ARBITRARY LAGRANGIAN EULERIAN ANALYSIS OF THE NEPTUNE FOUNTAIN IN FLORENCE SUBJECTED TO EXPLOSIVE LOADS

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ARBITRARY LAGRANGIAN EULERIAN ANALYSIS OF THE NEPTUNE FOUNTAIN IN FLORENCE SUBJECTED TO EXPLOSIVE LOADS

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Abstract

The present work aims to study the detonation of an explosive charge using a numerical approach. It continues a previous investigation conducted on the Neptune Statue located in Signoria Square, Florence. This case study has been proposed by the University of Florence with the aim of protecting the artistic and cultural heritage: thus, the question is about the blast effects on the statue in the case of a terrorist attack, so as to predict the damage and find possible mitigation or securing measures. In previous work, the focus was on the effects generated by the shock wave of a 45 kg TNT charge explosion placed on the pavement just outside the balustrade 8.8 m from the target. Because of the complexity of the geometry, laser scanning was necessary to obtain a numerical model of the statue, which resulted in a geometric model and finally a mesh. The pressure loads were estimated with the semi-empirical formulas. It is now desired to continue the investigation by constructing a numerical model simulating the explosion, so as to get rid of the limitations of the semiempirical formulations by increasing the accuracy of the analysis. The explicit LS_Dyna solver was used for this purpose. An arbitrary Lagrangian-Eulerian (ALE) approach was chosen, the use of which is already widely established in the literature. Here we limited ourselves to deriving the pressure load as a function of time and validating the numerical model with the results predicted by semiempirical theories. Neither damage analysis nor possible mitigation measures were addressed, which will be the subject of a future publication. For the time being, a rigid material was assigned to the statue; this greatly reduced the computational cost of the analysis.

Keywords: *Blast, arbitrary Lagrangian-Eulerian (ALE), artistic cultural heritage*.

1 INTRODUCTION

Works of art play a fundamental role in the definition and characterization of public environments (for example squares, streets and gardens). The artistic assets displayed outdoors enrich the artistic and tourist value of the countries that host them. In many cases they are exposed to risks, as they can be defaced, damaged, stolen, illegally exported or lost, in some cases lost forever.

This work deals with the evaluation of the behavior of the Fountain of Neptune, located in “Piazza della Signoria”, in Florence under explosive charges. The Fountain of Neptune is a marble and work created by Bartolomeo Ammannati between 1560 and 1565 [1, 2].

Therefore, the safeguarding of artistic heritage is a highly topical issue of great cultural and social importance [3, 4]. This paper aims to investigate the possible need to secure the heritage not only from environmental, man-made actions, vandalism and other well-known phenomena, but also from any terrorist attacks carried out with explosive charges.

The analysis focuses on the assessment of the effects of explosion on the statue through the definition of the pressure loads. These are defined through semi-empirical formulas and with a Eulerian-Lagrangian numerical model which simulates the explosion and allows to determine the pressure wave on the object under study. In this article, the pressure load as a function of time has been computed and compared to the results predicted by semi-empirical theories. This work provides the basis for future developments regarding damage analysis and possible mitigation measures, which will be the subject of a future publication. The adopted numerical model assigns a rigid material to the statue to allow reduced computational costs.

2 DEFINITIONS FOR BLAST LOADING

A shock wave can be defined as a discontinuity of pressure, temperature and density in a fluid [5]. This discontinuity, which constitutes the wave front, propagates at a speed greater than the speed of sound within it (Fig. 1). It is convenient to distinguish between:

- *incident overpressure peak*: pressure increase due solely to the propagation of the wave front.
- *overpressure peak*: pressure increment that takes into account reflections of the wavefront operated by the ground and/or solid structures present.
- *peak pressure*: actual measured pressure given by the sum of the atmospheric pressure and the overpressure generated by the blast load.

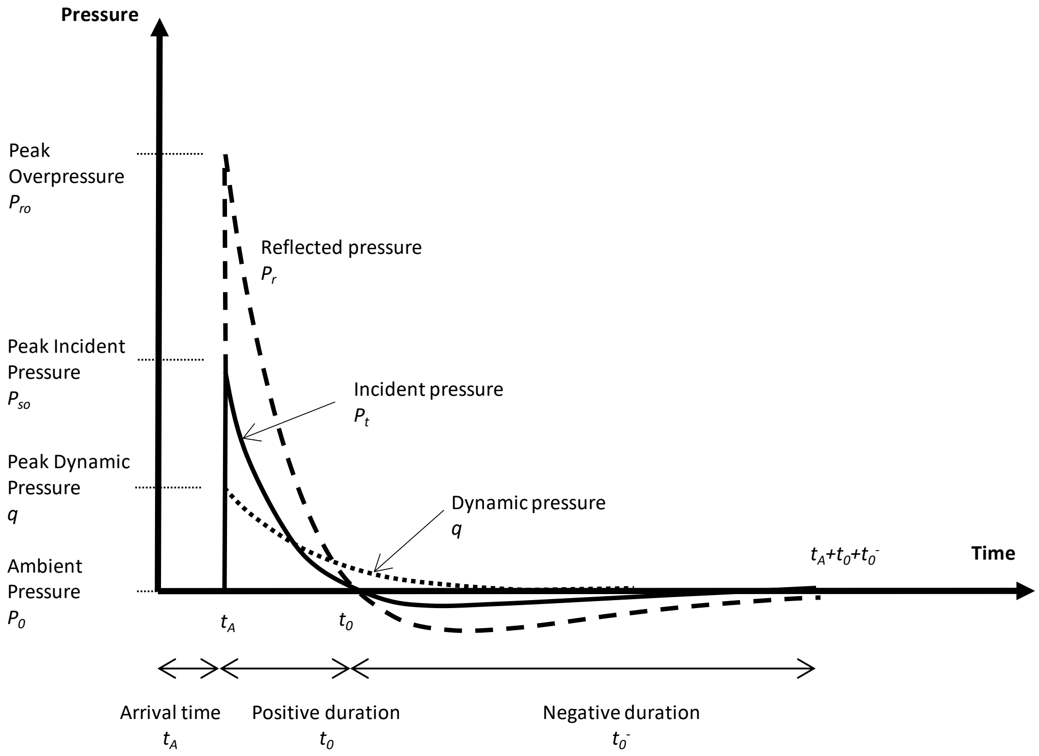

Figure 1: Blast Load [5].

2.1 Description of ALE Method

Using a Lagrangian approach, the mesh has the ability to move in space, and therefore a component can deform. The stresses within a component are calculated by the solver precisely on the basis of the deformation experienced by the mesh (and thus the nodes). This formulation is suitable for modeling solid bodies subject to mechanical loads. Mass flows through the edges of a component, which, moreover, are absent or negligible in solids, are not allowed. If the deformations are very large the distortions of the elements become significant, and may affect the goodness of the calculation.

An Eulerian mesh does not have the ability to move in space, so elements cannot deform and change shape. However, mass flows between elements are allowed. This makes this formulation particularly suitable for modeling fluids.

An Eulerian Lagrangian Arbitrary Mesh (ALE) [6] is a hybrid of the previous two and combines the advantages of one and the other. It is constrained only at the edges, so deformations of the elements are allowed within the domain. When element distortions become very important an adjustment of the mesh is performed automatically, which allows regenerating the compromised elements ensuring the stability of the calculation. What is more, mass flows between two adjacent elements are allowed.

Figure 2 shows the difference between a metal forming process modeled with a Lagrangian mesh versus an ALE mesh approach. In the former case, the material is inextricably bonded to the element. During plastic deformation, the elements are strongly deformed since the material cannot cross the domain of the individual element. In the second case, mass flow through the mesh is allowed, so mesh distortions are smoother.

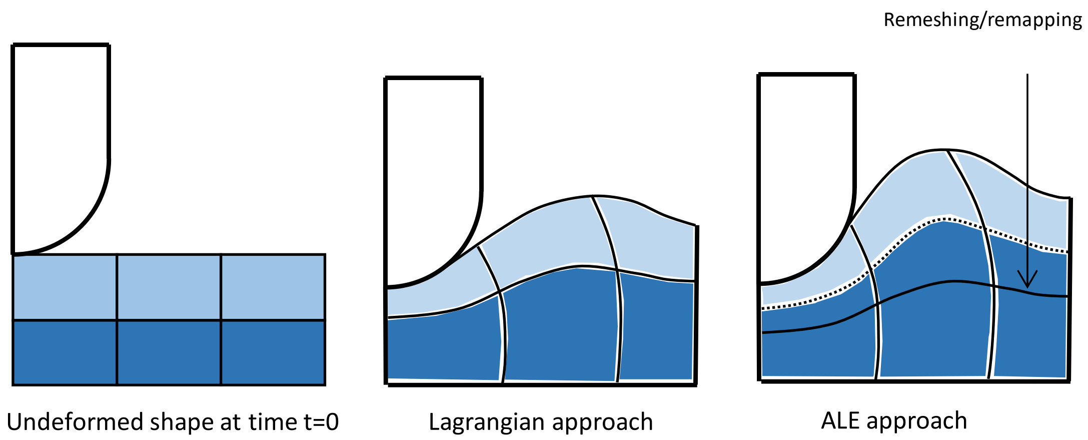

Figure 2: ALE mesh [6].

3 ALE NUMERICAL MODEL DESCRIPTION

Numerical simulation was obtained using LS_Dyna software [7]. This solver is mainly used for explicit analysis, although an implicit solver for static analysis has also been implemented [7]. When the geometry of the numerical model is generated, a number of nodes are associated with the individual element, and it is assigned to a *PART, characterized by:

- a definite material, the properties of which are placed within the keyword *MAT
- a *SECTION, which describes the type of element used (solid, shell...)

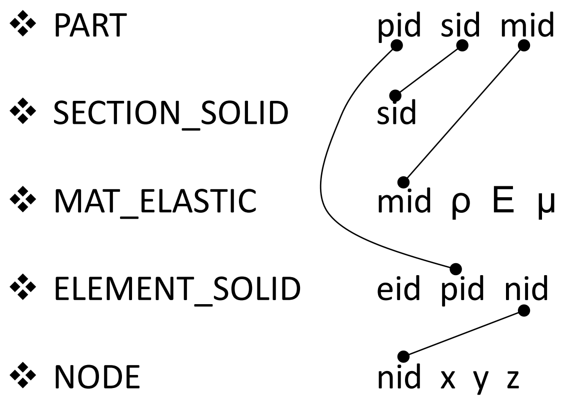

Figure 3: LS_Dyna keyword file structure [7].

3.1 Lagrangian part : Statue

A 3D CAD model of the statue had already been developed by laser scanning (see Figure 4) [8]. However, the previous numerical model was composed of solid elements, and the material realistically reproduced the characteristics of marble.

Since one is not interested here in calculating the stress or failure modes of the target, but only the pressure load acting on it, in order to simplify the numerical model and reduce the computational cost, shell elements were chosen instead of solid elements (*SECTION_SHELL). The keyword *MAT_RIGID was used for the material. The ALE formulation was not necessary for this either: the rigid material will avoid mesh distortions.

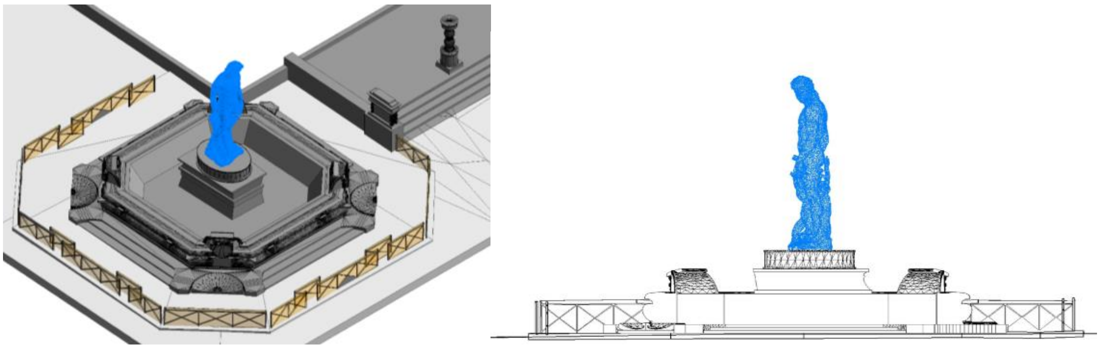

Figure 4: 3D Model of the fountain with FEM of the statue.

3.2 ALE Part: Model and Keyword

The explosive charge changes state after initiation: a chemical reaction converts solid reactants into gaseous products at high temperature and pressure. The wave front moves very rapidly, so the fluxes through the domain elements are intense. For these reasons, an ALE approach was chosen to model the explosive charge and air. Solid elements (*SECTION_SOLID) were used.

The properties of the air were defined by means of the two keywords *MAT_NULL and *EOS_LINEAR_POLYNOMIAL.

The explosive properties, on the other hand, are contained in the keywords *MAT_HIGH_EXPLOSIVE_BURN and *EOS_JWL. The initiation of the detonation is handled by the keyword *INITIAL_DETONATION. Recall that in the present case, an explosive charge of 45 kg of TNT was assumed, placed at a distance of 8.8 m from the target (see Figure 5), which is in line-of-sight.

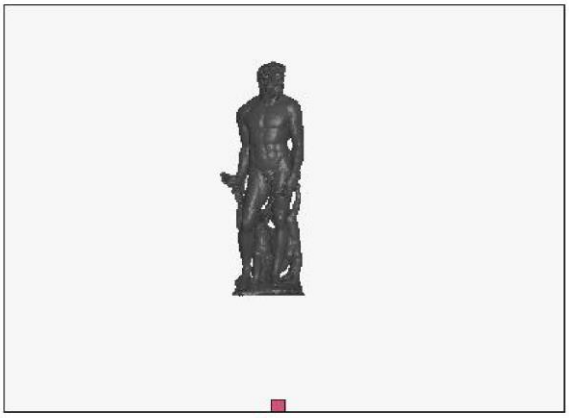

Figure 5: Complete Model.

To minimize reflections, a reasonably large domain was created, keeping in mind the need not to generate too many elements so as not to drive up the computational cost too much. A domain size of 14x12x8m was chosen.

For the analysis to work properly, it is essential to define the coupling between the ALE domain and the target Lagrangian mesh, via the keyword *CONSTRAINED_LAGRANGE_IN_SOLID.

Outputs are requested through the keywords *DATABASE: *DATABASE_BINARY_D3PLOT, *DATABASE_FSI_SENSOR, *DATABASE_FSI.

Finally, a number of control keywords are activated in the launch file: *CONTROL_TERMINATION, *CONTROL_TIMESTEP, *CONTROL_ALE.

3.3 Load Blast Enhanced Model

Building an ALE model is just one of the ways in which an explosion can be simulated in the Dyna environment. For example, the keyword *LOAD_BLAST_ENHANCED (LBE), which exploits the concepts of scaled distance and equivalent TNT, is also available.

By drawing on a database of experimental tests conducted for various load configurations (free-air spherical blast, ground hemispherical blast...) the solver is able to predict with great precision and accuracy the pressure load on the target.

This method does not require a mesh of the domain within which the blast wave propagates: the only mesh present is that of the target. The number of model elements is drastically reduced, as is the computation time. The great limitation of this keyword lies in the fact that it is unable to consider any obstacles interposed between the blast charge and the target. In the present case, where the exploding charge and target are in line of sight, the simulation can be considered accurate.

The following are the basic keywords to be activated. To generate the blast load, *LOAD_BLAST_ENHANCED is used. The coordinates of the charge, the mass of equivalent TNT, and the loading configuration are then to be defined. With this keyword it is mandatory to define a set of elements that will form the target-air interface, on which to go to calculate the pressure outputs generated by the blast wave.

You then go on to define a set of shell elements and activate *LOAD_BLAST_SEGMENT_SET.

To print the pressure outputs, you activate the keyword *DATABASE_BINARY_BLSTFOR instead.

4 ANALYTICAL APPROACH

Consider a certain type of explosive. The parameters that characterize an explosion depend on mass and distance. It is possible to predict the effects of an explosion using an approach called scaled calculus and was independently developed by Hopkinson [9] and Cranz [10]. The cube-root scaling law, also called the Hopkinson-Cranz scaled law, states:

"Two charges of the same explosive material having the same geometry but different sizes that are detonated under the same atmospheric conditions produce similar shock waves when compared at the same scaled distance."

Scaled distance is defined as the ratio:

$$Z = \frac{R}{W^{1/3}} \tag{1}$$

Numerous authors strove to find a simple formula that accurately described the effects generated by an explosion. All investigations led to an exponential law, known as the modified Friedlander equation [11 - 13]:

$$p(Z,t) = p_0 + p_s\left(1 - \frac{t}{t_0}\right)e^{-\frac{bt}{t_0}} \tag{2}$$

Where p_s, b, t_0 are experimentally determined parameters in which the scaled distance dependence Z is hidden. The differences between the models proposed by the different authors lie not in the pressure dependence law, which is always (2), but in the calculation of the three coefficients p_s, t_0, b.

Here we will refer to the formulations proposed by Mills [14] and Wei&Drahani [15], which provide the maximum and minimum estimates of the pressure load, respectively. All these formulas refer to a load condition in free air, not on the ground, so they do not take into account the reflections that occur in the real case.

Note that the keyword *LOAD_BLAST_ENHANCED (LBE) is based on precisely these semi-empirical formulations, with the difference that it is possible to select the type of loading configuration (confined, free-air...) and the shape of the wave front (spherical, hemispherical...) to obtain more accurate results.

5 RESULTS

To understand if the results obtained through the ALE model are acceptable, we have to compare them with those provided by the theories and the keyword LBE. For this purpose, 3 sensors have been defined, shown in Figure 6.

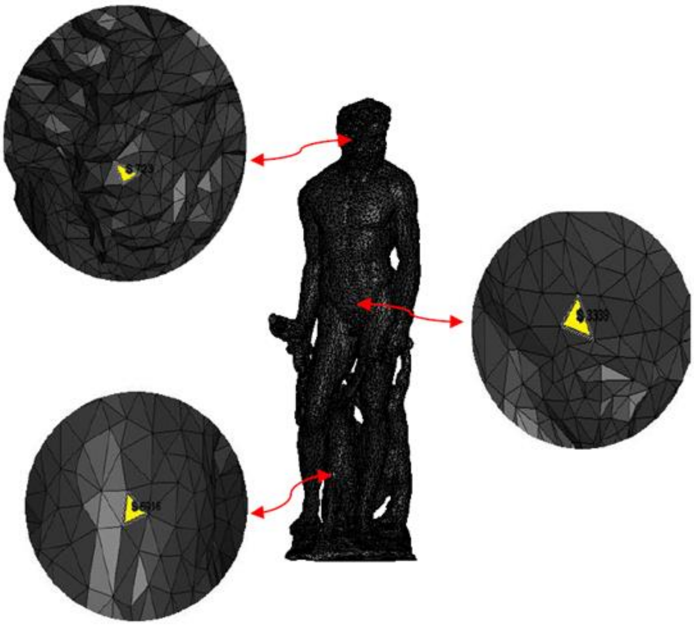

Figure 6: Position of three sensors in the FEM model.

The comparison was made considering the response of 4 different approaches for calculating the incident overpressure wave in the three points defined above (see Fig. 7), in particular:

- Incident overpressure, ALE method;
- Incident overpressure, keyword LBE;
- Incident overpressure, Mills' semi-empirical formula;
- Incident overpressure, Wei&Dharani semi-empirical formula;

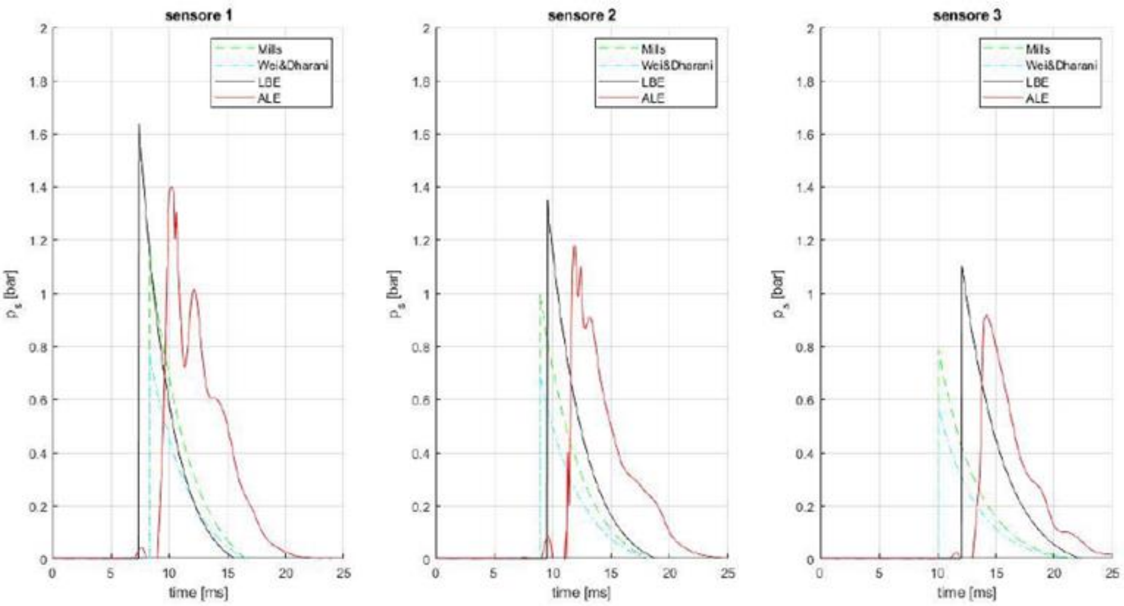

Figure 7: Incident overpressure for four different approaches.

As can be seen, there is a good match between the results predicted by the theory particularly with regard to *LBE and ALE. The discrepancy with analytical theories lies in the fact that they do not take into account the particular loading configuration.

Figure 8 shows, as an example, a plot of the incident overpressures recorded on the target (statue).

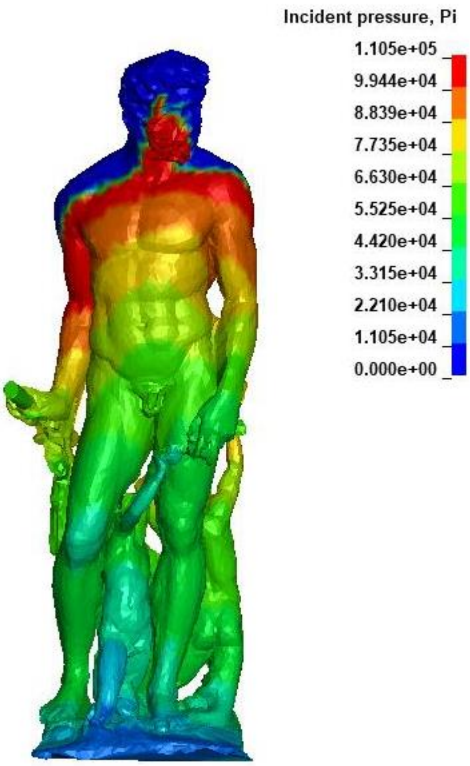

Figure 8: Incident overpressure.

Figure 8 shows the result of a simulation of the distribution of the incident peak overpressure. This reaches pressures equal to 1 bar in the chest neck part of the statue. This result, together with the comparisons between the various approaches, allows us to define the stress states acting on the statue in order to carry out subsequent verifications of the object's stability or safety.

6 CONCLUSIONS

The present work arises from the need to evaluate which action should be used to evaluate the behavior of art objects subjected to the effects of explosions due to various causes in order to adopt a simplified analysis approach, e.g. a Lagrangian finite element approach with semi-empirical loading conditions.

Thus, the definition of the shape and intensity of the waveform to be applied to the statue can be defined through approaches with different levels of simplification. In this paper we compare different approaches to evaluate the differences. The results obtained show an excellent agreement between the results of the ALE method, of the LBE method and the semi-empirical formulas, this demonstrates the goodness of the developed models. This result of concordance between different formulas allows to define that the calculated pressure loads can be considered reliable.

The results of the simulations carried out to determine the waveform and its intensity show how the pressure loads acting on the statue are considerable. These results make it possible to lay the foundations for future simplified or complex evaluations to define the behavior of the statue and evaluate any mitigation systems.

According to the authors, the system should provide good protection from the explosion load, without compromising the decorum of the work and of the square as a whole. The design of such a protection system, together with its numerical validation, will be the subject of future research efforts.

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