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The Current Practices of Analysis of Reinforced Concrete Panels Subjected to Blast Loading

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Abstract—For any country in the world, it has become a priority to protect the critical infrastructure from looming risks of terrorism. In any infrastructure system, the structural elements like lower floors, exterior columns, walls etc. are key elements which are the most susceptible to damage due to blast load. The present study revisits the state of art review of the design and analysis of reinforced concrete panels subjected to blast loading. Various aspects in association with blast loading on structure, i.e. estimation of blast load, experimental works carried out previously, the numerical simulation tools, various material models, etc. are considered for exploring the current practices adopted worldwide. Discussion on various parametric studies to investigate the effect of reinforcement ratios, thickness of slab, different charge weight and standoff distance is also made. It was observed that for the simulation of blast load, CONWEP blast function or equivalent numerical equations were successfully employed by many researchers. The study of literature indicates that the researches were carried out using experimental works and numerical simulation using well known generalized finite element methods, i.e. LS-DYNA, ABAQUS, AUTODYN. Many researchers recommended to use concrete damage model to represent concrete and plastic kinematic material model to represent steel under action of blast loads for most of the numerical simulations. Most of the studies reveal that the increase reinforcement ratio, thickness of slab, standoff distance was resulted in better blast resistance performance of reinforced concrete panel. The study summarizes the various research results and appends the present state of knowledge for the structures exposed to blast loading.

Keywords—Blast phenomenon, experimental methods, material models, numerical methods.

I. Introduction

THE concern of explosions is now not only limited to petrochemical facilities or military services but also affects civilization. Recent terrorist attacks on many structures around the world have increased the importance of analysis of structures under blast loading [1]. So now, it has become necessary to develop a proper guideline for blast resistant analysis and designs, and the methodology would be incorporated into the conventional construction design [2]. Recent studies carried out by many researchers, i.e. [3]-[6], have focused mainly on the failure (removal) of columns under extreme loads, and the problem might be magnified for a structural wall subjected to blast. This is attributed to the fact that, compared with columns, structural walls are more vulnerable under the blast, as they attract more load under the same Design Basis Threat (DBT) level because of their increased surface area. As such, the scenario of a structural wall with a large surface area attracting more load, combined with the walls reduced moment of moment of inertia and the possibility of brittle failure, might prove to be significantly more critical than a blast event involving the column under the same DBT [7].

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A. Explosion Phenomenon

There are many literatures available which can describe the explosion phenomenon and its interaction with structures. The subsequent topics were referred mainly from the UFC 3-340-02, Structures to Resist the Effects of Accidental Explosions [8]; Design of Blast –Resistant Building in Petrochemical Facilities [9].

B. Explosions and Its Types

The physical, nuclear, or chemical event in which a large-scale, rapid and sudden release of energy occurred is known as explosion. The physical state of explosive material can be classified as solids, liquids, or gases [10].

A high explosive is the one in which the speed of reaction is faster than the speed of sound in the explosive. High explosives produce a shock wave along with gas, and the characteristic duration of a high-explosive detonation is measured in microseconds (10^{-6} s). Explosives come in various forms, commonly called by names such as TNT, PETN, RDX, and other trade name.

C. Blast Loading Category

Different categories of the blast load are indicated in Table I.

D. Blast Phenomenon

Due to the explosion, there is the sudden release of energy to the atmosphere which results in the blast wave. This blast wave propagates outward at supersonic or sonic speed from the source in all direction. The characteristics of blast wave, i.e. magnitude and shape depend on the nature of energy released and the distance from the explosion epicenter [9].

Two types of blast waves are (Fig. 1):

a) Shock wave
b) Pressure wave

E. Blast Wave Propagation

The detonation of a condensed high explosive generates hot gases which has pressure up to 300 kilo bar and temperature of about 3000-4000 ˚C. This gas with very high pressure and temperature expands, and the surrounding air is forced out of the volume that it occupies. As a result, a layer of compressed air- blast wave forms in front of this gas, which contains most of the energy released by the explosion. The speed and strength of the blast wave falls with increasing distance. Fig. 2

indicates the variation of blast pressure with distance.

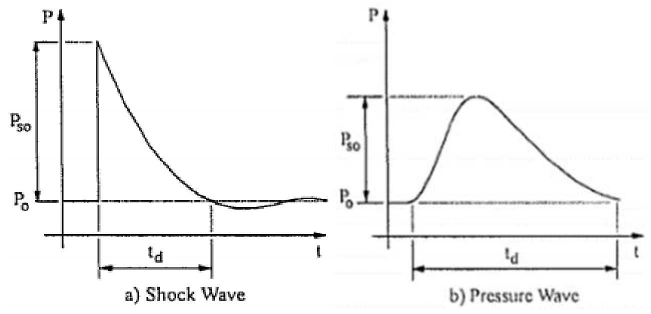

Fig. 1 Characteristic shapes of Blast Waves [9]

TABLE I
BLAST LOADING CATEGORY

Charge confinement	CATEGORY	Pressure loads	Protective structure
Unconfined explosions	1. Free Air Burst	a. Unreflected	Shelter
	2. Air Burst	b. Reflected	
	3. Surface Burst	b. Reflected	
Confined Explosions	4. Fully Vented	c. Internal shock d. Leakage	Cubicle
	5. Partially Confined	c. Internal shock e. Internal Gas d. Leakage	Partial containment cell or Suppressive Shield
	6. Fully Confined	c. Internal shock e. Internal Gas	Full Containment Cell

F. Blast Load Parameters

The detonation of explosive material releases the tremendous amount of energy which generates the gases at high pressure and temperature. As hot gases magnify the strong shock wave, the pressure front propagates radially into the surrounding atmosphere. The shock front termed as the blast wave which is characterized by an almost instantaneous rise from ambient pressure to peak incident pressure P_{so} as shown in Fig. 3. This shock front travels radially from the burst point with a velocity more than the velocity of sound, generally known as the shock velocity U. Gas molecules behind the front move with velocity u which is lower/ flow velocities. These latter particle velocities are associated with the dynamic pressure, whose maximum values are denoted $q_{o'}$ or the pressures formed by the winds produced by the passage of the shock front.

Fig. 3 indicates the typical shape of pressure time history at any point away from the burst. The shock front arrives at a given location at time t_A and the incident pressure rise to peak value, P_{so}. During the positive phase duration, the incident pressure decays from pick to the ambient value in time. The positive phase duration is followed by the negative phase duration that is usually much longer than the positive phase. The negative pressure having the maximum value of $P_{s\bar{o}}$ is developed during negative phase, as the positive phase having high pressure for smaller duration is more important in design than the negative phase with longer duration with less pressure intensity.

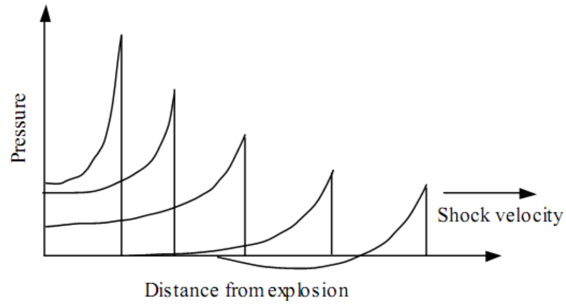

Fig. 2 Variation of blast pressure with distance [11]

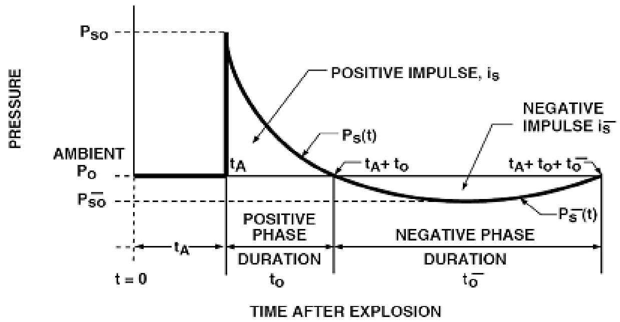

Fig. 3 Typical pressure-time history of an air blast in free air [8]

G. Cube Root Scaling

Blast load parameter for unconfined, open-air explosions can be calculated from the empirical curves based on Hopkinson (cube root) scaling. The scale distance can be calculated as (1) and (2)

$$\text{scaled distance x} = \frac{\text{Actual distance}}{W^{1/3}} \tag{1}$$

$$\text{scaled time } t_0 = \frac{\text{Actual time}}{W^{1/3}} \tag{2}$$

where W= Yield of explosion in equivalent weight of the reference explosive measured in tonnes, X= Scaled distance, t_0 = Scaled time

H. Prediction of Blast Pressure

Brode (1955) [11] introduced equation for estimation of peak overpressure due to spherical blast based on scaled distance $Z = R/W^{1/3}$ as (3) and (4):

For ($P_{so} > 10$ bar)

$$P_{so} = \frac{6.7}{Z^3} + 1 \tag{3}$$

For (0.1 bar $< P_{so} <$ 10 bar)

$$P_{so} = \frac{0.975}{Z} + \frac{1.455}{Z^2} + \frac{5.85}{Z^3} - .019 \tag{4}$$

The relationship to calculate maximum blast over pressure was introduced by Newmark and Hansen [12], Pso, in bars, for a high explosive charge detonates at the ground surface as (5):

$$P_{so} = 6784\frac{W}{R^3} + 93\left(\frac{W}{R^3}\right)^{\frac{1}{2}} \tag{5}$$

2Mills [13] introduced another expression of peak overpressure in kPa as in (6) in which W is expressed as the equivalent charge weight in kilograms of TNT, and Z is the scaled distance:

$$P_{so} = \frac{1772}{Z^3} - \frac{114}{Z^2} + \frac{108}{Z} \quad (6)$$

The air behind the shock front is moving outward at lower velocity as the blast wave propagates through the atmosphere. The velocity of air particles, and hence the wind pressure, depends on the peak overpressure of the blast wave. In the low overpressure range with normal atmospheric conditions, the maximum dynamic pressure, q_s, is given by (7)

$$q_s = {5p_{so}^2}\big/{2(p_{so} + 7p_o)} \quad (7)$$

If the blast wave encounters an obstacle perpendicular to the direction of propagation, reflection increases the overpressure to a maximum reflected pressure P_r as (8)

$$P_r = 2p_{so}\left\{\frac{7P_o+4P_{so}}{7P_o+P_{so}}\right\} \quad (8)$$

A full discussion and extensive charts for predicting blast pressure and blast durations are given by Mays and Smith (1995) [14] and UFC 3-340-02, 2008.

I. Blast Load vs Other Hazards.

On the basis of the ratio of the positive phase duration of blast loads, t_d, to the natural period of the structure T or the ratio of the td to the time for the structure to reach its maximum response, tm, there are three regimes of loading [14]

a) Quasi-static loading: When $10 < (t_d/T)$, the structure has reached its maximum response before the load is totally applied $(t_m/t_d) < 0.3$

b) Impulsive loading: When $(t_d/T) < 0.1$, the load has finished acting before the structure responds $3 < (t_m/t_d)$

c) Dynamic loading: When $0.1 < (t_d/T) < 10$ or $0.3 < (t_m/t_d) < 3$, the analysis is more complex.

The aforementioned three regimes are plotted into an exponential curve with respect to the logarithmic values of impulse, I and pressure, P as shown in Fig. 4. Such a curve may be used to indicate the damage threshold of the structure.

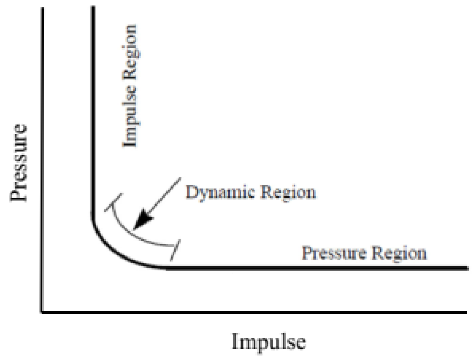

Fig. 4 Illustration of P-I diagram for positive phase blast load showing three regions of response [14]

The characteristics of the blast load are compared to loads arising from other hazards such as cyclones, earthquake persistent wind and flood and the difference in terms of its characteristics are summarized in Table II [15]

J. Interaction of the Blast Load with Structure

For enclosed building, the blast loads are typically applied to the exterior walls and roof and are transmitted through various structural members to the foundation. The energy of the blast is absorbed through elastic and more importantly, plastic deformation of the structure. The portion of blast energy not absorbed by the structure is transmitted into the ground. It is therefore necessary to establish a continuous load path with consistent tracking of the dynamic loads through the structure to ensure safe design as shown in Fig. 5 [9].

TABLE II
LOAD CHARACTERISTICS OF BLAST AND OTHER HAZARDS

Load Characteristics	Blast load	Cyclone	Earthquake	Persistent Wind	Floods
Forcing Function	P(R,W) I(R,W)	P (wind speed v^2, ρ)	Force F (mass m, acceleration a)	P(wind speed v^2, ρ)	F(flow rate Q^2, contact area A, ρ)
Duration	milliseconds	Seconds		Hours	
Loading Time History	Exponential	Random	Combined Sinusoidal	Random	Sinusoidal
Damage on Structure	Localized	Global			
Loading Regime	Impulsive or Dynamic	Dynamic		Quasi-static	

K. Design Guidelines: Manuals and Codes

There are several design codes that prescribe provisions related to design of structures (mostly buildings) to resist explosive loads or progressive collapse. A brief review of some codes including current Indian codes is presented in Table III.

II. SOME IMPORTANT LITERATURE

The details of experiments and FE methods in different literatures are summarized in Table IV.

III. CRITICAL APPRAISAL OF LITERATURE

A. Experimental Work

It can be seen from the study of various literature, many researchers such as [25], [30], [27], [29], have carried out experimental as well as numerical simulation of application of the blast load on reinforced concrete structure. However, field blast test is usually expensive, time consuming and often beyond affordability. In the same manner, the laboratory testing involves the physical blast simulator shock tube, the uniform impulsive loading simulator and other blast simulators, which are very expensive and not easily available in the general laboratory. So, in review of various literatures, it was observed that many researchers [28], [35], [39] used the experimental data already available in literature.

TABLE III
SUMMARY OF AVAILABLE GUIDELINES AND REPORTS

Standards and reports	Title
UFC 30340-01[16]	Design and analysis of hardened structures to conventional weapons effects
UFC 30340-02[8]	Structures to resist the effect of accidental explosions
UFC 30340-03[17]	Weapons effects: Designing facilities to resist nuclear weapon effects
ASCE design of blast-resistant buildings in petrochemical facilities [9]	Design of blast resistant buildings in petrochemical facilities
BS EN 1991-1-7:2006[18]	Actions on structures –Part 1-7: Accidental actions (include internal explosions due to burning of gases inside the structure like chemical facilities, vessels, sewage constructions dwellings with gas installations etc.)
FEMA 426 (Federal Emergency Management Agency, 2003b) [19]	Reference manual to mitigate potential terrorist attacks against building
FEMA 427 [20]	Primer for design of commercial buildings to mitigate terrorist attacks
FEMA 452[21]	Risk assessment, a how to guide to mitigate potential terrorist attacks against buildings.
IS: 4994-1968[22]	Criteria for blast resistant design of structures for explosion above ground
IS 6922-1973[23]	Criterial for safety and design of structures subjected to underground blasts

In the field test, TNT was used in the explosion in most of the literature i.e. [25], [29], [38], [41] because it is a standard high explosive, chemically safe and easy to cast. A detonator was inserted into the top of TNT. The cylindrical charge with diameter to height ratio of 2 was used. Wu et al. [45], Li et al. [31] used Comp B explosive for the field test. The other explosives like GOMA-ECO-2, ANFO were also used by [27] & [42] for the field test of panels subjected to blast loading. The specimens were tested in the field in horizontal position in most of literature although [25], [27] used vertical specimen for the field blast test. In all cases, the blast load was applied at concentrically, eccentricity of the blast was not noticed in any literature.

After the application of blast load, different damage levels and modes were studied by [41], [34], [29] by close observation of the scabbing holes formed on the opposite surface of the specimen, spall radius, etc. The deflection of the specimen under blast loading was measured by a cluster of steel needles which had stabbed into filled with fine sand as described by [29]. [48] investigated that the response of the slab can also be recorded using the high-speed camera. The results from the recording, pictures and videos can be used for further analysis. In experiment by [25], the high-speed camera was provided for monitoring the arrival time for the calculation of the propagation speed of the shock wave and predicting interaction of shock front and aluminum foil. To measure the strain rate effect, the strain gauge was used by [27]. In research conducted by Kakogiannis et al. [32] and Li et al. [30], researches used the high speed camera for monitoring the dynamic response of slab and Linear Variable Differential Transformer (LDVT) to measure vertical displacement at the centre of the slab. In the laboratory, the Blast load simulator (BLS) "shock tube" was used to simulate the air blast load on the vertically positioned panel by [32], [34].

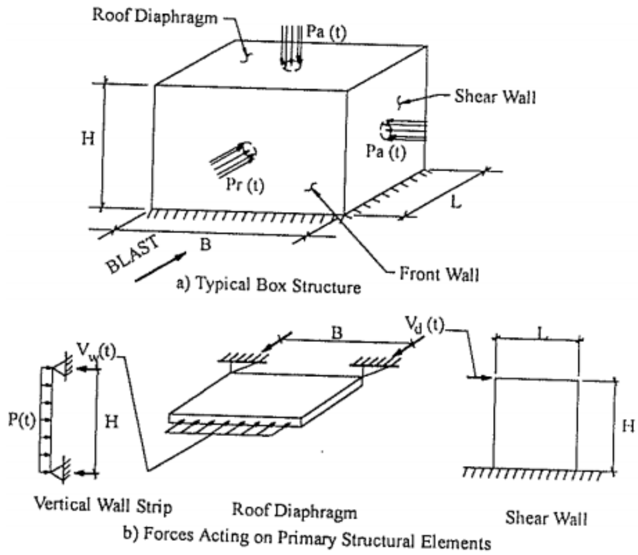

Fig. 5 Forces acting on primary structural element [9]

B. Materials

1) Concrete

The reinforced concrete is widely used material for construction. Reinforced concrete structures are extremely susceptible to producing airborne debris that might cause severe injury to occupants or damage sensitive equipment housed within the building. These concrete structures can be strengthened by steel plate or fibre composite sheet to enhance the energy absorption capacity of structures and to limit the structural damage in the structural component [42]. In the literature reviewed during the study, various types of concrete were used for better performance of the reinforced concrete structure subjected to blast loading. The performance of steel fibre reinforced concrete (SFRC) was studied by [46]. Foglar et al. [43] studied the effect of low ductility and low strength waste steel fibres, their combination with poly-propylene fibres on the blast performance of concrete. An experimental study was carried out on Carbon Fibre Reinforced Polymer (CFRP) strengthened the reinforced concrete slab specimen with fibre anchors by [37]. Ha et al. [42] have proposed new retrofit composite material by combining highly stiff CFRP with highly ductile material of Polyurea (PU) for strengthening RC panels under blast loading.

TABLE IV
SUMMARY OF FEW REFERRED RESEARCH STUDIES CARRIED OUT IN RECENT PAST

	Year	Experimental test	Position of panel	FE code	Blast simulation
Kilic S. A. [24]	2016	No	Horizontal	LS-DYNA	Conwep
Li et al. [25]	2016	Field test using 1 kg TNT (Contact explosion)	Vertical	LS-DYNA	Hybrid Finite element and Smooth Particle Hydrodynamics (SPH) method
Li et al. [26]	2016	Field test using TNT	Horizontal	No	NA
Ona et al. [27]	2016	Field test using GOMA-ECO-2	Vertical	LS-DYNA	Not given
Yan et al. [28]	2016	Field test	Horizontal	NA	NA
Yao et al. [29]	2016	Field test using TNT	Horizontal	LS-DYNA	Conwep
Li et al. [30]	2015	Field test using TNT (contact explosion)	Horizontal	LS-DYNA	Free air explosion test by Wu et al. was simulated using Load_Blast in LS-DYNA SPH Method for contact explosion simulation-MAT_High_Explosive to simulate the high explosive material
Li et al. [31]	2015	Field test using Comp B	Horizontal	LS-DYNA	Load_Blast
Thiagarajan et al. [32]	2015	**Blast load simulator (Shock tube)**	Vertical	LS-DYNA	Not given
Mao et al. [33]	2014	No	Vertical	LS-DYNA	Load_Blast
Stolz et al. [34]	2014	Shock tube test	Vertical	SDOF	NA
Xia et al. [35]	2014	No	NA	SDOF	NA
Kakogiannis et al. [36]	2013	Field test	horizontal	LS-DYNA	Conwep
Orton et al. [37]	2013	Field test	Horizontal	No	NA
Wang et al. [38]	2013	Field test using TNT	Horizontal	AUTODYN	High Explosive is simulated by Jones Wilkins Lee Equation of State
Zhao et al. [39]	2013	Field test using TNT	Horizontal	LS-DYNA (Arbitrary-Lagrangian-Eulerian Approach)	High Explosive is simulated by Jones Wilkins Lee Equation of State
Alostaz et al. [40]	2012	No	Vertical	LS-DYNA	Conwep
Wang et al. [41]	2012	Field test using TNT	Horizontal	No	NA
Ha et al. [42]	2011	Field test with TNT and ANFO	Horizontal	No	NA
Mutalib A. & Hao H. [43]	2011	NO	Horizontal	LS-DYNA	Empirical formulas by Wu and Hao (2005) [47]
Tai et al. [44]	2011	No	Horizontal	LS-DYNA (Arbitrary-Lagrangian-Eulerian Approach)	High Explosive is simulated by Jones Wilkins Lee Equation of State
Wu et al. [45]	2011	Field test using Comp B	Horizontal	No	NA
Wang et al. [46]	2009	NO	Horizontal	LS-DYNA	High Explosive is simulated by Jones Wilkins Lee Equation of State

The Ultra-High-Performance-Concrete (UHPC) which has high compressive and tensile strength, large energy absorption capacity as well as good workability and anti -abrasion ability is now widely applied. Li et al. [26], Li et al. [30] & Li et al. [31], Mao et al. [33] demonstrated the performance of UHPC under blast loading. The effect of mineral admixtures and the steel fibre volume contents on the behaviour of High Performance Fibre Reinforced Concrete was investigated by [49]. Slurry Infiltrated Micro-Reinforced Concrete, commercially known as DUCON is a new and innovative Ultra-High-Performance Concrete (UHPC). Alostaz et al. [40] performed analytical simulations and experimental testing to study the effectiveness of SIMRC for blast protection. The bearing resistance of plate elements made of the ductile concrete DUCON under blast loading condition was investigated by [34]. The details of concrete used in various studies are tabulated in Table V.

2) Steel

Steel bars or steel wire can be used as reinforcement in reinforced concrete structures. High strength deformed steel bars have wide applicability to use as reinforcement. Thiagarajan et al. [32] investigated that use of high strength bars in normal strength concrete is more effective than its use in high strength concrete. Use of steel wire mesh as reinforcement is the general construction practice in Germany. Li et al. [25] studied the performance of steel wire mesh the reinforced concrete slab under contact explosion. In [27], author investigated the response of normal strength concrete with steel rebar retrofitted with Kevlar coating. Static and dynamic behaviour of concrete slabs reinforced with chemically reactive enamel-coated steel bars and fibres were investigated by [28]. Xia et al. [35] investigated that in addition to different types of concrete and steel used in blast resistant design of buildings, the metal foam cladding can also be used for blast protection. Wu et al. [45] investigated that aluminum foam layers effectively mitigate the blast effect on RC slabs. Table VI shows the details of various types of reinforcement used in different studies.

C. Numerical Simulation

There are two types of numerical simulation considered for dynamic analysis of RC members subjected to blast load (a) blast load simulation and (b) simulation of response of the structure subjected to the blast load. It was observed from all literature review the LS-DYNA, ABAQUS, AUTODYN are key commercial codes used for blast load analysis.

TABLE V
SUMMARY OF CONCRETE AND CONCRETE MATERIAL MODELS USED IN VARIOUS STUDIES

	Material for concrete	Concrete material model
Kilic S. A. [24]	Conventional concrete with 43 MPa strength	MAT_WINFRITH_CONCRETE
Li et al. [25]	High performance self-compacting concrete (60 MPa) High performance self-compacting concrete with steel fibers (85 MPa)	Cover layer fibre reinforced concrete – MAT_ELASTIC_PLASTIC_HYDRO core in refined mesh – MAT_ CONCRETE_ DAMAGE_ REL3 Core in coarse mesh - MAT_PSEUDO_TENSOR
Li et al. [26]	Ultra-High Performance Concrete Conventional concrete	NA
Ona et al. [27]	Self-compaction concrete (52.6 MPa) Self-compacting steel fibre reinforced concrete (42.18 MPa) Self-compacting polypropylene fibre reinforced concrete (34.98 MPa)	Cohesive crack model with strong discontinuity
Yan et al. [28]	Conventional concrete (44 MPa)	**NA**
Yao et al. [29]	Conventional concrete (39.5 MPa)	MAT_ CONCRETE_ DAMAGE_ REL3
Li et al. [30]	Conventional concrete Ultra-High Performance Concrete	MAT_ CONCRETE_ DAMAGE_ REL3 for normal strength concrete MAT_ELASTIC_PLASTIC_HYDRO for UHPC
Li et al. [31]	Ultra-High Performance Concrete	MAT_ELASTIC_PLASTIC_ HYDRO for UHPC
Thiagarajan et al. [32]	High strength concrete (107 MPa) Normal strength concrete (27.6 MPa)	MAT_WINFRITH_CONCRETE MAT_ CONCRETE_ DAMAGE_ REL3
Mao et al. [33]	Ultra-High Performance Concrete	MAT_ CONCRETE_ DAMAGE_ REL3
Stolz et al. [34]	Slurry Infiltrated Micro Reinforced Concrete	NA
Xia et al. [35]	Normal strength 32 MPa with metallic foam cladding	NA
Kakogiannis et al. [36]	C40/50	Riedel, Hiemayer and Thoma concrete model
Orton et al. [37]	Conventional concrete (RC panel with CFRP sheet)	NA
Wang et al. [38]	Conventional concrete (39.5 MPa)	Riedel, Hiermaier and Thoma(RHT) dynamic damage model
Zhao et al. [39]	Conventional concrete (39.5 MPa)	MAT_ CONCRETE_ DAMAGE_ REL3
Alostaz et al. [40]	Slurry Infiltrated Micro Reinforced Concrete	Three Invariant Shear Surface with Cap
Wang et al. [41]	Conventional concrete (39.5 MPa)	NA
Ha et al. [42]	Conventional concrete (RC panel with Carbon Fiber reinforced polymer (CFRP) sheet and Polyurea (PU) spray or hybrid composite of CFRP-PU)	NA
Mutalib A. & Hao H. [43]	Conventional concrete (RC Panel with FRP composite)	MAT_ CONCRETE_ DAMAGE_ REL3
Tai et al. [44]	Normal strength	Johnson Holmsquist concrete model
Wu et al. [44]	Conventional Concrete (39.5 MPa) (RC slab with aluminum foam protection)	NA
Wang et al. [46]	Steel Fiber Reinforced Concrete	MAT_ELASTIC_PLASTIC_HYDRO

1) Simulation of Blast Load

From the review of literature, it reveals that in most of research carried out by [24], [46], [40] modelling of blast load using LS-DYNA was carried out by the semi-empirical method using CONWEP which is built in LS-DYNA to generate pressure histories. Li et al. [31] simulated blast load using the Load_Blast function in LS-DYNA which is developed based on a report by Randers-Pehrson and Bannister. The explosive and the air elements were modelled using multi-material arbitrary Lagrangian Eulerian (ALE) formulations by [44]. Zhao et al. [39], Wang et al. [38] simulate the blast scenario using AUTODYN. In this study, the air was modelled by an ideal gas expression of state and high explosive was modelled by Jones-Wilkins-Lee EOS. The hybrid Finite Element (FE) and Smoothed Particle Hydrodynamics (SPH) were adopted for numerical simulation by [25] & [30]. SDOF analysis is very widely used as cost effective approach requiring limited input data [50]. The simplified equivalent SDOF method was used to simulate the behaviour of RM walls subjected to blast load [7]. Nickerson et al. [51] access the SDOF methodologies used to design concrete wall components subjected to combined flexure and axial loading to develop an improved methodology for integrating axial loads into the SDOF framework as applied to conventionally reinforced and Prestressed concrete wall panels.

2) Material Model for Concrete

Winfrith material model was used to simulate nonlinear behavior of the concrete by [24], [32]. The Riedel, Hiermayer and Thoma (RHT) material model which is enhancement to the Johnson and Holmquist concrete model and includes the influence of the strain hardening was used by [36], [38]. The material behaviour is modelled as linear-elastic with no failure in the compressive domain and failure under tension was modelled using Cohesive Crack Model by [27]. Li et al. [30], Li et al. [31] and Wang et al. [46] modelled concrete as elastic-plastic hydrodynamic material using MAT_ELASTIC_

PLASTIC_HYDRO material model in LS-DYNA. It was studied that, to investigate the interactive mechanism and the dynamic response of the reinforced concrete slab under blast loads, a proper and reliable dynamic damage model that reflects the characteristics of concrete material behavior at the high strain rate is needed. It can be seen from [29], [44], [39] that the third release of Karagozian and Case (K&C) concrete model which is available as MAT_CONCRETE_DAMAGE_REL3 in LS-DYNA is widely used for simulation of dynamic behavior of concrete. The details of concrete material models used in various studies are tabulated in Table V.

3) Material Model for Steel

The Johnson and Cook material model for reinforcement steel is suitable for modelling the strength behavior of materials subjected to large strains, high strain rates and high temperatures [36], [38]. Li et al. [25], Mutalib et al. [43] used Piecewise Linear Plasticity material model for steel material. The plastic kinematic type material model was used by [24], [29], [32], [44], [39] to model the steel material (Table VI).

TABLE VI
SUMMARY OF TYPE OF REBAR AND STEEL MATERIAL MODELS USED IN VARIOUS STUDIES

	Type of rebar	Steel material model
Kilic S. A. [24]	Rebar of 10 mm diameter	MAT_PLASTIC_KINEMATIC
Li et al. [25]	Steel reinforcement Steel wire mesh	MAT_PIECEWISE_LINEAR_ PLASTICITY
Li et al. [26]	Steel bars (360 MPa)	NA
Ona et al. [27]	Steel bars	**Not given**
Yan et al. [28]	Chemically reactive enamel coated Steel bars Chemically reactive enamel coated Steel fibres	NA
Yao et al. [29]	6 mm diameter steel bars	MAT_PLASTIC_KINEMATIC
Li et al. [30]	Steel bars used only for normal strength concrete	MAT_PIECEWISE_LINEAR_ PLASTICITY
Li et al. [31]	Mild steel bars (300 MPa) High strength bars (1750 mm) Reo bar (600 MPa)	MAT_PIECEWISE_LINEAR_ PLASTICITY
Thiagarajan et al. [32]	Conventional steel reinforcing bars High strength low alloy vanadium reinforcement	MAT_PLASTIC_KINEMATIC
Mao et al. [33]	Steel bars	MAT_PLASTIC_KINEMATIC
Stolz et al. [34]	Micro mate steel reinforcement	NA
Xia et al. [35]	12 mm diameter 500 MPa strength	NA
Kakogiannis et al. [36]	10 mm φ S500	Piecewise Johnson Cook model
Orton et al. [37]	Not specified	NA
Wang et al. [38]	Steel bars (600 MPa)	Johnson Cook model
Zhao et al. [39]	Steel bars (600 MPa)	MAT_PLASTIC_KINEMATIC
Alostaz et al. [40]	Steel Wire Mesh	Multi Linear Plasticity Model With Kinematic Hardening
Wang et al. [41]	Steel bars (600 MPa)	NA
Ha et al. [42]	10 mm diameter steel bars (400 MPa)	NA
Mutalib A. & Hao H. [43]	Steel reinforcement (415 MPa)	MAT_PIECEWISE_LINEAR_ PLASTICITY & For FRP-Mat Enhanced Composite Damage Title
Tai et al. [44]	Steel bars (414 MPa)	Hardened model
Wu et al. [45]	Steel bars (600 MPs)	NA
Wang et al. [46]	NO	NA

IV. SUMMARY

The present paper overviews the various research carried on the reinforced concrete panels subjected to blast load. The research carried out can be classified in to two categories, i.e. experimental works and numerical simulations using well known generalized finite element methods using available applications. The overview is summarized in the crisp form as below.

1. Based on various literature studies, it was observed that in many experimental works, the researchers attempted to investigate the blast load effect on the horizontally placed plain reinforced concrete panels, i.e. panels acting as slab and the concrete strain/ displacement was measured during the field experiments. However, in many research experiments works, effect of type of concrete was investigated using different concrete material types i.e. varying the properties using concrete like normal strength concrete, steel fiber reinforced concrete, ultra-high-performance fiber reinforced concrete, steel fiber reinforced concrete, carbon fiber reinforced concrete etc. In the other research experiments carried out by [24], [29], [38], it was observed that solid steel bars were mostly used as reinforcement. Li et al. [25] also investigated the performance of steel wire mesh as reinforcement. It is observed from [27], [28] that the reinforcement steel bars or fibers can be coated with different types of coating like Kelvar coating, chemically reactive enamel coating, etc. to improve blast resistance performance. In most of the experiments, the RCC panel was supported by steel frame (either on two sides or on

four sides) idealizing the support condition between fixed and pinned.

2. It is also observed that most of the numerical simulations of experimental work were carried out using LS-DYNA. For the simulation of blast load, CONWEP blast function or equivalent numerical equations were used. Based on the published results as given by [29], [44], [39], it is observed that that the concrete damage model as the concrete panel under specified blast load could reasonably represent the behavior of concrete at high strain rate in adequate. Hence, for most of the numerical simulations, researchers recommended to use concrete damage model to represent concrete under action of blast loads. It is also observed that many researchers simulated the material properties of steel using plastic kinematic material model. Many parametric studies were carried out by various researchers to investigate the effect of various reinforcement ratios, thickness slab, different charge weight and standoff distance. It was observed in various experiments carried out by various researchers that the increase reinforcement ratio, thickness of slab, standoff distance was resulted in better blast resistance performance.

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