid with no deformation during the explosion tests. TNT charges will be bare spheres with 76 mm diameter and expected mass of 320 g. The A36 steel sheets, measuring 533 x 400 mm in size, will be replaced in each test. Two edges of sheets will be fixed on mechanical support with thick steel bars and six bolts. The A36 sheets will have a clear span of 433 mm. A metallic rod will be fixed in the middle of the test sheet, linked with the measuring apparatus. It is expected that the rod and measuring system will weigh around 70 g.

Both steel sheet thicknesses and explosion stand-off distances are unknown at the writing of this paper and the objective of the present study is to identify feasible values for carrying out the planned tests.

C. Modeling the problem in FEM software

The A36 steel sheet were modeled as S4R Lagrangian shell elements, considering its small thickness compared with the other dimensions. The constitutive model was JC as previously defined in item A. The A36 JC parameters were found in literature [22] [23] and it is summarized in Table I.

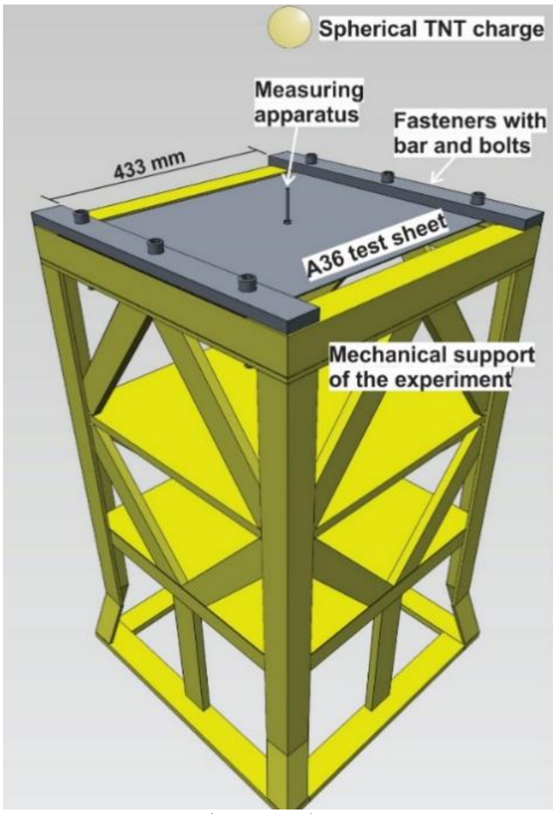

Fig. 1. Tests layout

TABLE I. A36 STEEL JOHNSON-COOK PARAMETERS [22] [23]

Dimensional		***Dimensionless***	
Density (kg/m³)	7850	ν	0.26
E (GPa)	200	n	0.228
A (MPa)	285.9	m	0.917
B (MPa)	499.8	C	0.0171
Tm (K)	1811	D1	0.4025
To (K)	300	D2	1.107
$\dot{\varepsilon}_0$	1.00	D3	-1.899
		D4	0.00961
		D5	0.3

Proper boundary conditions are applied in the simulation.

The simulation also considered the mass of the measuring system as well, considering a 70g distributed mass around the center of the sheet.

The CONWEP® [24] plug-in in Abaqus® was used to calculate the blast loads impacting the steel sheet, as it is a widely validated tool for air blast based on empirical data from the equations of Kingery and Bulmash [25]. Such equations are used by several defense manuals and international institutions [6] [26].

The elements mesh size was around 3mm, resulting in simulations with 23.810 nodes and 23.454 linear quadrilateral elements of type S4R. Tests with finer mesh of 2mm did not reveal any improvement in the results, only resulted in higher computational cost.

The final simulation configuration implemented in Abaqus® software is presented in Fig. 2. Fig. 3 details the mesh refinement.

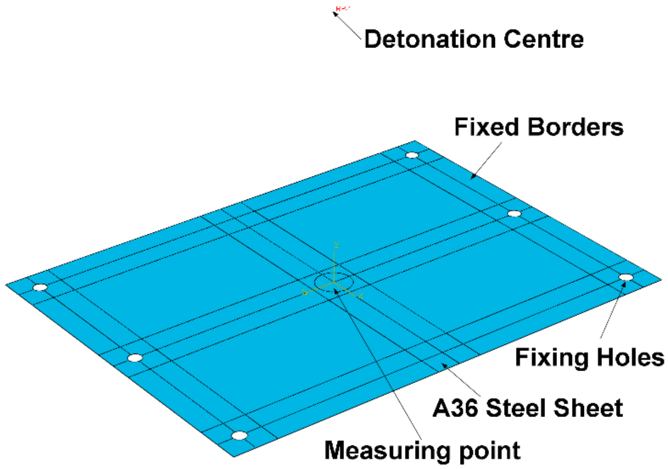

Fig. 2. Simulation configuration in FEM program

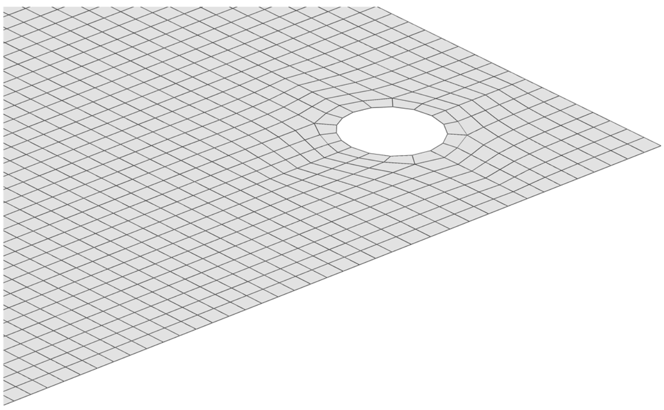

Fig. 3. Mesh refinement detail

D. Simulation Process

Each simulation was run with 100ms after the detonation event, which was sufficient to observe the main and important response effects in the steel sheet. The simulation took more than 1 hour of processing for each case, using 4 parallel processors of 3.3 GHz and 12 GB of RAM.

Detonation stand-off distances from 200 mm to 1,300 mm were studied with an increment of 100 mm. The sheet thickness chosen were 1.50, 2.00, 3.00 and 3.75 mm, following the A36 thin steel sheets available on the market in Brazil. In total, this resulted in 48 different simulations.

A Python Macro, specific to Abaqus® software, was developed to change the characteristics of each case, run the simulation, open the result files, read the information and export data and image files. Altogether, the computational effort for all simulations took more than 56 hours.

III. Results and Analysis

The Python macro generated a massive amount of data, considering the 48 simulations. The following section only presents a summary of the most important results and examples from a representative simulation.

A. General results

The most important information obtained were the displacement (U) in the center of the steel sheet. The maximum displacement is used to predict the level of damage on structures as defined by [5] and [6]. Fig. 4 presents the maximum displacement at the center of the sheet. Each curve represents the thickness of steel and *x-axis* shows the variation of stand-off distance between the center of detonation and the face of the sheet.

Other important data used for analysis is the Plastic Equivalent Strain (PEEQ), i.e., the level of definitive deformations experienced beyond the elastic limit. The higher the value of PEEQ, the greater the irreversible damage to the material. Fig. 5 shows the maximum PEEQ at the center of the sheet, similar to Fig. 4.

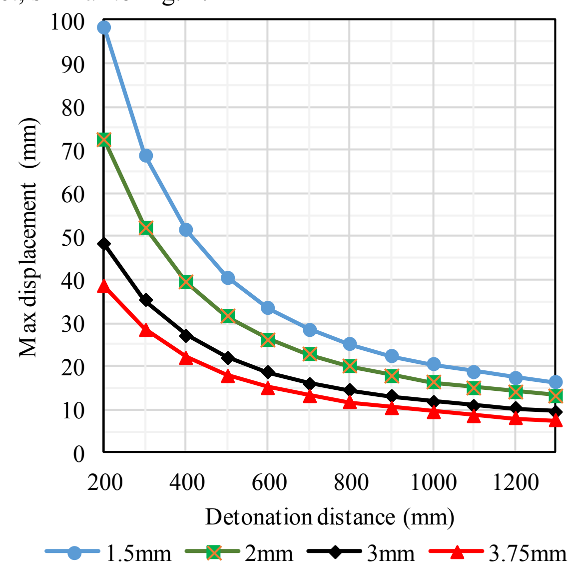

Fig 4. Max displacement at the sheet center as a function of detonation stand-off distance and steel sheet thickness

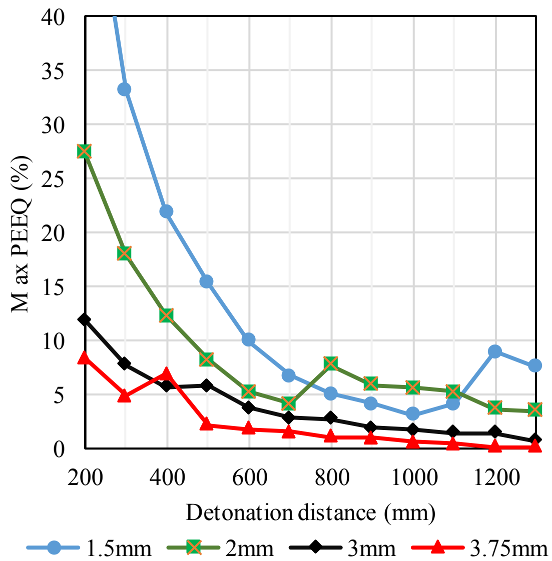

Fig 5. Max PEEQ at the sheet center as a function of detonation stand-off distance and steel sheet thickness

B. Simulation example results

A representative simulation for the steel thickness of 2 mm and an explosive stand-off distance of 600 mm is presented here, as it falls in the middle of the ranges of values.

Fig. 6 details the displacement contour across the entire steel sheet at 1.4 ms, the time when the central point reaches the maximum displacement. The displacement at the center of the sheet over time is presented in Fig. 7. Although the simulation was 100 ms long, for better visualization of the initial events, only 50 ms are displayed on the chart.

The Von Mises stresses at 1.4 ms can be observed in Fig. 8 and the Plastic Equivalent Strain accumulated on the sheet over the course of the simulation is shown in Fig. 9.

The maximum absolute velocity at center of the sheet was 33.23 m/s, resulting in an acceleration of up to 2.41 x 10^5 m/s^2.

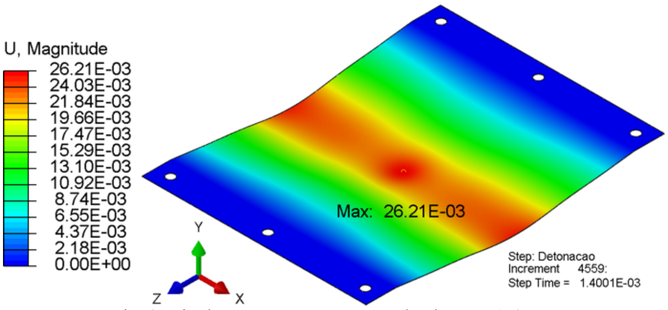

Fig 6. Displacement across example sheet at 1.4 ms.

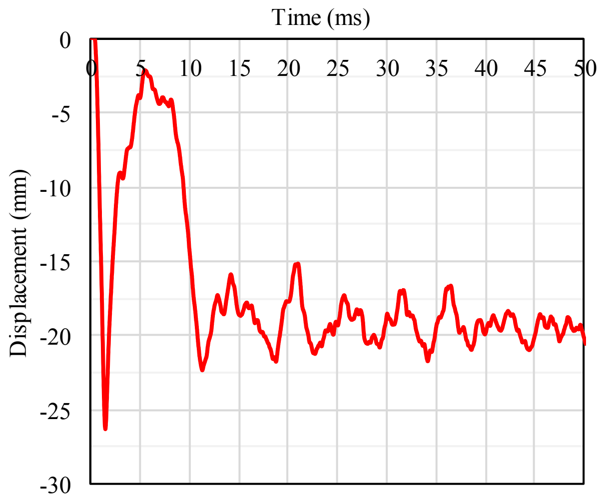

Fig 7. The displacement at the center of the example sheet over time.

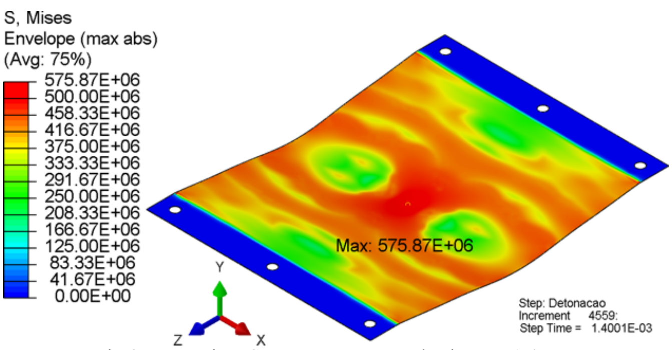

Fig 8. Von Mises Stress across example sheet at 1.4 ms.

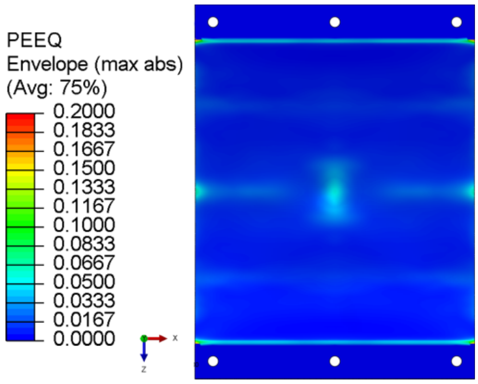

Fig 9. PEEQ accumulated on the sheet over the course of the simulation.

C. Analysis

The main objective of this paper is to observe the effects of TNT loads on steel sheets before conducting a real blast experiment. Figs. 4 and 5 summarize the prediction obtained in the present paper. As expected, the thinner the sheet and the closer the detonation, the more pronounced the effects on the steel are, demonstrating the viability of the adopted model.

The sheets measuring 3 and 3.75 mm in thickness were less sensitive to the variations in the blast stand-off distance, which is not ideal for studying the effect of changing this parameter. For the sheets measuring 1.5 and 2 mm in thickness, stand-off distances less than 300 mm resulted in large effects with displacement greater than 50 mm and PEEQ of approximately 20% to 60%. As a reference, tests on A36 steel bars fail at 20% elongation [27].

For all sheets, stand-off distances greater than 800 mm led to milder results with little difference in results. From this distance, the maximum displacements were determined to be about 10 to 25 mm. On the other hand, PEEQ was less than 10%, and the flattened values resulted in small “inversions” in the results, explained precisely by the low values, high sensitivity of the parameter and concentrations of stresses. Note that the measurements took place in the center of the sheet, and there are concentrations of deformations at other points.

The example simulation presented in item *B* is within this range and represents an average model of what should occur in the real tests. The first relevant aspect is that even under average conditions, the effects of detonation are significant. Stresses in the order of 580 MPa are observed in Fig.8, close to the material's rupture limit [27]. Velocities at the center of the sheet reached about 33 m/s in just 1.4 ms, which resulted in accelerations on the order of 10^5 m/s^2. This highlights the need for robustness of the measurement systems.

The graph in Fig. 7 shows the displacement response at the center of the sheet, which quickly reaches a peak negative displacement of 26 mm, has an elastic restitution effect and, after that, starts to vibrate close to the 20 mm region. This behavior is expected and observed in real detonation tests [7]. The displacement profile in Fig. 6 corresponds to a bi-supported plate, with greater deformations in the central line between the supports.

Fig. 9 shows that the greatest plastic strain occurred in the central measurement region, on the sheet's axis and close to the supports. PEEQ were lower than 20% across the region.

IV. Conclusion

Based on the results and analysis (item III), it is concluded that the 1.5 mm and 2 mm thick sheets for stand-off distances between 300 and 800 mm were shown to be suitable for conducting the actual experiments. Other configurations resulted in severe or negligible effects.

The present work achieved its objective of determining the best configurations for the future experimental tests. High explosive field tests are expensive, in terms of material, team and safe space. The finite element method proved to be an economical and fast solution, and its capacity has already been demonstrated in other works in the academic environment, such as [28] [29].

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