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Simulation of Shock Wave Loading on RC Columns

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ABSTRACT:
This paper presents the numerical procedure of fluid dynamics for simulating the shock wave loading on RC columns. It starts from the fundamentals of explosion and blast wave as well as prediction of blast loading technique. Modelling procedure of blast wave using AUTODYN including Euler analysis method, and smooth particle hydrodynamic analysis (Lagrange analysis method) are described. The propagation modelling of blast wave is also explained with highlighting on definition of geometry properties, remapping method, boundary conditions, and interaction & contact Points. Validation studies were carried out to compare the results of former experimental researches of blast loading on square and rectangular reinforced concrete columns with results derived from finite element modelling (FEM) using AUTODYN explicit Program.

KEYWORDS: Blast Loading; TNT; Reinforced Concrete Columns; AUTODYN; Finite Element Modelling; JWL Explosive Model.

1. Introduction

The capability to predict the consequences of explosion through computer simulations is of great practical importance. The physical processes involved in a detonation phenomenon, though, are extremely complex [1,2]. So, many sorts of software computer analysis programs using different techniques are used for modelling blast load effect on structures [3-5]. Three categories of programs are found: single degree of freedom (SDOF) systems, empirical programs, and hydrocodes. SDOF analysis systems are considered to be the fastest and easiest technique [1,2,5]. Other programs like Blast-X and ConWep are examples of the empirical and semi-empirical programs [5] in which the blast loading relations given in [1,2] are implemented. AUTODYN [6] is an example of hydrocode software. It is a highly specialized numerical program that is used to assess dynamic response of structures subjected to shock events such as blasts or impacts.

As a part of an advanced coupled model for the dynamic response of blast-loaded RC columns [7], the simulation of shock wave loading is described in this paper. Fundamentals of explosion process, blast waves, and TNT equivalency are first presented. Prediction of incident and reflected blast overpressures is reviewed. The numerical modeling procedure of blast wave using AUTODYN software [6] including Euler analysis method, and smooth particle hydrodynamic analysis is explained using Lagrange analysis method. Propagation modelling of blast wave is given according to the suitable equations of state for air and TNT materials, geometry properties, and remapping technique. Finally, validation studies are presented to compare the measured and predicted blast overpressure-time histories for square and rectangular RC columns, tested before in the literature [8,9].

2. Prediction of Blast Loading

2.1 Blast Wave Configuration Parameters

Blast loading parameters such as peak incident overpressure, peak dynamic pressure, peak reflected overpressure, duration, and impulse are considered primary parameters for outlining a blast dynamic loading. While, shock front velocity, and blast wavelength are thought to be secondary parameters. Secondary parameters are derived from blast primary parameters [1,3,4].

The profile of a blast wave shown in Figure (1) is a time history of a blast pressure wave, including a positive sector (overpressure) and a negative sector (under-pressure) denoted by (t_d+) and (t_d-) respectively. The time of arrival that the wave takes to hit a recording station, the pressure represents the overpressure, or the height incident pressure recorded at the station that is higher than the close air pressure (P_o). The overpressure is believed to be more necessary than the under-pressure, and typically, the result of the under-pressure is neglected for the dynamic analysis of most structures. The impulses are denoted by the area beneath the pressure-time curve [4,5].

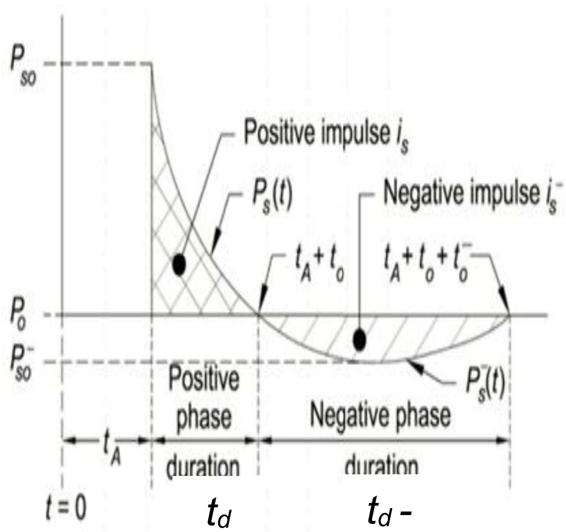

Fig. 1: Blast Pressure Wave Profile [4,5].

2.2 TNT Equivalency

Several blast pressure results of a spherical charge of TNT explosive can be inferred to other explosives such as nuclear weapons, by relating the explosive energy of the effective charge weight of those materials to that of an equivalent weight of TNT [1]. The equivalency of material against TNT is depending on many parameters like the material geometry (flat, square), the explosive quantity, explosive confinement, nature of source and the pressure range. Referring to TNT, the amount of the energy output of explosive material can be defined as a function of the heat of detonation from Equation (1) below.

$$W_{TNT} = \frac{H_{exp}}{H_{TNT}} . W_{exp} \qquad (1)$$

where W_{TNT} = equivalent TNT charge weight, W_{exp} = Weight of the explosive in question, H_{TNT} = Heat of the detonation of TNT, and H_{exp} = Heat of detonation of explosive. Table (1) shows equivalent masses for TNT [1,2] for the frequently used explosive materials in engineering practice.

Table 1 : Equivalent TNT mass factors [1,2]

Explosive Type	Pressure Equivalent TNT Mass Factor
ANFO	0.82
A-3	1.09
B	1.11
C-3	1.08
C-4	1.37
H-6	1.38
HBX-1	1.17
Octal (75/25)	1.06
Pentolite	1.42
RDX	1.14
TNT	1.00
Tritonal	1.07

2.3 Prediction of Incident and Reflected Over Pressure

a) Incident Over-Pressure Prediction

Figure (2) demonstrates a swift technique for computing the expected overpressure on a structure for a specific explosive weight and stand-off distance [1]. The x-axis represents the probable explosive weight of TNT and the y-axis with an identified stand-off distance from a structure. The range of damage, that the different components of a structure might experience, can be computed by associating the consequential effects of overpressure with other information. The vehicle icons in the figure state the comparative size of the vehicles that might be used to carry different amounts of explosive materials. The following form of Friedlander's Equation has been proposed [3,6], and is widely used to describe this rate of decrease in pressure values:

$$P_S(t) = P_{SO}\left(1 - \frac{t}{t_o}\right) e^{-b\frac{t}{t_o}} \qquad (2)$$

where P_{so} is the peak overpressure, t_0 is the positive phase duration, b is a decay coefficient of the waveform, and t is the time elapsed, measured from the instant of blast arrival.

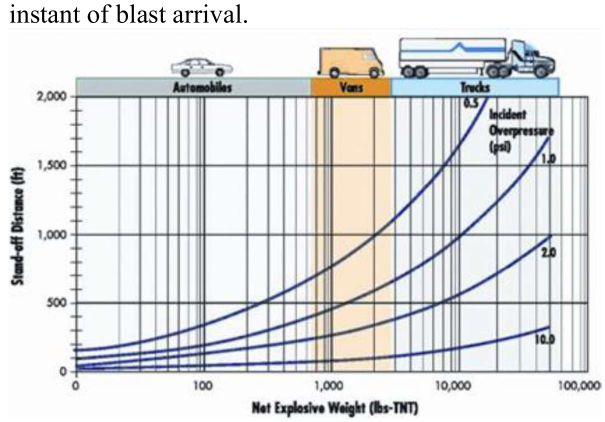

Fig. 2 : Incident Overpressure Measurement [1].

b) Reflected Over-Pressure Prediction

Momentum alteration resulted in reflection, when the progressing air blast imposes upon surface in the way of propagation as shown in Figure (3). The percentage of reflected overpressure to incident overpressure is named the reflection factor [1,2] which is a function of the peak overpressure in the incident wave and the angle at which the wave interacts with the surfaces. When the blast hits an object at near right angle (=90°), the resulting reflection creates a peak reflected overpressure, P_r, given by Equation (3) .

$$P_r = 2P_S + (1 + \gamma_h)P_d \qquad (3)$$

Taking into account, the ideal gas conditions (γ_h = 1.4) and replacement for P_d from Equation (3), the peak reflected overpressure is defined as :

$$\frac{P_r}{P_S} = 2 + \frac{6P_S}{P_S + 7P_o} \qquad (4)$$

Equation (4) is applicable for ideal gas for the overpressure, P_s less than 10 bars. For Ps greater than 10 bars, the following relationship is proposed [1,2,5]:

$$\frac{P_r}{P_s} = 4\,log P_S + 1.5 \qquad \frac{P_r}{P_s} < 14 \tag{5}$$

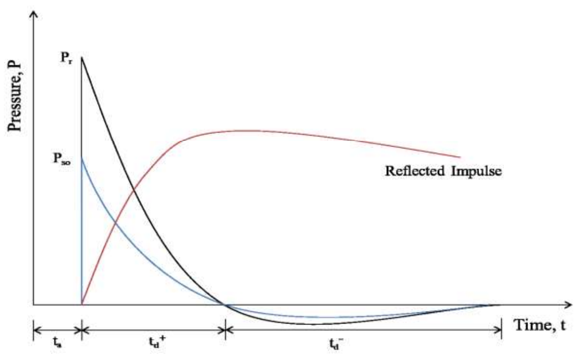

Fig. 3: Reflected Pressure and Reflected Impulse [1,2].

3. Modelling Procedure of Blast Wave Using AUTODYN

3.1. Euler Analysis

To solve the prevailing conservative equations of mass, momentum and energy using a control volume method, Euler solver is used [6]. The Euler-FCT processor is designed specially to solve gas dynamics problems and in specific blast simulations. Opposing to the Lagrangian processor, the Euler processor comprises a material movement between the mesh elements as shown in Figure (4). All variables are cell centered in a mesh in an Euler solver, as x means the displacement, u stands for the velocity, F for the force, m for the mass, σ for the stress, ε for the strain, p for the pressure, e for the internal energy, and ρ for the density. The definition of the element properties at the cell center helps to simplify coupling with other solvers required to address fluid-structure interaction problems. only the material moves from one location to another while the mesh remains stationary in each time step. Each time step must satisfy the CLF or Conart condition as given in Equation (6):

$$\Delta t < \frac{\Delta x}{(c+\|v\|)} \tag{6}$$

where Δt is time step, Δx is the element size, C is the local speed of sound, and V is the element velocity

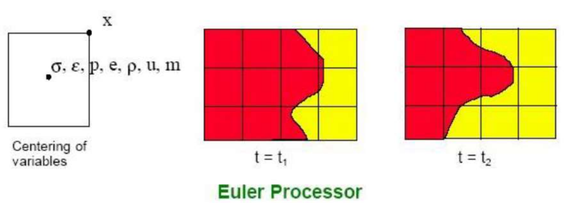

Fig. 4 : Material Flow Through a Stationary Grid in an Euler Analysis [6].

3.2. Smooth Particle Hydrodynamic Analysis (Lagrange technique)

Smooth Particle Hydrodynamic (SPH) is a Lagrangian technique, but with the grid-less "mesh free" advantage method (which helps in solving computational continuum dynamics problems). SPH techniques have the advantage of tracing the material deformation and trace history-dependent behavior efficiently [6,7]. By comparing the SPH with the Euler technique, SPH technique was found to be more efficient since it needs only to model sections where the material exists not from where the material will flow, and so complex constitutive models can be included more easily Figure (5).

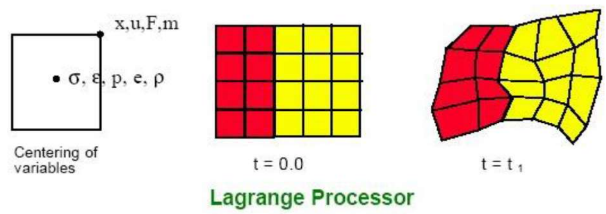

Fig. 5 : Grid Deformation in a Lagrange Analysis [6].

3.3. Equations of State for Air and TNT

The equation of state is a thermodynamic equation used to describe the material status and properties using relations between different variables. The general form of the Equation of State (EOS) for pressure is function of the local density (or specific volume) and the local specific internal energy of material. For dynamic loading, such as explosion-structure interaction, the non-linear material behavior must be taken into account where high pressures and high strain rates are expected.

a) Air

Equation (7) represents the ideal gas EOS that was used to model the Air [6].

$$P = (\gamma - 1)\rho e + P_{shift} \tag{7}$$

where P is pressure, γ is ideal gas constant, ρ is density, and P_{shift} is pressure shift (small initial pressures to give zero starting pressure in a model).

b) TNT

"Jones-Wilkins-Lee" (JWL) EOS characterizes the explosive material in terms of TNT. To model the rapid expansion of high explosive detonation before converting to ideal gas EOS. Equation 8 states the relation between the pressures of the expanding gas to different parameters depending on the type of explosive. The obtained diameters were from dynamic experiments for different explosives and they are available in the AUTODYN material Library [6,7].

$$P = \left[A\left(1 - \frac{\varpi.\eta}{R_1}\right)e\right]^{-\frac{R_1}{\eta}} + \left[B\left(1 - \frac{\varpi.\eta}{R_2}\right)e\right]^{-\frac{R_2}{\eta}} + \varpi.\rho.e \tag{8}$$

where η is (ρ/ ρ_0), ρ is density, ρ_0 is reference (initial) density, and A, B, R1, R2, ϖ are empirically derived constants.

4. Propagation Modelling of Blast Wave using AUTODYN

4.1. Definition of Geometry Properties

Air domain are modeled as Euler-Flux Corrected Transport (Euler-FCT) sub-grid AUTODYN program [6,7]. Applying boundary conditions for air domain to represent the gas flow restrictions. For air, the ideal Gas equation of state (EOS) was used. The strength model parameter is outlined as a Hydro (i.e. no strength), whereas no failure mode has been outlined. Concerning the explosive compound, the Jones-Wilkins-Lee (JWL) EOS was used. The strength model parameter is outlined as a Hydro (i.e. no strength), whereas no failure mode was outlined. Whereas the material properties of the air and TNT are outlined in Table (2) .

Table 2 : The material data for Air and TNT [6,7]

Material	Air	TNT	TNT (Ideal)
Equation of State	Ideal Gas	JWL	Ideal Gas
	$\gamma = 1.4$	Standard	$\gamma = 1.35$
	$\rho = 1.225 \times 10^{-3}$ g/cm^3	Library data	$\rho = 1.0 \times 10^{-3}$ g/cm^3
	Ref. Energy = 0.0 μJ		Ref. Energy = 0.0 μJ
	Press. shift = 0.0 kg/cm^2		Press. shift = 0.0 kg/cm^2
Initial Conditions	$\rho = 1.225 \times 10^{-3}$ g/cm^3	Default	From detonation
	Ref. Energy = 2.068x 10^5 μJ/mg		Model/remap data

4.2. Remapping Method and Boundary Conditions

Remapping approach is used in AUTODYN program for reducing time of calculations in blast modelling simulation by solving the explosion propagation in 1-D in the distance between the middle of the explosion and the nearest object then, remodel it into 2-D or 3-D models. The used portion to simulate a 2-D explosion is named the "Wedge" [6,7]. This may be meshed within the native reference frame "I" and "J". The meshing is completed through the "I" direction whereas keeping it constant within the "J" direction and adequate to one cell, 2 "J" lines. Similarly, the remapping is completed exploitation mesh size 10 millimeters. The equivalent range of cells for size is one hundred cells as shown in Figure (6).

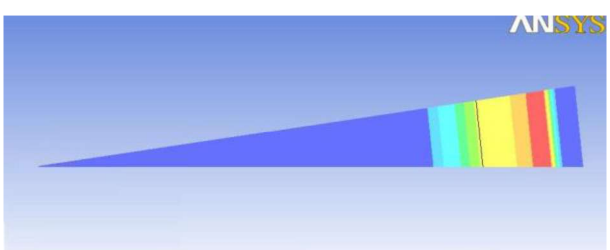

Fig. 6 : The Wedge Part used to Simulate 1-D Initial Expansion Model of TNT [6].

The AUTODYN explosive material library avails The TNT material data in a 3-D code. The density of TNT is ($\rho_{TNT} = 1.63$ g/cm^3) and was used to calculate the radius of spherical TNT charges using equation (9) as follows :

$$r_{TNT} = \sqrt[3]{\frac{3 \times W \times 1000}{1.63 \times 4 \times \pi}} \qquad (9)$$

where r is radius of spherical charge in cm, and W is mass of charge in kg.

Simulating the boundary conditions in the experimental researches requires using different boundary conditions on different parts of the numerical model. The upper and lower supports of the column are movement fixed support condition as in the experimental field tests [8,9]. The same boundary conditions were modelled by adjusting the translational and rotational velocities of the nodes to zero as shown in Figure (7). On all the four sides of the region of air modelled box, an outflow boundary condition was used. The outflow boundary condition allowing the blast waves to exit the region of air without reflecting back to the column. While the reflecting boundary condition was used and applied for the ground surface at the bottom of the air region.

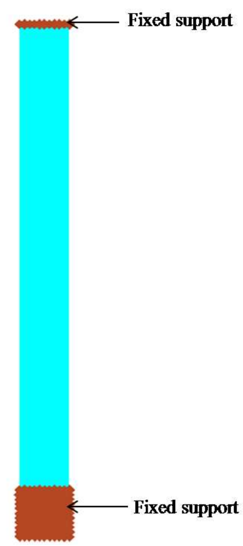

Fig. 7: Fixed Supports Condition of Column [7].

4.3. Interaction and Contact Points

The interaction between the columns and thus the region of air is important in achieving desired results. Much coupled interactions were used for every Eulerian and Lagrangian elements based on this. The wholly coupled interaction allowed the air to transfer the explosion energy to the concrete column at the interface between the columns and air [6,7]. In addition, the beam parts (reinforcing bars) and therefore the concrete parts were joined rigidly at the nodes to make sure of good bond without slippage (strain compatibility) as seen in Figure (8). The gap contact algorithmic program uses a time step restriction to assure a stable interaction method. Such restriction assumes that in one computational time step, a surface node cannot travel above 20 percent into the contact detection zone.

$$\Delta t = 0.2\frac{\delta}{V} \tag{10}$$

where δ is the gap size and V is the velocity of the penetrating node.

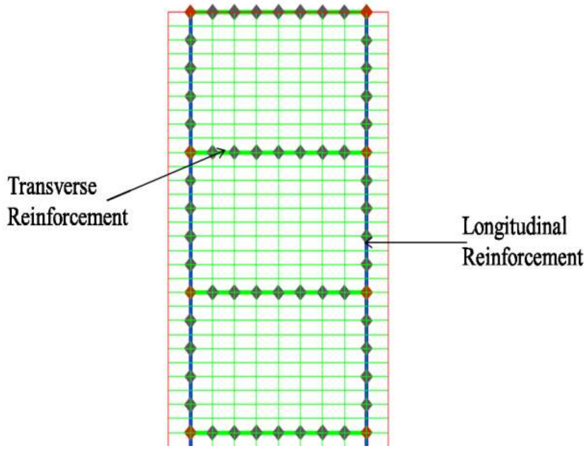

Fig. 8: Joints at Nodes of Column [7].

5. Validation Studies

5.1. Blast Loading Simulation for Square RC Columns

In the first validation study, a square RC column; tested by Siba [8] under blast loading (CONV-2 test) was selected. The geometrical and material data are shown in Figure (9) and Table (3). It was a square specimen with compressive strength of 35 MPa, of dimensions (300x300) mm, and a height of 3200 mm, the reinforcement enclosed by the concrete comprises 4 longitudinal bars of diameter equals 19.5 mm with yield strength (F_y) equals 474.4 MPa and yield strain of 0.22%, horizontal stirrups of diameter equals 11.3 mm spaced at 300 mm with yield strength of 465.2 MPa, the concrete covering the longitudinal bars was 40 mm in all sides. The column specimen was tested numerically in the FE AUTODYN program, simulating the experimental 123 Kg of TNT blast load, which was placed at a height of 650 mm above the ground, with the remapping method from 1-D explosion to a 3-D analysis based on using a suitable sensitive mesh element size study. The stand-off distance for CONV-2 test was 1300 mm.

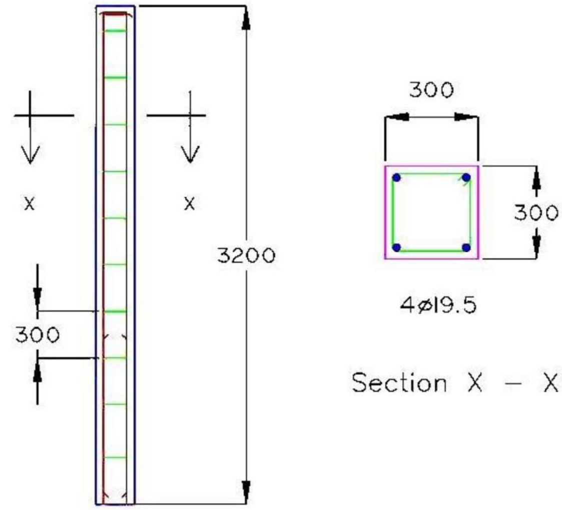

Fig. 9 : Square Columns Dimensions Details, [7].

Table 3 : Basic data for square RC column [8]

Model by		Farouk Siba [8]
Concrete Dimension (mm)		300 x 300
Height (mm)		3200
Concrete Cover (mm)		40
F_{cu} (MPa)		35
Longitudinal RFT	Bar Diameter (mm)	**4 □ 19.5**
	F_y (MPa)	474.4
Transverse RFT	Stirrups Diameter (mm)	11.3
	Stirrups Spacing (mm)	300
	F_y (MPa)	465.2
Charge TNT weight (kg)		123
Stand-off Distance (SOD) mm		1300
Pressure (MPa)		51

Euler-FCT solver in AUTODYN was used [6,7]. The finite element mesh of the Euler-FCT Air space contains 384000 cells with a grid of 80×30×160 nodes graded zoning. The cell dimension is chosen in such a way that one Euler-FCT cell cover half of the smallest concrete cover of a column specimen (40 mm) to simulate the striking media. The RC column specimen is represented by 18000 Lagrange cells with a grid of 8×8×80 cells. Steel bars are represented by 78 beam cells with a grid of 1×78 cells. Comparison between numerically predicted and experimental pressures is shown in Figure 10. As the peak pressure reached by the experimental test was (51 MPa) while that reached by AUTODYN was (52.3 MPa), illustrates that the hydrocode software is able to predict pressures with less than 10% error. AUTODYN predictions generally overestimate those of the experimental ones. To explain this, in general, numerical methods smear the shock over at least one element. The smaller the element is, the better the peak pressure is resolved. The true peak pressure can be determined at the limits when element sizes and time-steps tend to be of very small values [6].

Figure (10) represents the pressure time history for concrete column specimen CONV-2, the solid blue line represents the pressure-time history from the field experiment [8], while the red dotted one represents the pressure-time history from the AUTODYN program [7]. In Figures (11) & (12), a comparison is made between the measured experimental blast overpressure-time history, the numerical one using AUTODYN, and the empirical on using ConWep program. The numerical curves are more accurate than the empirical ones for different explosive weights and different stand-off distances (SOD).

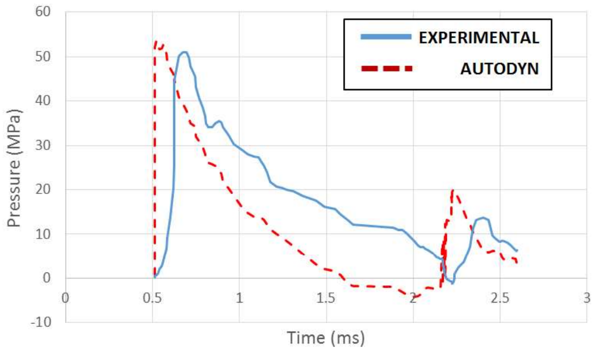

Fig. 10: Pressure Time History for Square Column (123 kg TNT charge, 1.3 m SOD)[7].

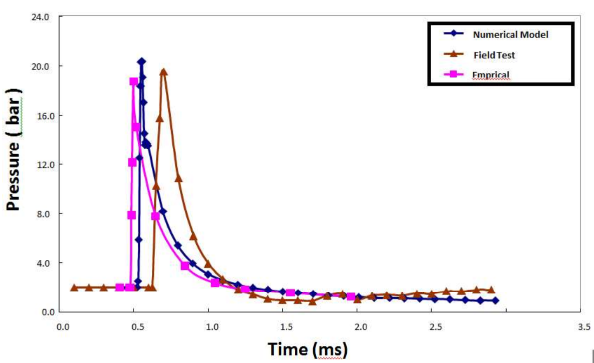

Fig. 11 Pressure Time History for 10 kg TNT Charge and SOD 3.0 m [7].

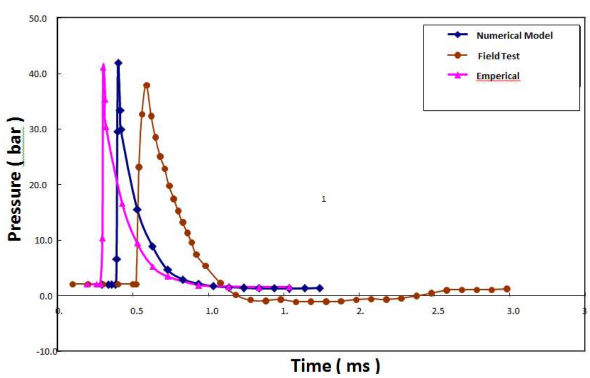

Fig. 12 Pressure Time History for 30 kg TNT Charge and SOD 3.0 m [7].

5.2. Blast Loading Simulation for Rectangular RC Columns

A blast-loaded rectangular RC column; tested by Lloyd A. [9], was considered in the second validation study. The material and geometry data are given in Figure (13) and Table (4). As shown in Figure (13), it was a rectangular model with compressive strength of 58 MPa, of dimensions 100 mm x 150 mm, total height including the two supports of 2438 mm while the free height between the two supports of 1980 mm. The longitudinal reinforcement was 4 bars M10 (one bar at each corner with equivalent diameter of 11.3 mm) with longitudinal reinforcing ratio of 2.67%, with yield strength of 483 MPa, while the horizontal reinforcement (stirrups) are of diameter equals 6.3 mm spaced at 25 mm with volumetric ratio of 1.52% with yield strength of 580 MPa, the concrete covering the longitudinal bars was 20 mm in all sides.

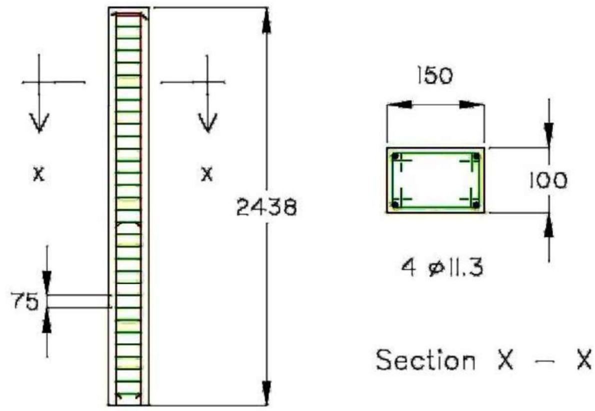

Fig. 13 Rectangular Column Dimensions for Test RC 3-1 [9].

Table 4 : Basic data for rectangular RC column[9]

Model by		Alan Lloyd [9]
Concrete Dimension (mm)		100 x 150
Height (mm)		2438
Free Height (mm)		1980
Concrete Cover (mm)		40
F_{cu} (MPa)		58
Longitudinal RFT	Bar Diameter (mm)	**4 □ 11.3**
	F_y (MPa)	483
Transverse RFT	Stirrups Diameter (mm)	6.3
	Stirrups Spacing (mm)	25
	F_y (MPa)	580
Equivalent TNT Charge weight (kg)		33.4
Equivalent Stand-off Distance (SOD) mm		1300
Pressure (KPa)		12.02 KPa (Shock Tube)

Finite element mesh of the Euler-FCT Air space contains 1024800 cells with a grid of 140×30×244 nodes graded zoning. The cell dimension is chosen in such a way that one Euler-FCT cell cover half of the smallest concrete cover of a column specimen (20 mm) to simulate the striking media. The reinforced concrete column specimens are represented by 36600 Lagrange cells with a grid of 10×15×244. Steel bars are represented by 242 beam cells with a grid of 1×242 cells.

Figure (14) represents the pressure time history for concrete Column for Test RC 3-1. AUTODYN pressure values are dropped on the graph obtained from the previous experimental programs as Comparison between predicted and experimental pressures. Blue solid represents the peak pressure reached by the experimental test (12.02 KPa) which is equivalent to 33.4 kg TNT with stand of distance 1300 mm, while the red dotted one represents that reaches by the AUTODYN was (13.4 KPa).

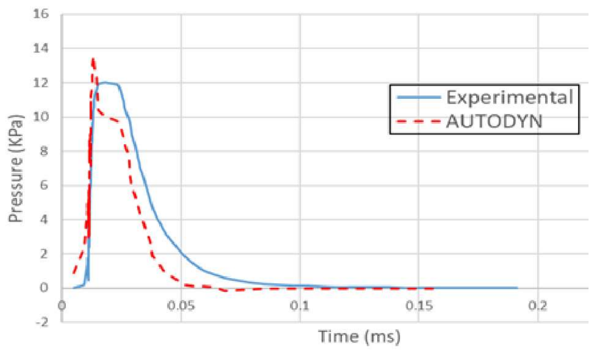

Fig. 14: Pressure Time History on Rectangular Column for (12.02 KPa Shockwave Tube) [7].

6. Conclusions

From modelling and validation studies, the following conclusions can be drawn:

1- Three-dimensional coupled numerical modelling of detonation and explosion effects illustrate that AUTODYN program can provide an accurate and efficient tool for simulating the blast shock waves on RC columns. It is able to predict blast overpressure amplitude and time history on square and rectangular RC columns with less than 10% error.

2- The Euler analysis combined with Lagrange technique is suitable for modelling blast waves simulation. It smears the shock over at least one element. The smaller the element is, the better the peak pressure is resolved. The true peak pressure can be determined at the limits when element sizes and time-steps tend to be of very small values.

3- The equation of state of Jones-Wilkins-Lee (JWL) for TNT explosives is suitable to model the rapid expansion of high explosive detonations on RC members before converting to ideal gas equation of state. For different explosive weights and stand-off distances, the predicted overpressure values are accurate in comparison with measured field blast overpressure.

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