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DYNABlast 1.1 – Development of an Educational Software to Simulate Blast Loads in Plates

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Abstract. Blast incidents, such as the one in the port of Beirut (Lebanon), have become increasingly frequent, highlighting the need for more in-depth studies on the dynamic behaviour of structures subjected to blast loads. In this context, DYNABlast 1.1 was developed in Matlab® environment as an analytical software to simulate the behaviour of Kirchhoff plates under explosive loads, evaluating displacements, strains, stresses, and natural frequencies. The software uses a SDOF (Single Degree of Freedom) model based on von Karman's theory, which is viable for simplified structures since most of the energy from an explosion is concentrated in the fundamental mode of the structure. This study focuses on simply supported plates subjected to explosive loading, considering geometric nonlinearity, the immovable and stress free membrane condition. DYNABlast was validated by comparing its results with numerical simulations performed by the Finite Element software ABAQUS 6.14-1, focusing on the positive, negative, and extended positive phases of the explosion. In addition, analytical software offers advantages over numerical software through the development of parametric analyses that are produced in less time and with greater ease.

Keywords: Dynamic analysis; analytical software; Blast loads; Membrane effect; DYNABlast 1.1.

1 Introduction

With the advent of explosions in the 21st century, whether accidental or intentional, studies on this type of phenomenon have become essential to better represent the type of load on civil structures. Examples featured on major news channels intensify global concern about the issue, as fatalities are counted, such as the cases of the port of Beirut, Lebanon [1], for accidental occurrences, and the Russian-Ukrainian war [2], for intentional explosions.

Explosions are phenomena characterized by their high impact and variation in physical characteristics in the environment, with significant increases in pressure, temperature, and supersonic speed in the release of energy when ignition occurs. Explosions are generally characterized by two moments, positive and negative phases, the latter being recurrently neglected. However, studies conducted by Rigby et al [3] and later confirmed by Reis [4] observed that the negative phase is of great importance for characterizing and determining the behaviour of displacements, stresses, and deformations in civil structures.

Considering the effect of shock waves, the structure commonly used to absorb the energy from this case corresponds to plates. Reis et al. [5], based on the complexity of the loading in question, developed software, DYNAblast 1.0, to simulate the displacements of plate structures subjected to explosions, considering the output results to be the displacements, stresses, deformations, and applied loading. To perform such simulations, it is considered that the analytical model applied corresponds to Single Degree of Freedom (SDOF), as suggested by the US Department of Defence [6] and ASCE [7].

This paper aims to present the update of the DYNAblast software to version 1.1, [8], which presents additions to the type of load applied and used in the literature, in addition to considering analysis based on the distance from the explosive source to the barrier and presenting a behavioural surface of the relationship, based on the variation between the mass of explosive (W_{TNT}), its distance from the barrier (R) and maximum displacement recorded w/h, for each dynamic analysis with R variation.

2 Explosive Phenomena

2.1 Shockwave

The explosive phenomenon is characterized by an abrupt and rapid release of energy from an explosive source, causing variations in pressure, temperature, and velocity. According to the US Department of Defence [6], explosions can be classified as spherical and hemispherical, which depends on the local. In the first case, the energy moves freely in the environment, generating a spherical shock wave. In the second case, the explosive source is close to or in contact with the ground, causing the energy to expand in a hemispherical shape. Figure 1 below shows three types of subcategories indicated by [6]. The first subcategory is defined as a spherical explosion with free movement of energy in the air, the second subcategory is characterized by free energy in a spherical explosion coming into contact with a barrier. Finally, the hemispherical explosion is represented by subcategory 3, regardless of whether it is in contact with a barrier or not.

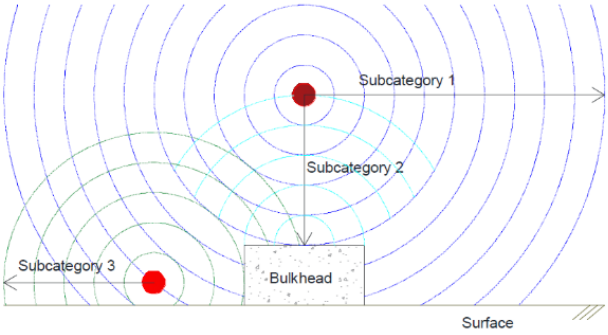


Figure 1 - Subcategories of an explosion. Source: Reis [9]

2.2 Dynamic Load

The explosive charge is determined through empirical and semi-empirical results in order to determine the value of the parameters to be inserted in the equation of the curves. In this case, the US Department of Defence [6] presents two tables that correlate the explosion parameters $p_{máx}$, $p_{mín}$, i_d, i_d^-, t_d, and t_d^- (maximum and minimum pressures, positive and negative impulses, and periods of the positive and negative phases, respectively) with the type of shock wave, spherical explosion, and hemispherical explosion. Subsequently, Rigby et al [3] and Reis [5] presented proposals for the mathematical calibration of these curves, so that equations could be extracted that related these parameters to the scaled distance Z, i.e., $Z = R/\sqrt[3]{W_{TNT}}$.

With regard to the equations that characterize the shock wave, represented in Figure 2, several proposals are found in the literature to describe it. Thus, considering the positive phase, described as pressures above atmospheric pressure, the Friedlander Equation is the most widely used and well-regarded in the literature. In this case, the Friedlander Equation is directly related to the maximum applied pressure (p_{max}), positive phase time (t_d), and decay coefficient (a'), as shown in Equation 1. In the literature in general, this equation is considered only for the positive phase, while the other parts of the load are given as zero. The literature also considers the Extended Friedlander Equation, i.e., the application of the Friedlander Equation to the positive phase and its extension to the negative phase, as in Equation 2. However, Rigby et al [3] observed that the best description for the negative phase corresponds to the application of Granström's Equation [10], characterized by the cubic polynomial, which is directly related to the minimum pressure and times of the positive and negative phases.

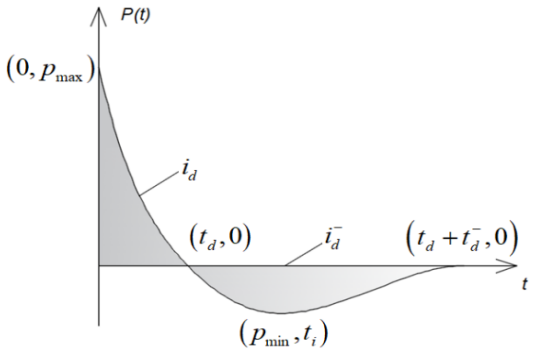


Figure 2 – Shockwave curve [5]

$$p(t) = \begin{cases} p_{máx}\left(1 - \frac{t}{t_d}\right) e^{-\frac{a\prime t}{t_d}} & , t \leq t_d \\ 0 & , t > t_d \end{cases} \quad (1)$$

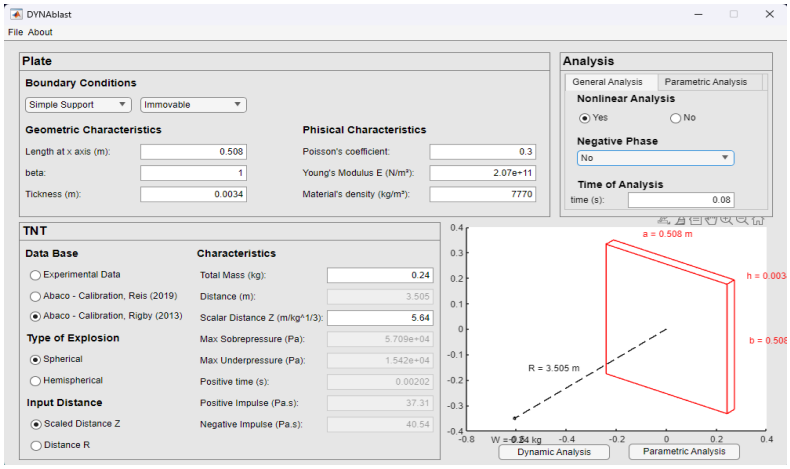
$$p(t) = \left\{ p_{máx}\left(1 - \frac{t}{t_d}\right) e^{-\frac{a\prime t}{t_d}} \right. \quad , t > 0 \quad (2)$$

$$p(t) = \begin{cases} p_{máx}\left(1 - \frac{t}{t_d}\right) e^{-\frac{a\prime t}{t_d}} & , t \leq t_d \\ -p_{mín}\left(\frac{6.75(t - t_d)}{t_d^-}\right)\left(1 - \frac{(t - t_d)}{t_d^-}\right)^2 & , t_d \leq t \leq t_d + t_d^- \\ 0 & , t \geq t_d + t_d^- \end{cases} \quad (3)$$

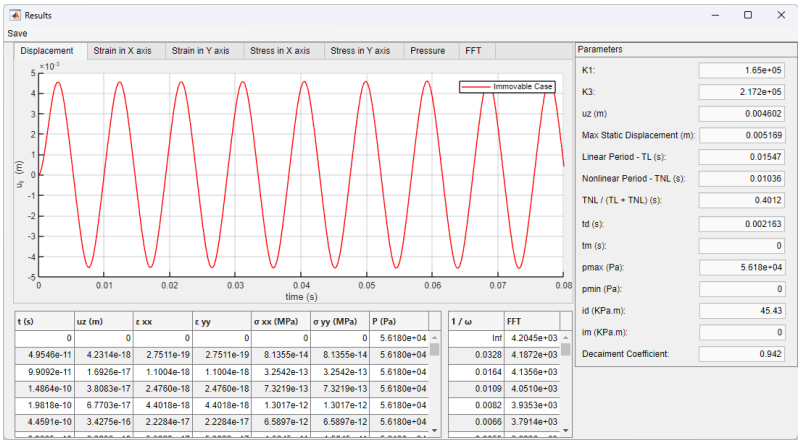
3 DYNABlast 1.1 Software

The DYNAblast 1.1 software [8] fulfils this role of performing simulations of thin, isotropic plate structures with linear elastic material, considering the loading as a shock wave. The three types of loading, presented in Equations (1) to (3), are implemented in the current version of the software. Figure 3 shows the input and output data interface, where it can be seen that the physical and geometric characteristics of the structure, as well as data relating to the loading and type of analysis, are requested. Further information and a description of the software can be found in Reis et al [8] and Reis [11].

Regarding the updates from DYNABlast version 1.0 to 1.1, some examples that can be highlighted include the addition of a new type of loading, the extended positive phase, and the option for the user to directly enter the distance R. It is important to note that there are some new cases of parametric analysis in the new version.



(a)



(b)

Figure 3 – Interface DYNAblast 1.1 [11], (a) Input data, (b) Output data

In addition to the dynamic analysis, U_z/h x time, proposed for simulation, the DYNAblast software has the capacity to perform parametric analyses based on the variation of one of the three main parameters of an explosion, Z, W_{TNT}, or R. For this purpose, 10 different cases are implemented, one of which is a 3D analysis in a surface model with variation of two explosion parameters (W_{TNT} and R). For the present work, four cases are presented, in addition to the 3D surface, applied to plates considering the membrane effect to immovable and stress-free cases, Reis [4].

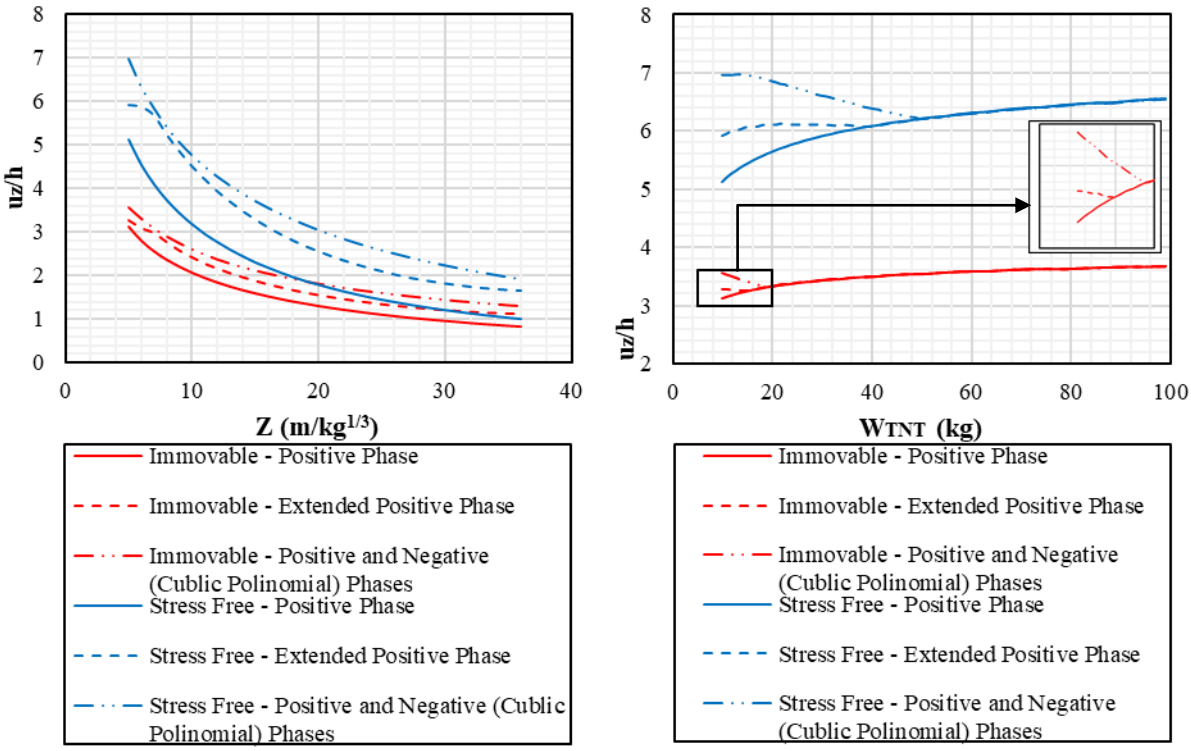
4 Parametric Analyses

The relevant dynamic analyses were then presented in Reis et al. [9], noting the excellent congruence of the DYNAblast 1.1 software with the results compared to the ABAQUS 6.14-1 finite element software [12]. For the present work, parametric analyses applied to cases of immovable and stress-free membrane effects are observed.

Among the membrane conditions used in the analyses, the distinction between them is related to their application. In the immovable case, there are restrictions in the three directions of displacement, i.e., on the x, y, and z axes. In the stress-free case, there are no restrictions on any of the axes, Reis [4].

4.1 Case 1 (Z x u_z/h) and Case 2 (W_{TNT} x u_z/h)

Based on Figure 4, it is possible to observe constant behaviour in the maximum displacement obtained for both cases of analysis, both in the membrane effect in the immovable case and in the stress-free case. In Figure 4 (a), it can be seen that greater displacements are recorded for both membrane effects when the negative phase characterization loading is applied as the cubic polynomial, highlighting the importance of its presence in the quality of the loading and, as presented by Rigby et al [3], the best equation to describe the shock wave curve equation. This type of analysis is confirmed in Figure 4 (b), which shows maximum displacements based on the variation in W_{TNT} mass. In this case, the behaviour of the structure for low masses (immovable case being $W_{TNT} \leq$ 20 kg and stress-free $W_{TNT} \leq 50$ kg) presents greater displacements when the negative phase characterization is applied as the Granström polynomial [10]. From the increase in mass, it is observed that the negative phase has little influence on the maximum displacements, which are recorded during the positive phase.



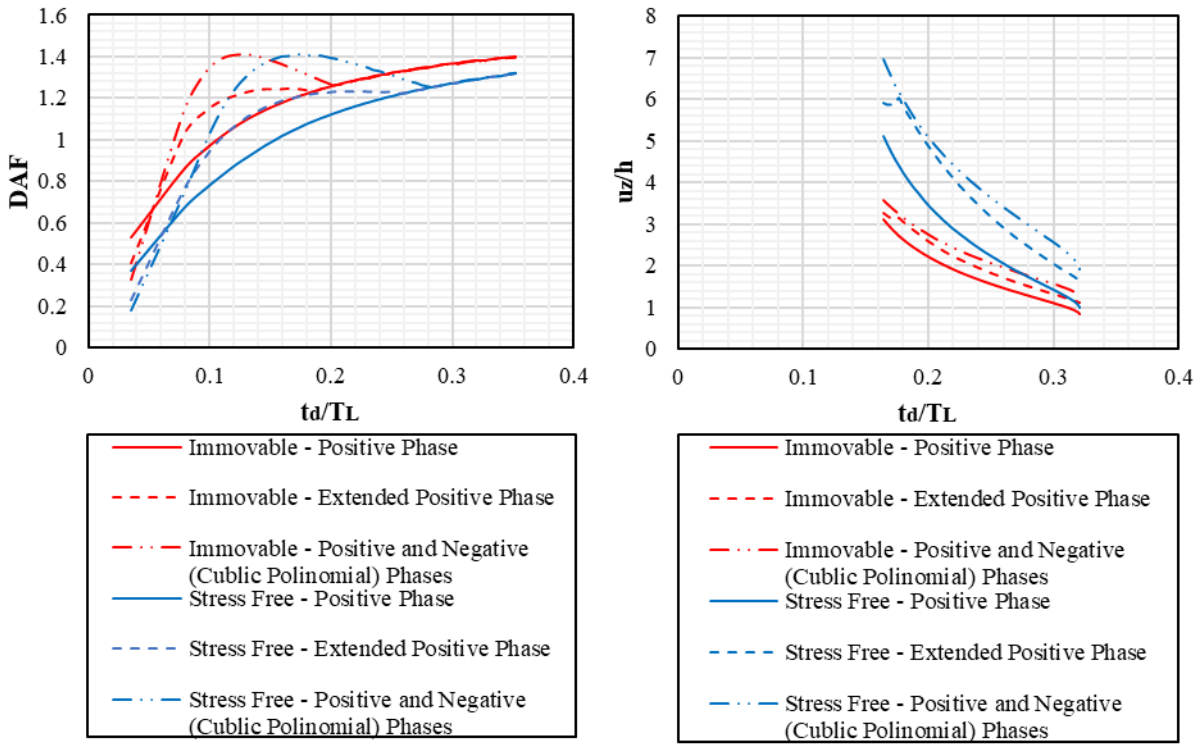
(a) (b)

Figure 4 – Parametric Analyses, (a) Z x u_z/h, (b) W_{TNT} x u_z/h

4.2 Case 4 (t_d/TL x FAD varying W_{TNT}) and Case 7 (t_d/TL x U_z/h)

In line with what is shown in Figure 4, Figure 5 (a) shows that the negative phase is highlighted by a peak at low td/TL ratio values, once again characterizing the determination of the maximum displacement values found during the negative phase. Furthermore, this process is highlighted when the cubic polynomial equation is applied, Granström [10], presenting higher Dynamic Amplification Factor (DAF) values. It is observed that the Extended Friedlander Equation (or extended positive phase) similarly presents the relevant crest, both in immovable membrane effect models and for stress free models. However, when disregarding the negative phase in the application of the load, this crest ceases to exist, and a continuous and smooth curve is observed. From values of td/TL $\geq$ 0.2 for the immovable case and td/TNL $\geq$ 0.26 for the stress-free case, all loading curves converge to the curve that considers only the extended positive phase. This means that the largest displacements, and consequently the largest DAFs, are observed during the positive phase, which is consistent with Figure 4.

In the case of Figure 5 (b), a behaviour similar to that of Figure 4 (a) is observed. In this Figure, 5 (b), there is also a variation in the scaled distance Z, which directly influences the duration of the positive phase of the loading. Thus, higher values of scaled distance result in longer values for the duration of this phase, according to Reis [12], so that the td/TL ratio becomes constant, since the linear period of the structure is permanent, regardless of the loading intensity.



(a) (b)

Figure 5 – Parametric Analyses, (a) t_d/T_L x DAF, (b) t_d/T_L x u_z/h

5 Conclusions

Given the increasing occurrence of explosions, whether accidental or intentional, there is a growing need for research and development of technologies capable of increasing the resistance and safety of civil structures. Shock waves have a wide range and complexity, significantly influencing the dynamic behaviour of structures, so that more accurate analyses of their effects are fundamental to the improvement of design and risk mitigation methods.

In this scenario, DYNAblast 1.1 proved to be an efficient tool for the dynamic analysis of plates subjected to explosive loads, incorporating advances over the previous version by considering different shock wave characterization equations, including the negative phase. The results demonstrated that the adoption of Granström's cubic equation provides a better representation of the phenomenon, especially in situations of low explosive mass and small scaled distances, highlighting its relevance in determining maximum displacements and dynamic amplification factors.

Comparison with numerical results obtained by ABAQUS software confirmed the reliability of the analytical model, validating the application of a simplified single degree of freedom (SDOF) model for plate structures. In addition, parametric studies demonstrated the tool's potential to provide rapid analysis at low computational cost. Unlike ABAQUS, which requires several independent simulations for each parameter evaluated, DYNAblast allows the user to obtain complete graphical results in a practical and automated way, reducing time and effort. Another highlight is its ease of use, since the user only needs to enter the input data for the software to automatically generate the analyses and graphical representations.

DYNAblast 1.1 software also offers different study modalities: general analyses of the dynamic response of the structure, parametric analyses based on the variation of fundamental quantities of the phenomenon (such as WTNT, R, and Z), in addition to the construction of three-dimensional surfaces that relate parameters such as dimensionless displacement uz/h, explosive mass, and distance to the target. These features expand its applicability in both exploratory research and educational studies, promoting a better understanding of structural behaviour in explosion scenarios.

Thus, DYNAblast 1.1 is a significant contribution to academic research and teaching, providing an accessible, low-computational cost, and easy-to-use resource. Future implementations may expand the scope of the tool to include non-isotropic materials and more complex boundary conditions, further strengthening its relevance as a technology to support the analysis and safety of civil structures

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