

Chapter 14

Different Approaches of Numerical Simulation of Blast for Civil Engineering Applications



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Abstract The aim of the paper is to describe various approaches of numerical simulation techniques, with a special focus on air blast effects on structures. In this regard, the document summarizes and describes commonly available commercial software tools for the design and simulation of civil engineering structures and components under impulsive dynamic loads. In conclusion, some useful examples of numerical modelling of selected constructional elements are also presented.

Keywords Numerical simulation · Blast wave · Explosion effects · Blast resistant structures

14.1 Introduction and Analytical Methods

Especially in the last few years, given the increasing number of tragic events and observations from terroristic attacks, several research studies have been carried out to study the performance of constructional systems under explosions, with major efforts and attention for several blast-related effects and phenomena. These include laboratory investigations on material dynamic properties (i.e., to characterize their mechanical performance under high-strain pressures and shocks), analytical solutions for the simplified analysis of the response of constructed facilities under impact, numerical modelling investigations for the vulnerability assessment of materials and structures subjected to air blast waves, laboratory or field blast tests to validate the prediction and performance of buildings and assemblies, as well as the efficiency of possible mitigation and retrofitting solutions for novel or existing structures claddings.

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Within all these studies, the first fundamental steps are related to the reliable estimation and description of the structural behaviour of a given material/system under dynamic loads like explosions. For design purposes, the most suitable approach is represented by simplified methods, where a given complex mechanical system could be investigated based on simple computational models. Despite the computational advantage of such a general solving strategy, on the other hand the accuracy of simplified methods may be compromised, with severe effects on the reliability of blast-induced effects estimates and fail-safe design goals.

More in detail, to describe a given system, both the following analytical methods can be used:

1. Single degree of freedom.
2. Multi degree of freedom.

14.1.1 *Single Degree of Freedom*

The degree of freedom of the structure describes the minimum number of coordinates required to define completely the positions of all its parts of a system at any instant of time. A single degree of freedom system requires only one coordinate to describe its position at any time step (called springmass-damper system). Damping of blast loaded structures has much less importance because the maximum response will be reached in a very short time, before the damping forces can absorb much energy from the structure (Fig. 14.1).

Generally the effects of damping in blast analysis are not considered because of the reasons:

- Damping has very little effect on the first peak of response.
- The energy dissipated through plastic deformation is much greater than that dissipated by normal structural damping.
- Ignoring damping is a conservative approach.

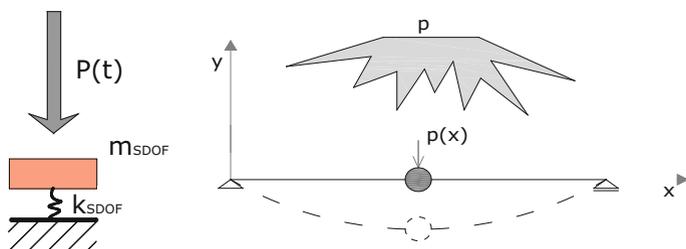


Fig. 14.1 SDOF system presentation [1, 2]

If we want to make the SDOF system response equivalent to the real system, equivalent SDOF factors are used to obtain the effective mass, force, and resistance terms [3].

14.1.2 Multi Degree of Freedom

A multi degrees system (MDOF) is a system requiring at least two coordinates to describe its motion. If they are independent of each other are called general coordinates and they are equal in number to the degrees of system freedom. The difference between MDOF system and the single DOF system is that we have n natural frequencies and for each of the natural frequencies corresponding to the natural state of vibration with a shift configuration known as normal mode. Vibrations in normal mode are free vibrations, depending only on the weight and stiffness of the system, its distribution.

Systems with 2 degrees of freedom can be solved analytically, but for a larger degree of free systems, numerical analysis using computer to find natural frequencies (eigenvalues) and mode shapes (eigenvectors) can be used [4].

14.2 Numerical Methods

Numerical methods have been developed to help engineers understand, to analyse, and predict all physical phenomena that occur under different load conditions. They are of great importance, especially for dynamic loads, because the fast-dynamic loads, such as blast load, are solved with analytical methods with difficulty and structural behaviour of such loaded structures is hard to describe.

14.2.1 CFD (Computational Fluid Dynamics)

The Computational Dynamics of Liquids is a fluid mechanics industry that uses numerical analysis and data structures to solve and analyze problems that involve fluid flows that are used to perform the calculations needed to simulate the interaction of fluids and gases with surfaces defined by boundary conditions.

For a reliable estimate of the explosion from a gas detonation, it is first necessary to know the intensity of the explosion itself, and this aspect may involve a series of uncertainties with severe effects on the numerical predictions. For example, the source explosion may not be symmetrical. In common practice, pressure waves can in fact reflect or deviate when construction/obstacle objects are struck. Even worse, blast waves can spread inside buildings or tunnels with very low decay rates. The use of CFDs for near and far wavelength forecasting, in this context, has many

advantages. They include in fact more accurate energy estimates, hence resulting in enhanced blast wave pressure simulations, as well as the ability to evaluate unbalanced effects due by real/complex geometries, where gas cloud and ignition sites could change. This is essential in assessing the likelihood of a source of leakage as a cause of the explosion or in assessing the potential risk associated with the source of leakage due to the impact analysis [5].

14.2.2 TNO Multi-energy Method

The TNO multi-energy method proposed by Van den Berg determines the maximum overpressure due to the different gas explosion force depending on the limitation. Obstacles in the gas cloud can affect the degree of explosion of gases by increasing the flame rate, i.e., turbulence, which is caused by the passage of liquid through the obstacles, thereby accelerating the flame of the explosion. Given the fact that the turbulence regulates the force of the explosion wave, this method uses geographic conditions as the main factor in estimating the potential energy of the gas explosions (e.g., they are confined or obstructed). From different sources of ignition in the steam cloud, sub-explosions of different strengths are determined, positive overpressures and positive phases of duration are defined. The procedure for the determination of the explosion force with TNO MEM is as follows:

1. Determine an obstacle and/or an unrestricted region.
2. Determine the class number and estimate the strength of sources in each region.
3. Determination of the gas cloud radius.
4. Calculation of scaled distance, positive pressure phase and duration (explosion parameters).
5. Calculation of positive overpressure, duration and positive impulse (actual parameters).

Explosion parameters are determined based on the class number and the guidelines suggested by Kinsell, Roberts and Crowley can be used for the class number (Tables 14.1 and 14.2). However, these guidelines define the range of a class number rather than a specific value. The user can make a final decision when selecting a class number, although not sufficiently objective [6].

14.2.3 FEM (Finite Element Method)

Last very useful method called the Finite Element Method is method that divides the CAD model (structure) into small shapes of various geometry. All these shapes and components represents the so-called Finite Element network.

Table 14.1 Guidelines by Kinsella for class number [6]

Ignition energy		Obstacle density		Confinement			Strength
Low	High	Low	High	No	Existing	No	
	X		X		X		7–10
	X		X			X	7–10
X			X		X		5–7
	X	X			X		5–7
	X	X				X	4–6
	X			X	X		4–6
X			X			X	4–5
	X			X		X	4–5
X		X			X		3–5
X		X				X	2–3
X				X	X		1–2
X				X		X	1

Table 14.2 Guidelines by Roberts and Crowley for class number [6]

Types of flame expansion	Mixture reactivity	TNOMEM charge strenght		
		Obstacle density		
		High	Medium	Low
1-D	High	10	10	10
	Medium	9–10	9	7–8
	Low	9–10	7–8	6
2-D	High	9	7–8	4–5
	Medium	7–8	6–7	2–3
	Low	6	5–6	1–2
3-D	High	6	3	1
	Medium	3–4	2	1
	Low	3	2	1

After the division of a structure into the small parts, partial differential equations (PDEs) describing the physics are applied for each element. In each element a simple function (linear or quadratic polynomial) with a final degree of freedom (DOFs) is solved. Collecting the contributions from all the elements, a large system of isosceles matrix equations is created.

The type of solver used depends on the original physics, each type of physics brings a unique trace to the structure of the matrix. Customized numerical method is used to speed up the situation. The method is used mainly for structural analysis. During the last years, it has been found that the finite element method is also suitable for a large class of multi-physical problems [7].

14.2.4 Implicit and Explicit FEM

Numerical simulations can be used to predict the behaviour of different structural materials and components/systems affected by a given blast-wave. These numerical simulations are not intended to replace the experimental tests, but can be used as an efficient and robust tool in support of test scheduling, prediction and assessment of experimental results, or performance of parametric studies (by changing, for example, boundary conditions, geometry, material properties or explosion features). Most FEM solutions are based 1D (beams), 2D (shells) or 3D (bricks) type of elements. Each corner (i.e., extremity) of the element is defined by a node. The association of all elements represents the structure or the environment of the structure (boundary conditions or air) and is called the structure of the mesh.

Implicit and explicit time integration schemes are the two main available methods in use for FE dynamic analyses. The most appropriate method is selected, case by case, based on the nature of the problem to be solved, and in most of the cases requires a certain experience of the final user for the appropriate calibration of input parameters. Whilst the implicit methods are generally preferred for earthquake load and linear behaviour under impulsive dynamic loads, nonlinear phenomena due to shock events are mainly calculated using explicit time integration approach [8].

14.3 Solvers

The Lagrangian solver is the most commonly used, within the framework of structural FEM analyses. The network represents the structure and its deformation. For example, during the analysis of effects induced by a high-pressure load, the structure may be subjected to large deformations and the computational network may be highly deformed to generate premature convergence issues, and hence calculation aborts. In order to overcome this difficulty, Lagrangian's standard approach can be used. Such an assumption means that - according to Euler's assumptions - a given mesh/grid is fixed and the materials in use (solids, liquids or gases) can flow through this grid. Eulerian analyses are effective for applications involving extreme deformation to fluid flow. In these applications, the traditional Lagrangian elements became very distorted and lost the accuracy. Liquid spraying, gas flow and most penetration problems can be effectively resolved using Eulerian analysis [8] (Fig. 14.2).

To improve the quality of numerical access, many of the current codes include the Euler-Lagrange analysis link (but also the ALE - Arbitrary Lagrangian-Eulerian approach). In this case, the spatial domain is divided into two parts, the first part is dedicated to the Lagrangian solution, and the second part is for Eulerian solution. This combined approach is very useful in simulating, in a single run, the shock wave

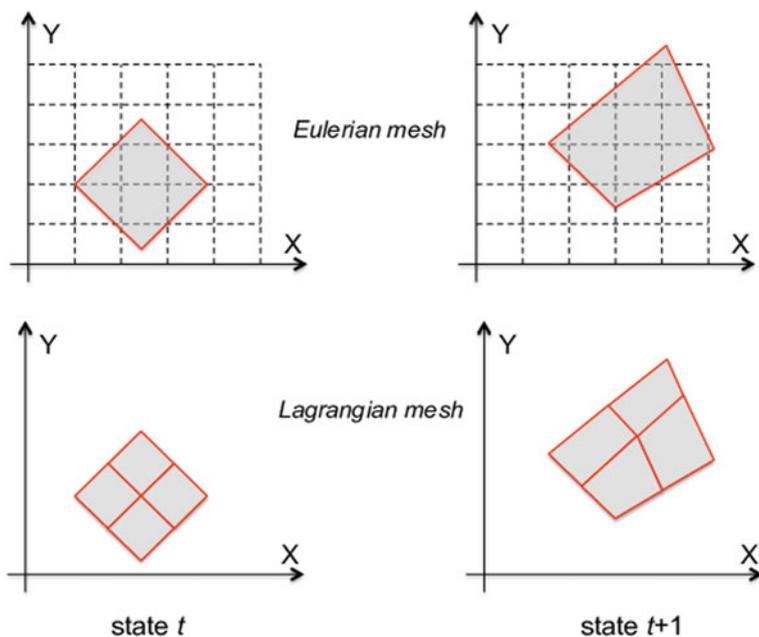


Fig. 14.2 Lagrangian vs Eulerian description [7]

propagation and structure response. Another possibility of increasing the accuracy of fluid structure interaction is to use mesh adaptivity (automatic mesh refinement AMR). The idea is to use very fine mesh fluids in structures and high pressure gradient zones to better capture the details of wave development in these areas [8].

14.4 A Brief Overview of Selected Commercial Software Packages

In Table 14.3, a concise overview of key features for the solving method and discretization approach is reported for a selection of possible software products.

Among the typical structural engineering software VISUAL FEA can be classified. It allows to do various types of analysis: Structure linear static (nonlinear, dynamic, sequentially staged), Heat conduction (steady state, transient), Seepage (steady state, transient, confined, unconfined), Coupled analysis (structure and heat conduction, structure and seepage) (Fig. 14.3).

The blast load can be simulated as a load on the element in the form of non-linear function. The response spectrum can be drawn based on the loads.

Table 14.3 Software products

Software	Implicit method	Explicit method	Discretisation		
			Lag.	Eul.	Lag/Eul
ABAQUS	X	X	X	X	X
ANSYS	X	X	X		
LS-DYNA	X	X	X	X	X
AUTODYN		X	X	X	X
MSC.DYTRAN	X	X	X	X	X
NASTRAN	X	X	X		
EUROPLEXUS		X	X	X	X
ASTER	X		X		
SOPHIA		X	X		
ProSAir		X		X	
Apollo Blast Simulator		X		X	
VISUAL FEA					

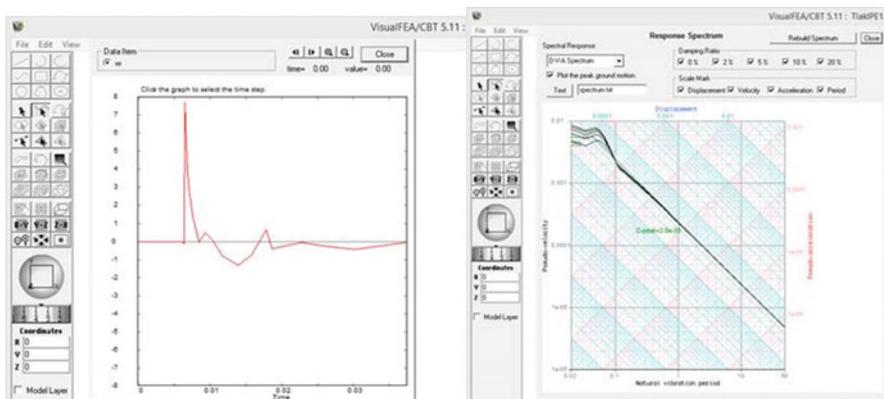


Fig. 14.3 Simulation of blast load in VISUAL FEA

14.5 Discussion of Typical Simulation Results for Blast Loaded Structures

The dynamic numerical simulation in ABAQUS is based on the Finite Element Method and the key input features from the user are related to the geometrical properties of the object/system to investigate, the used materials, the presence of possible constraints and contact interactions, as well as the mesh (Lagrangian or Eulerian), including time-varying loading pressures. While the potential of the software package is represented by a wide series of mechanical interactions/constraints and damage material models (see for example [9–11]), the simulation of the explosive event itself (i.e., the detonation and the blast wave propagation) is not available.

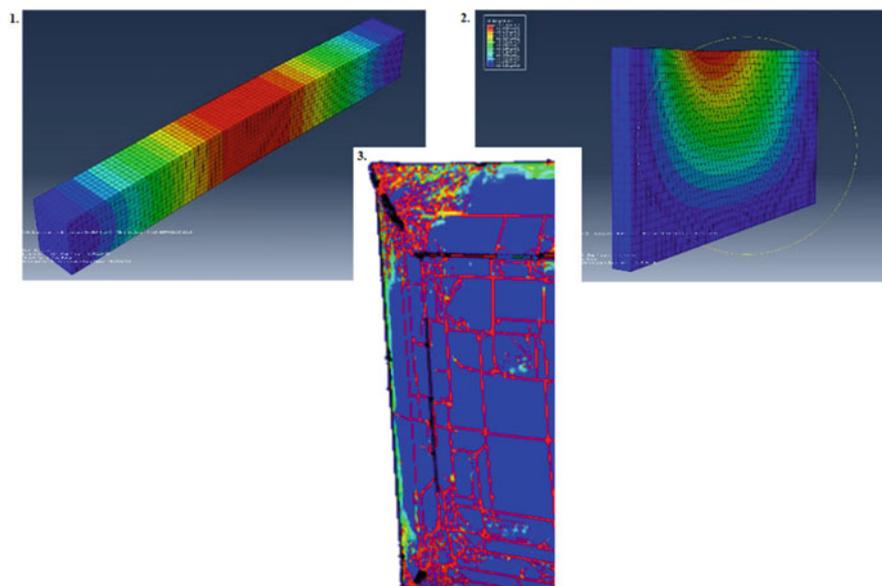


Fig. 14.4 Simulation of blast load

In Fig. 14.4, the effects of a given blast load at different time intervals are shown for several building components, such as: (1) A steel beam, (2) A concrete wall with steel reinforcement mesh, and (3) A tempered glass panel belonging to a curtain wall facade.

Of course, the process of building and loading the object takes a lot of time and several times more partial actions to finish the desired result (the simulation of blast load). The load results can be transferred as numeric data or charts into Excel and then work with them. The individual methods used in the blast wave simulation are described in the paper “Analysis of blast load steel beam” [10].

Another example of numerical simulation is reported in Fig. 14.5, in the form of selected results from AUTODYN, where the effects of a given blast wave on a concrete wall are presented. The concrete wall is anchored to the floor and its scaled distance from the charge is $Z = 1.0 \text{ kg/m}^{1/3}$. In addition, the width of the wall is $b = 0.5 \text{ m}$, $h = 0.5 \text{ m}$ is depth (wall stiffness $K = 5.14 \times 10^6 \text{ N/m}^2$ and mass ratio = 20). The Eulerian mesh is used for air and for the explosive charge (TNT), while a Lagrangian mesh is used for concrete wall.

In Fig. 14.5, several phases of the blast wave propagation are shown, from the very beginning of the detonation, through the diffraction of the waves on the surface of the wall, until it is reformed behind the concrete wall [11].

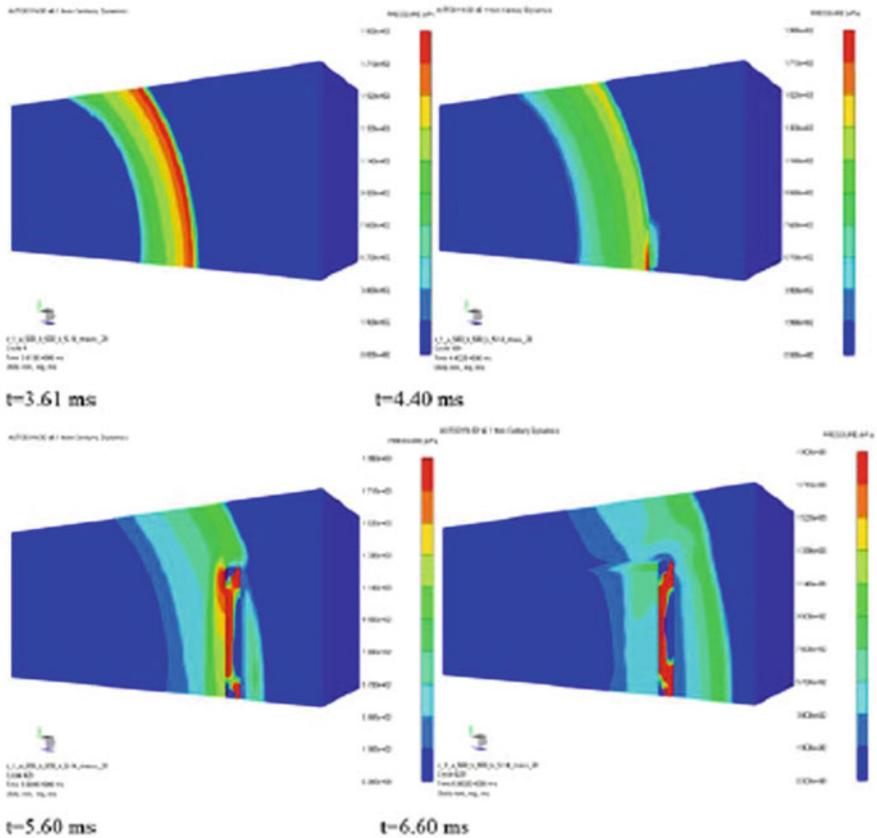


Fig. 14.5 Blast wave propagation on a concrete wall [12]

In Fig. 14.6, the reflected pressure and impulse at various points of the concrete wall can be observed, with evidence of selected time instants corresponding to (1) the front surface, (2) the base and (3) the back surface of the wall [11].

The results of changing the blast wave parameters in relation to the density of the mesh for different distances ($R = 0.2$ m, 0.3 m) can be represented in LS-DYNA by the finite element model as follows (Fig. 14.7):

At the same time, we can notice that when the mesh is refined, it is gaining a spherical shape even though the mesh is rectangular.

From Fig. 14.8, it is also apparent that the coarse mesh models have maximum values along diagonals, while the minimum values are located along the axis [15].

For more numerical test see [16, 17].

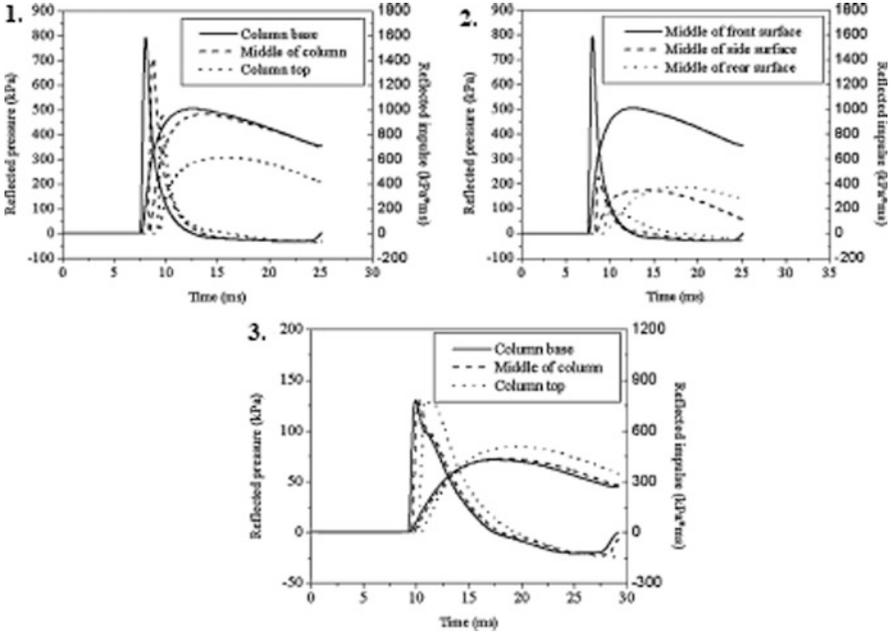


Fig. 14.6 Reflected pressure [13]

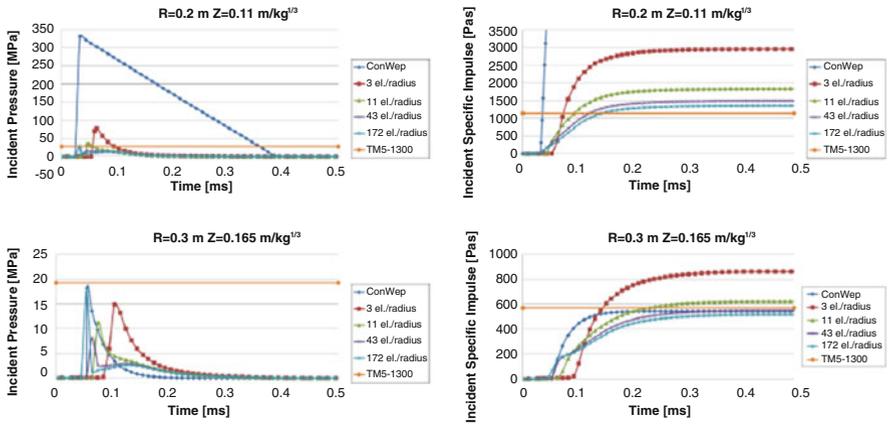


Fig. 14.7 Profile of blast wave in free air [14]

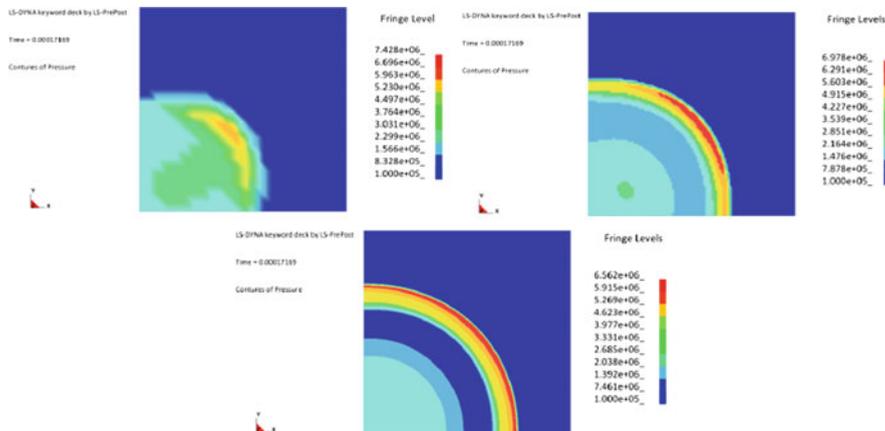


Fig. 14.8 Pressure contours for three different meshes [14]

14.6 Summary and Conclusions

In this paper, a concise overview and discussion of numerical approaches in use for the advanced analysis of structural materials, components and systems subjected to blast loads was presented. As shown, despite the many approaches exist and could be potentially used in the advanced numerical simulation of a given explosion and related effects on constructed facilities, the Finite Element Method (FEM) is largely used in most of the cases. Certainly, the accuracy and the time cost of calculations can be detected as the main reason for why many researchers choose the FE approach, in place of other possible methods. This is also the case of commercial software tools such as Abaqus, Ancys or LS-Dyna. Beside such a basic assumption, the importance of understanding the actual behaviour of building materials under the effects of an incoming blast pressure is the basis for understanding the consequences that may arise in such an extraordinary event, for the fulfilment of fail-safe design goals. The problem of assessing the potential risks that can greatly endanger the safety of people is further dealt with by prof. Loveček, et al. in [18, 19].

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