ASPS Conference Proceedings 1: 1265-1272 (2022)

Proceedings of

12th Structural Engineering Convention-An International Event (SEC 2022)

Available at https://asps-journals.com/index.php/acp

A Systematic Approach for Analysis of Structure under Blast Load – An Overview

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Paper ID - 090421

Abstract

An explosion is an unwanted phenomenon that may be caused accidentally or intentionally. It may be occurred within or near the structure that causes massive damage to the same. An explosion becomes disastrous when the structural elements collapse partially or totally. Many works have been made to grow the techniques/methods of blast resistance structures. A detailed understanding is required for blast load and its effect on the several structural members in terms of dynamic responses to analyze and design a safe engineering structure. Further, in this article, a comprehensive overview of a systematic approach for the analysis of structure under blast load has been presented. For the computation of blast load, different types of empirical relations are available, which are in the pattern of pressure-time functions. Here, the same is represented concisely with an easier way of understanding. Prediction of blast load by the empirical, semi-empirical, and numerical method has been presented. Modelling of blast load for various numerical simulation techniques and material models are also described here for modelling the advanced structural material that may mitigate the blast response of the structure as per the Hydrocodes.

Keywords: Blast load, Friedlander wave equation, Impulse, ConWep.

1. Introduction

In the present scenario, considerable emphasis has been given to the structure susceptible to explosion and earthquake. The earthquake problems are old, and most of the knowledge regarding the same has been grown since the last 50 years. The blast is a painful word all over the world and preferably a new problem among all dynamic hazards. The information in this field is mainly through the publication of research manuals and papers. Nowadays, terrorist attacks are a common problem for national and international aspects. In most of the cases, a terrorist used to choose the places that are crowded or have socio-economic importance such as government building, bridges, atomic power plants, shopping malls, etc. On 11th September 2001, the attack on the World Trade Centre in New York showed the requirement of research in this field. The researcher has given the attention against the structural response, i.e. analysis, design, and protection under blast load.

The explosion is classified based on their nature: physical, chemical, and nuclear explosion. The failure of the compressed gas cylinder, volcano emission etc. are the examples of a physical blast. At high-temperature, mixing of two liquids, oxidation of fuel substances etc. are the examples of a chemical explosion. In the case of a nuclear blast, energy is released during the formation of different atomic nuclei automatically or forcefully by the reallocation of different particles. The origin of a chemical explosion is mainly from terrorist attacks. Most of the explosives are in condensed form, i.e., either liquid or solid. Two terms that are related to the explosion are deflagration and detonation. Deflagration is the process in which explosive material reacts at a rate lower than the speed of sound. Detonation is the crucial type of high-intensity explosives and produces a high-potency shock wave during the reaction of combustible material. Explosives are categorized based on their reactivity to ignition and classified as primary & secondary. Lead azide is the example of a primary explosive which are easily detonated by fundamental ignition. Secondary explosives are Ammonium Nitrate Fuel Oxide (ANFO) and Tri-Nitro Toluene (TNT); when fired, they produce shock or blast waves in the form of mass scale failure to the adjoining. In this paper, the literature on blast loads, unique problems in describing these loads, the probability of vulnerability assessment, and standard structural analysis software are mainly focused for risk mitigation with assessment done with limited non-linear capabilities. It is also represented that, with the present knowledge and standard software, it is possible to perform the analysis of structures subjected to blast loads to determine their response. The main objective is to represent an overview of the analysis of any

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Proceedings of the 12th Structural Engineering Convention (SEC 2022), NCDMM, MNIT Jaipur, India| 19-22 December, 2022

Published online: December 19, 2022
doi:10.38208/acp.v1.650

structure with the help of the previous study under blast loading.

2. Blast Load

Blast load is one kind of impulsive loading acting for a very short time. The graphical representation of the blast load in design is triangular. Hot gases are generated when detonation occurs. A temperature of about 3000ºC to 4000ºC and a maximum pressure of up to 30000 MPa may cause during the burst. The hot gas rapidly spread by forcing out the volume it inhabits. The energy releases mostly during the explosion and forms a layered compressed air (blast wave) in front of this gas volume. The blast wave spontaneously increases above the ambient atmospheric pressure. That is known as side-on pressure. It decays as a shock wave, which propagates outward from the location of the explosion. The same is reduced to negative ambient pressure after a short time.

2.1. Blast Wave

The blast wave is the expanded flow and pressure resulting from the large quantity of energy deposited in a small or large localised volume. An area of pressure is represented as a blast wave in easier terms, which is spreading rapidly beyond an explosive core. The compressed gases are the leading front shock of a blast wave. The negative pressure is followed by a blast wave that may drag the items back towards the centre. A blast wave is dangerous, especially when the location of constructive interference is very close to the centre. The blast wave is specified by an immediate expansion of pressure from ambient atmospheric pressure (P_0) to a Peak incident overpressure (P_{so}). The peak overpressure exponentially deteriorates with time. Furthermore, the overpressure at positive phase duration is returned to ambient air pressure at a time t_0. It is again moved along with the negative pressure wave with a duration t, and about two to five times the period of the positive stage, as shown in Fig. 1. Fig. 2 Shows blast wave propagation with different locations. In most of the cases, this negative phase is being neglected for its minimal value. Friedlander's equation described the profile of blast wave for a spherical charge, detonated in free air [1]:

$$p(t) = p_{so}\left[1 - \frac{t}{t_0}\right]\exp[\frac{A(t - t_{0)}}{t_0}]$$

In which P_{SO} is the peak/maximum positive pressure, and P_0 is the atmospheric pressure. Current time is t, and t_d is the time, representing the duration of the positive pressures. When the blast wave attacks an object on its way, it creates reflected pressure (P_R), which is two to eight times powerful than P_0. It is so because the particles/elements at the frontline of the blast wave do not have any space to move due to structural interface. But they are tried to move forward with the particles coming behind.

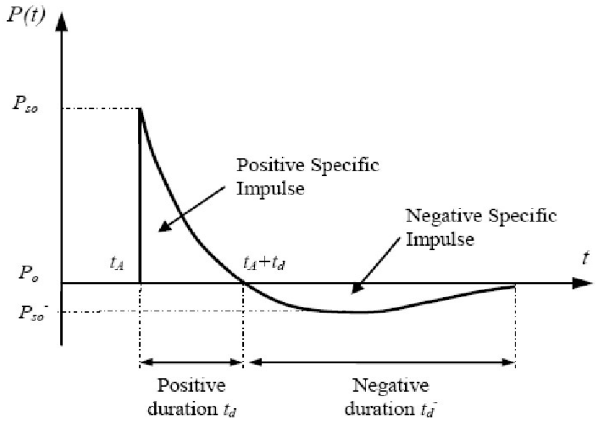

Fig. 1. Blast wave pressure-time history

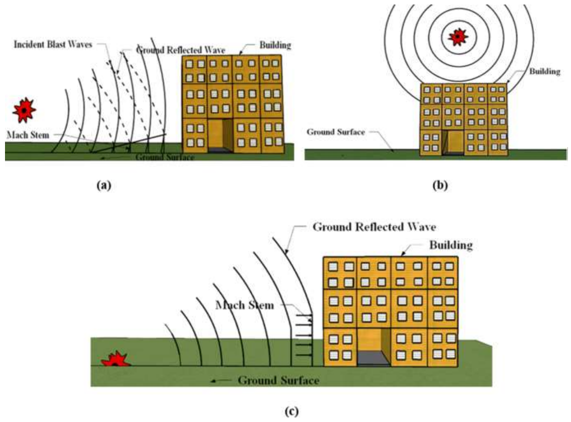

Fig. 2. Blastwave propagation at different location of the blast

2.2. Blast Scaling Law

In an explosion, a massive amount of energy is released within a minimal time. This energy is transmitted in the form of the blast wave from the point of explosion. Generally, the blast wave magnitude and distance from the blast, control all the variables responsible for structural damage. This law state that "self-similar blast waves are produced at identical scaled distances when two explosive charges of similar geometry and the same explosive but of different sizes are detonated in the same atmosphere." Hopkinson and Cranz independently proposed a mathematical form of blast scale law as shown in below-

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

Where Z is the scale distance in equivalent form, R is the distance between the structure and charge centre in m, and charge weight is denoted by w in kg of equivalent TNT. This mathematical form is widely used and known as cube root scaling law.

2.3. Blast Pressure

In the 1950s and 1960s, several studies on blast helped to identify the parameters for the conventional high explosive materials. Brode (1955) introduced an expression based on the scaled distance to estimate the peak overpressure due to spherical blast:

$$\mathrm{P_{SO}} = \frac{6.7}{\mathrm{Z}^3} + 1\ \mathrm{bar}\ (P_{\mathrm{so}} > 10\ \mathrm{bar})$$

$$\mathrm{p_{so}} = \frac{0.975}{\mathrm{Z}} + \frac{1.455}{\mathrm{Z}^2} + \frac{5.85}{\mathrm{Z}^3} - 0.019\ \mathrm{bar}$$

$$(0.1\mathrm{bar} < \mathrm{P}_{so} < 10\mathrm{bar})$$

For the calculation of the maximum blast overpressure P_{so}, Newmark and Hansen (1961) introduced a relationship in bars, at the ground surface for a high explosive charge as:

$$\mathrm{P_{so}} = 6784\frac{\mathrm{W}}{\mathrm{R}^3} + 93\left(\frac{\mathrm{W}}{\mathrm{R}^3}\right)^{\frac{1}{2}}$$

Mills introduced another expression for the peak overpressure (in kPa) in 1987, in which W is expressed as the equivalent charge weight in kilograms of TNT, and scaled distance represented as Z:

$$P_{\mathrm{so}} = \frac{108}{\mathrm{Z}} - \frac{114}{\mathrm{Z}^2} + \frac{1772}{\mathrm{Z}^3}$$

Blast waves spread across the atmosphere as the air around the shock front moves outward at lesser velocity. Both wind pressure and the air particles' velocity depend upon the blast wave's maximum or pick overpressure value. This later air velocity is related to the dynamic pressure, q(t). The maximum value (q_s) is given by

$$\mathrm{q_s} = 5\mathrm{P_{so}^2}/2(\mathrm{P_{so}} + 7\mathrm{P_o})$$

When the blast wave propagates in a perpendicular direction, have some obstacle, the overpressure increase with maximum reflected pressure (P_r) as:

$$\mathrm{P_r} = 2\mathrm{P_{so}}\left\{\frac{7\mathrm{P_o} + 4\mathrm{P_{so}}}{7\mathrm{P_o} + \mathrm{P_{so}}}\right\}$$

3. Calculation of Blast Load

Blast is the most unpredictable dynamic force-system. Blast load calculation depends on the many factors like volume of explosive, scaling distance, type of surrounding weather, placing explosives, and many others. All over the globe, several methods have been adopted for the prediction of blast load on the structures, most adopted methods are described below:

3.1. Empirical Analytical Method

It is essential to correlate the physical parameters and experimental data's outcome to predict the after explosion parameters without any experiment. Based on the experimental data, there are limited empirical methods for calculating the loads imposed on the structure due to blast. Through accuracy of these empirical equations reduces in case of nearby field blast. In this section, more popular empirical methods are summarised below.

3.1.1. TM-5-1300

TM-5-1300 is the most popular, among all available documents for civilian and military sectors to design the structures, protect against explosion, reduce the blast effect, and it has used before the development of UFC's manuals (Unified Facility Criteria). UFC's manual furnished the design methods for protective construction used for inspection, modification, demilitarisation, development, testing, production, and maintenance. The main objective of this manual is to set up the construction techniques and design procedures to prevent blast waves' propagation or to protect the valuable equipment of the same. The secondary aim is to set up different blast load parameters for protective structure and its response calculation under dynamic loading. Guidelines for blast-resistant structure and constructional details ware emphasised in this manual. Also, it gives the cost-effectiveness in both analysis and design. It contained step-by-step design and analysis methods incorporated with information on blast loading of the reinforced concrete (RC) and structural steel design with non-linear dynamic. The design techniques in this handbook ware based on several full and small-scale structural responses and explosive tests. Several computer programs are also available in this manual, which later established the foundation of other related design programs or handbooks. Four types of protective category presented in this manual which ware named 1 to 4. In this manual, the design curves were shown using scaled distance as a function to calculate the blast wave parameters for three environmental conditions, i.e. surface blast, free air blast, and air blast. This manual gave the scaling chart only for the positive phase blast wave parameters. It is applicable for a surface blast of hemispherical and spherical shaped TNT, and the explosion occurs in free air at sea level [2]. It also provided blast load pressures and scaling distance at any standoff distance from the ground level for a specific type of explosive. The duration and blast pressure are computed by using that chart.

3.1.2. TM5-855-1

In this manual, the analysis and design procedure of the protective structure expressed to conventional weapons. It is more helpful for structural engineers who are engaged in this type of exclusive design. It provides the effect of blast loads on structures, air blast effects, and auxiliary systems (piping, air ducting, etc.). Closed-form equations are also offered to prepare pressure-time histories for air blast in this manual. The effect of blast loading on multi-story buildings is also being discussed in this manual. TM5-855-1 also represents the load-time history for building and provides methodology and calculation for the same. The following steps are concerned to determine the blast response.

i). At first for each small zone, an impulse and pressure-time history are evaluated following a surface, convert into sub-sections.

ii). each sub-section is summing up to obtain the total impulse of the surface.

iii). the average peak pressure for all the surfaces is calculated assuming the average peak, which is defined from the whole load-time history with exponential form.

The actual physics related to blast wave-structure interaction is neglected, which is the main disadvantage of this simplified method. The same load-time history is used all over the surface, which is not valid according to practical consideration. In the case of near field blast condition, this assumption provides a poor approximation. At the time of total summing up, a load of each subsurface to calculate full load is used, and another algorithm is required to avoid limitation. TM5-855-1 allows the calculation to predict the load-time history and estimate total impulse for different load versus time relationships [3].

3.1.3. ConWep Air Blast Load Model

ConWep is an automated computer program developed by Kingery and Bulmash [4], by their widely used equations to predict the air blast parameters. They created the equations from hemispherical surface burst and spherical air burst. This model is commonly used for the determination of field pressure at the free and loaded structure. ConWep complied with blast test data from less than 1 kg to over 400000 kg of charge weight and represented it with a high-order polynomial equation. Friedlander's wave equation was used by considering exponential decay of pressure with time, which made ConWep more realistic. The program finds the wave decay co-efficient by using blast parameters such as peak pressure, impulse, and duration. ConWep provides values of blast pressure at a different time step by using Friedlander's wave equation. Finally, structural models are analysed with this pressure-time history using any suitable simulator software.

3.1.4. UFC3-340-02

Explosives are kept in a safe and secure place where those materials are safe from nearby external explosions. So the construction of a protective barrier is very much essential to facilities for production, testing, development, modification, maintenance, storage, inspection, and disposal of explosives [5]. Propagation of blast waves may be prevented by designing and constructing protective barriers and protecting valuable and personal equipment. It is a modified version of TM 5-1300.

3.1.5. IS 4991: 1968 (Reaffirmed 2013)

Ductile elements like steel and RC can withstand a significant amount of strain energy, but brittle parts like PC, timber, brick masonry, glass, etc. fail suddenly and abruptly. IS 4991-1968 [6] has unable to deal with the different kinds of loads developed due to blast in the structure. They required further explanation as the engineers have no guidance on designing or evaluating structures for the blast anomaly for which an elaborated understanding is needed. Though this topic is of prime importance in the military circles and essential data derived from tests and experiments, it has been restricted to army-use only. This paper explores the literature on blast loading, the explanation of special conditions in defining these loads, and the exploration of the vulnerability assessment and risk management of structures with standard structural analysis software having non-linear capabilities. Questions on earthquake despite being very old, most of the research on this subject has been agglomerated during the past 50 years, but this condition is different in the case of blast loading. Many more incidents have demonstrated the need for a thorough examination of the structures subjected to blast loads. With the present knowledge and software application, it is feasible to perform analysis and evaluation of the response of structures, bare to blast loads.

Table-1. Examples of simulation techniques used in the computer program

Sl No.	Name	Type of analysis	Purpose
1	BLASTX	CFD code	Blast prediction,
2	CTH	CFD code	Blast prediction,
3	FEFLO	CFD code	Blast prediction,
4	FOIL	CFD code	Blast prediction,
5	SHARC	CFD code	Blast prediction,
6	DYNA3D	CFD (Coupled analysis)	Structural response
7	ALE3D	CFD (Coupled analysis)	Structural response
8	LS-DYNA	CFD (Coupled analysis)	Structural response
9	AIR3D	CFD code	Blast prediction,
10	CONWEP	Empirical	Blast prediction
11	AUTO-DYN	CFD (Coupled analysis)	Structural response
12	ABAQUS	CFD (Coupled analysis)	Structural response

3.2. Numerical Method

Numerical methods depend on the equation of mathematics, which mainly represents the fundamental laws of physics. Conservation of mass, energy, and momentum are included in these principles. The physical behaviour of materials expresses constitutive relationships. Computational Fluid Dynamics (CFD) coupled with Finite Element Analysis (FEA) are the most regularly used modelling method. Internal stresses and strains are mainly predicted by FEA, which are tougher to measure experimentally. Critical parameters and failure patterns of the structure are also recognising by FEA. When conducting field tests are more challenging to perform, commercially available software packages with the advancement in computational techniques estimate the response of the structure under impulsive loading. Table 1 shows the most rapidly used software packages. The next part represents the most useful and commonly accepted relation for the determination of blast time history.

4. Numerical Modeling and Simulation in Blast Analysis

Primary three methods are used for the analysis of numerical simulation of the effect of blast load on the structure-

i) Modelling of blast load
ii) Modelling of materials
iii) Numerical solver

4.1. Modelling of Blast Load

Following methodologies are generally used for modelling the load, which is generated during the explosion –

4.1.1. Pulse Vs. Time Curve

The pulse-time curve is the slightly simple and most comfortable process of directly defining blast load modelling. The structural modelling with coupling effect (such as shock wave reflection and structural curvature) and load is not easy. Therefore, sometimes this simulation is not given more satisfactory results. However, the pulse vs time curve method depicted the fundamental behaviour of the structure. So till now, this method has been widely used.

4.1.2. *Blast Pressure Function*

Blast pressure functions (ConWep) is commonly used for blast loading. ConWep is one of the blast pressure functions that create a non-uniform load that acts on the exposed surface of the structure. Blast function is used in two cases: spherical charge detonation in free air condition and hemispherical charge detonation at the ground surface [4].
The following equation is taken into account for the determination of surface reflection and then computes total blast pressure

$$p(t) = p_r \cos\theta^2 + p_i(1 + \cos\theta^2 - 2\cos\theta)$$

Where, θ represents the angle of incidence, defined by the targets surface and the tangent to the wavefront, P_r is reflected pressure, and P_i is incident pressure.
The blast wave angle is taking into account when reflected pressure is evaluated and applied to the designated surface using ConWep. This cannot be useful for simulating impulsive loads that are purely localised and produced explosive flakes or prisms. It is the principal disadvantage of ConWep.

4.1.3. *By Modelling of Explosive as Material*

Explosive materials may be modelled with the help of CFD code. CFD codes are used to describe the equation of state of the explosive. At the detonation time, the explosive volume enlarged significantly and generates shock waves, which affects the structure. The contact force is calculated between the enlarged flammable product and the structure. Detonation point position, burn speed, and shape of the explosive have defined the expansion. The high explosive equation (Jones-Wilkins-Lee) of the state is mainly used to simulate the combustible material, which describes detonation pressure.

4.2. *Modelling of Materials*

4.2.1. *Explosive*

MAT_HIGH_EXPLOSIVE_BURN represents the explosive charge in ALE models and is always combined with the equation of state described by Jones-Wilkins-Lee (JWL).

$$p = A\left(1 - \frac{w}{R_1 v}\right)e^{-R_1 V} + B\left(1 - \frac{w}{R_2 v}\right)e^{-R_2 V} + \frac{wE}{v}$$

This equation calculates the blast pressure as a function of internal energy E and relative volume, $v = {}^{p_0}/_{p}$, for an explosive element. Where A, B, R_1, R_2, and w is the parameters related to the combustible material properties, as shown in Table 2.

Table -2: Material Properties and JWL Parameters of TNT

P (kg/m^3)	D (m/s)	p_{cj} (GPa)	A (Gpa)	B (Gpa)	R_1 (-)	R_2 (-)	W (-)	E (J/m^3)
1590	6930	21.0	3.712	3.231	4.15	0.95	0.3	7×10^9

4.2.2. *Air*

MAT_NULL is the most useful equation for perspective, which is considered as an ideal gas. Air is defined with the help of a linear polynomial equation as given below;

$$p = (\gamma - 1)\frac{\rho}{\rho_0}E$$

Where, specific heat ratio, current density, initial density and initial internal energy of air are denoted by γ, ρ, ρ_0, and E respectively. Here,γ = 1.4, ρ_0 = 1.29 kg/m3, and E = 250 KJ, measured at 1 bar atmospheric pressure.

4.2.3. *Structural Material – Concrete and Steel*

Properties of the materials are fed into the simulation software based on their characteristics. Concrete is modelled as a brittle material, and steel is modelled as elastoplastic material. Concrete and steel are represented by *MAT_CSCM and *MAT_STEEL, respectively. For concrete, the essential condition is taken into account, which is erosion allow or not. It depends on the analysing process of the material. For steel, all the properties like mass density, elastic modulus, passions ratio, plastic strain value, etc. need to feed at the modelling time. Validation of any experimental data with the software simulation gives confidence to researchers.

4.3. *Numerical Solver*

Prediction and calculation of the blast response of structures are generally associated with two major streams of computational methods in the blast effects mitigation area. First-principle and semi-empirical methods are typically used to predict the blast and structural response. Uncoupled and coupled analyses are categorised by the first principle method of program. The uncoupled study calculates the blast loads for the rigid structure (and its components) and then applies them to the structure. The shortcoming of this procedure is applicable only for a rigid structural model and also over-predicted load on the structure. During the loading period, significant motion or failure occurs. The structural response module and blast simulation module are linked during the coupled analysis. In this type of research, the model of the computational solid and fluid mechanics work simultaneously to predict the response after the application of blast load. LS DYNA, ABAQUS AUTODYN, and DYNA3D are the most useful computer codes for determining pressure on the structure due to blast, and these predict more accurately [7, 8, 9, 10]. Table 1 represents the computer programs that are used nowadays to analyse the effects of blast on structures. Structural response due to blast pressure involves highly non-linear behaviour. Computational methods are compared with experiments to validate blast response prediction. A significant amount of skill is required to assess the correctness of the output of computer code and its usefulness. If modelling has some errors and flawed interpretation, then obtained results is worthless. Therefore, engineers have to take precautions during computational modelling on specific blast scenarios.
The numerical solvers who are utilised in hydrocodes fall into the following classes: Lagrange, Euler, ALE, Structural, and

Meshless methods. Every solver has some applicability and limitation, which are described below. The choice of solvers is made by its optimal solution, accuracy, and efficiency of the simulation process.

4.3.1. Lagrange

A Lagrange solver is more useful for the explanation of solid materials. Shell boundaries represent the free surfaces and interfaces of the materials, and as such, the calculation is well maintained throughout. In the framework of lagrangian solver, mainly forces (F), velocities (u), coordinates (x), and masses (m) are defined at corner nodes. At the cell centre stresses (σ), energies (e), strains (ε), densities (ρ), and pressures (p) are required to define. The numerical mesh becomes distorted when severe deformation occurs. It is the primary short comes of lagrangian solver and provide less accuracy for small time steps.

However, rezoning and erosion features are included in additional programs to extend an analysis of the Lagrange solution. The "regular" mesh through the mapping is renewed as Rezoning, and also the distorted mesh quantities are converted to a newly defined mesh. In the high deformation situations of Lagrange technique, many problems arrived, which is overcome by an erosion technique. If an element reached limiting strain condition, the part is then "eroded." The pieces are then discarded, and the solid components are transformed and detached to the free mass node. Due to the mesh distortion problem, this technique requires to be avoided.

4.3.2. Euler

The Euler solver is more suitable for the gas and fluid explosion. Material interfaces and the free surface can pass along the fixed Euler mesh. The motion of material is tracked by a sophisticated numerical technique, which is more useful. Mesh distortion does not occur because it is fixed and valuable for large deformations or inflow situations. Maintaining the interfaces and the numerical diffusion limit requires extra computational work, which is a tradeoff. The history of the materials of stress tensor and concrete behaviour must be conveyed from cell to cell. Several approaches have been used for the centring of variables historically. To facilitate coupling with other types of solvers, have a facility by which collar all variables (stress, strain, pressure, density, energy, and velocities) are cell-centred.

4.3.3. Structural Solver

Beam, thin structure, rods, and other structural elements are modelled using a structural solver, applying a concise time step. This is imposed with a standard Lagrange/Euler solver. In case of a shell solver, the thin structure is mainly modelled with assumed biaxial state of stress. The wave propagates in one direction only along the length, but no wave propagates in the direction of shell thickness. The zonal dimension along the length, the time step is constrained.

4.3.4. ALE Solver

An ALE (Arbitrary Lagrange Euler) solver applicable for "automatic rezoning." The ALE domain entirely depends on the specified motions, i.e., Lagrangian/Eulerian. In Lagrange motion, the nodes are move with the material motion, whereas, in Eulerian motion, the nodes are fixed, but the material moves through the fixed mesh or something in between.

Solids, fluids, and gases are modelled using ALE. For fluid-structure interaction problems, ALE is the most applicable method of modelling. Eulerian simulation is used for explosion and fluid dynamics regions, and solid structures are modelled with Lagrange constraints. ALE solver for a single material is free from boundaries, or the material interfaces are strictly Lagrangian for all nodes. In the ALE domain, the material does not flow in or out of it, and no individual cells do not carry more than one material. The ALE formulations do not have such limitation for multiple Euler schemes, and also, the material can flow from cell to cell.

4.4. Coupling Technics

Impacts, fluid-structure interactions, explosions, etc. ("coupled" problems techniques) have been formulated to allow interaction between solvers to optimise the solution. Thus, several numerical solvers can be applied for the modelling purpose, mainly according to the requirement, and then automatically linked together in time and space.

4.4.1. Lagrange-Lagrange

The impact-slide surface and glued (joined) surface are two interacting processes of Lagrange type domains (including Shell and ALE). The surfaces of Lagrange bodies are allowed by the impact-slide surface to interact in a very general manner, including the opening and closing of gaps. A large variety of facts, including impact and penetrations, are simulated using the Lagrange-Lagrange interactions process. The SPH-Lagrange interactions process also uses impact-slide surfaces.

4.4.2. Euler-Lagrange

An Euler-Lagrange interface is a combination of a Lagrange domain and an Euler domain. A pressure boundary is set to the Lagrange domain of Euler domain, whereas the Lagrange domain perfume as a geometric constraint to the Euler region in an Euler-Lagrange interface. For the Fluid-structure or gas dynamic-structure interactions, this is more advantageous.

4.4.3. SPH-Lagrange

Lagrange/Lagrange and Euler/Lagrange have some limitations. In massive distortion and large flow region, SPH/Lagrange coupling is mainly used to model fluid and structure to determine the response with traditional Lagrange/structural approaches. When SPH nodes and structural or Lagrange elements interact together, they are treated as Lagrange/Lagrange interactions. In this situation, SPH nodes are represented as slave nodes of the Lagrange body.

5. Case Study

5.1. Runqing Y. et al., 2017 [11]

An efficient tool is a fragility curve to assess the damage in the engineering structure, which is generally used to predict the failure possibility. So many parameters like uncertainties in materials, dimensions, and load are considered to modify a deterministic non-linear analytical approach for the reinforced concrete column under blast load. In this study, a fragility curve was generated to evaluate the parametric sensitivity of an RC column.

5.2. Zhongxian L. et al., 2016 [12]

The dynamic analysis of a reinforced concrete member widely used model is the traditional fibre beam (TFB), model. However, in blast loading, its application has been restricted due to its inability to capture shear failure.

In this study, a TFB model proposed in which both rate-dependent shear behaviour and damage effects have taken into account. Modified compression field theory was used to achieve this with the concrete damage model and bilinear steel model. Material losses due to spalling are neglected in this case. The proposed model has been implemented in the general FE of LS-DYNA simulation and convenient for the dynamic analysis of RC structure under blast loading.

5.3. Jingyu W. et al., 2020 [13]

Important structures under socio-economic consideration, bridges, building, etc. are highly susceptible to the terrorist effect. The column is the main structural component when any structure experiences the blast load to avoid the total collapse of the same. In this study, UMPFRC proposed to strengthen the conventional RC column subjected to blast load. A comparative study carried out between the UHPFRC supported column and traditional column to show the superiority of this advance material, which minimises the blast load effect.

5.4. Runqing Y. et al., 2018 [14]

The damage level of the structural element under blast loading usually assess by the pressure-impulse diagram. In this article, a new non-dimensional pressure diagram discussed under different failure modes. Nine non-dimensional vital parameters based on Euler beam theory had proposed. An elastoplastic method submitted to calculate RC beam-columns dynamic response under different failure modes such as bending failure, shear failure, combined bending, shear failure, etc. Non-dimensional method to analyse the dynamic response of the RC beam-columns, based on the continuous beam theory discussed in this study.

5.5. Chaojie S. et al., 2020[15]

A systematic approach discussed to investigate prestressed concrete bridge girders' performance under hydrocarbon and fire exposure. A 3D non-linear FEM model developed using the computer program ANSYS and analysed the response of the same under the combined effect of fire exposes and structural loading. The proposed model discretised the box-girder and predicted the RC box girder on fire response during the simultaneous application of hydrocarbon and structural loading.

5.6. Urgessa G. et al., 2018 [16]

It has been seen that the polymer coating gives a better result to mitigate the effect of blast load for RC and masonry structure. GFRP & CFRP (Glass and carbon fibre reinforced polymer) have been found to strengthen the structure under blast loading. In this paper, available experimental and numerical studies compiled together to understand the utility of polymer coating over the structure to reduce the effect of the blast.

6. Key observation

The researcher widely uses Hopkinson & Cranz equations due to its convergence with the experiment. Friedlander's wave equation is used to complete the wave profile, is exponentially decaying in nature. The use of coupled techniques is recommended for a detailed analysis of the structure. Many key parameters like equivalent TNT charged standoff distance, axial force, column height, material strength, cover depth, etc. in which damage of structure under blast load depends. The fragility curve may assess the deterioration of the RC column quantitatively as well as conveniently. It is found that damage to the structure under blast load may be reduced using advanced materials such as GFRP & CFRP. SPH coupling is more reliable, considering other coupling techniques.

Disclosures

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