Influence of critical parameters on UHPFRC structural elements subjected to blast loading

Rizwanullah[1] · H. K. Sharma[1]

Abstract

Response of structures subjected to blast loading is a highly complex phenomena involving time-dependent deformation, geometric and material nonlinearities and loading rate based material properties. During an explosion, blast loads act as an impulsive load of very short duration developing enormous heat and pressure. With increasing terrorist threats, attention is needed to study dynamic response of structures under blast loading. Ultra high strength concrete (UHPC) has been found to considerably enhance strength, member size, weight reduction and workability and is now a day used due to improved energy absorption capacity, workability and anti-abrasion ability. Investigations conducted by several researchers to study blast-resistant capacities of UHPC have demonstrated possibilities of using the material in structures susceptible to terrorist attack. The present paper provides comprehensive review of published research to study blast loading effect on Ultra high performance fibre reinforced concrete (UHPFRC) structural elements in terms of variables like standoff distance, charge weight, types of blast loadings, grades of UHPFRCs, etc., both analytically and experimentally. UHPFRC slab panels, beams, columns, and other fibre composite structures have been studied at structural level to draw fruitful inferences and conclusions. It has been found that UHPFRC possesses increased capacity to disseminate large amount of energy during blast loading and demonstrates better performance after blast damage contrasted with normal strength concrete and High strength concrete. Detailing in UHPFRC structural elements under seismic condition offers improved blast performance, and UHPFRC can more effectively resist compression and shock waves. Low Strength and low ductility fibres added to UHPFRC further illustrates minimal influence on the blast performance and fracture energy. Shear failure is also found to be one of the dominant modes in UHPFRC under blast loading at close standoff. Based on extensive review, further research is proposed to solve complex problems to achieve appropriate design of structural UHPFRC members.

Keywords NSC · UHPFRC · Blast loading · Contact explosion · RPC · Local damage · RUHPFC

1 Introduction

The behaviour of concrete subjected to extreme loading is generally different from static loading due to strain rate effect. More attention is therefore needed to study structural dynamic response subjected to blast loading. The structural response subjected to blast loading is a complicated problems as it includes material and geometric nonlinearity, loading rate and structural deformation properties. In recent decades, a new innovative material called ultra high performance fibre reinforced concrete (UHPFRC) is used in the concrete industry for structural components. UHPFRC which consists of extremely fine particles, fibre reinforcement, to obtain compressive strength of higher order. Because of inclusion of fibres, UHPFRC is known for

✉ Rizwanullah, rizwan_6170002@nitkkr.ac.in; H. K. Sharma, hksharma1010@yahoo.co.in | [1]Civil Engineering Department, National Institute of Technology, Kurukshetra, Haryana 136119, India.

its enhanced durability, ductility, impact and blast resistant capacity as compared to conventional concrete [17].

Extensive research was conducted to study the performance of UHPFRC structures subjected to blast loading environment. Use of UHPFRC remarkably enhanced blast performance of structural memebers by minimizing the residual dispalcements, improved damage tolerance, and eliminating blast fragments [1, 2, 17, 25, 32]. It was seen that in case of impulsive load, UHPFRC can support higher than 400% higher impulse that would make normal strength concrete (NSC) columns to fail. The investigations on UHPFRC columns and slab panels subjected to static and balst laoding conditions, further, demonstrated the outcomes of using such materials. The blast resistant of slabs constructed with UHPC and reinforced concrete (RC) are investigated by [42]. It was demonstrated that UHPC slabs out performed the normal strength slabs with significant damage after blast. While various tests have been examined on the performance of UHPFRC subjected to impact loading [8, 9, 23], few studies have been published on UHPFRC subjected to blast loading.

2 Ultra high-performance fibre reinforced concrete

A new class of UHPFRC material was presented by Richard et al. in 1990s, which shows outstanding structural properties such as compressive strength (> 150 MPa), tensile strength (> 15 MPa), flexural strength and energy absorption capacity. The exceptional mechanical properties were accomplished by using water/binder proportion of around 0.2, ultra- fine powders silica flour and fume, heat curing (90 °C), and the inclusion of micro steel fibers. Table 1 illustrates constituent materials used by various researchers for obtaining UHPFRC. It may be seen that very few researchers have used ground granulated blast furnace slag (GGBS) and steel fibres. Since, UHPFRC is quite expensive than normal strength concrete and requires special heat curing,

the composite needs to be appropriately designed and used in special buildings or infrastructures.

Performance assessment of structural components against blast loading is now a day an important issue due to increasing terrorist attacks and accidental explosions. Numerical analysis and computer modeling are now proven to be a valuable tool to simulate the behaviour of such structures under blast loading. Dynamic response of structures subjected to blast loading is an important topic as these loads produce structural damage which may cause threat to the people and appliances protected by RC structures. To diminish effects of blast on buildings, UHPFRC is now extensively studied. Figure 1 illustrates performance of UHPFRC over NSC under different loading conditions. In high-performance structures subjected to extreme earthquakes, ballistic loads and blast loads, UHPFRC has been extensively used.

3 Classes of structures

For effective design of structures subjected to blast loads, it is essential to recognize them in terms of risk, post disaster serviceability and blast consequences. The structures are thus divided into four groups based on sensitivity and vulnerability, and are classified into class 1,2, 3 and 4 depending on severity of risk (higher, medium, lower and very lower risk). Class 1 includes public buildings like hospitals, broadcasting stations, etc. Class 2 comprises power transmission towers, assembly buildings, bank buildings and road bridges, etc. Class 3 involves four or higher storey buildings and other structures in between the category above and below this one. Similarly, class 4 includes residential buildings up to 3 storeys, private dwellings, minor road bridges, service stations, etc. The first three class require some attention against blast resistant design whereas class 4 structures have to fulfil blast design codes and building standards [15].

Table 1 Constituent materials used in production of UHPFRC

S. no	Authors	Material used (kg/m³)						
		Cement	GGBS	Silica fume	Silica sand	Superplasticizer	Water	Steel fibre
1	Hassan et al. [12], Mao et al. [22]	657	418	119	1051	40	185	157
2	Li et al. [16, 17] Ductal	680	–	204	1130	44	150	156
3	Tayeh et al. [37]	610–1390	–	50–334	490–1390	9–71	126–261	40–250
4	Li et al. [17]	750	–	415	1030	16	190	–
5	Li et al. [18]	1155	–	437	178	40	305	–
6	Xu et al. [43]	995	–	229	1051	–	16	–
7	Su et al. [35]	750	–	225	1220	16	190	60
9	Turker et al. [38]	690	276	138	1050	17.25	199	33

Various ranges of strain rates in case of different extreme load conditions are shown in Fig. 2. Blast loads are categorized in a very higher strain rates. For structures subjected to extreme loadings, strain will increase due to the effects of strength of concrete and reinforcement. It can be understood that ordinary strain rate varies between 10^{-6} and 10^{-5} s^{-1}, while strains varies between 10^2–10^4 s^{-1} in cases of blast loading [25].

4 Explosion and blast waves profile

Explosion generates large dynamic loads, which would be more than initial loads for which the elements of the structures are analyzed, Fig. 3. Normally, traditional structures are not intended to oppose blast loads because its magnitude is very high in comparison to normal design loads.

While considering the explosion effects on the structures, there are some fundamental characteristics which are to be considered irrespective of the source. Immediately after explosion, pressure waves are propagated through the atmosphere, which are main cause for the damage of the structure. Depending on the charge weight W, these waves travel faster than speed of sound and collide with the structure, Fig. 4a. Figure 4b demonstrates a blast pressure profile. The surrounding pressure is equal to the pressure at the ambient. The ambient pressure p_0 increases instantaneously to the peak pressure p_{so} at the initial time t_A, when shock wave reaches at that point. The time required for pressure to reach its peak value is called

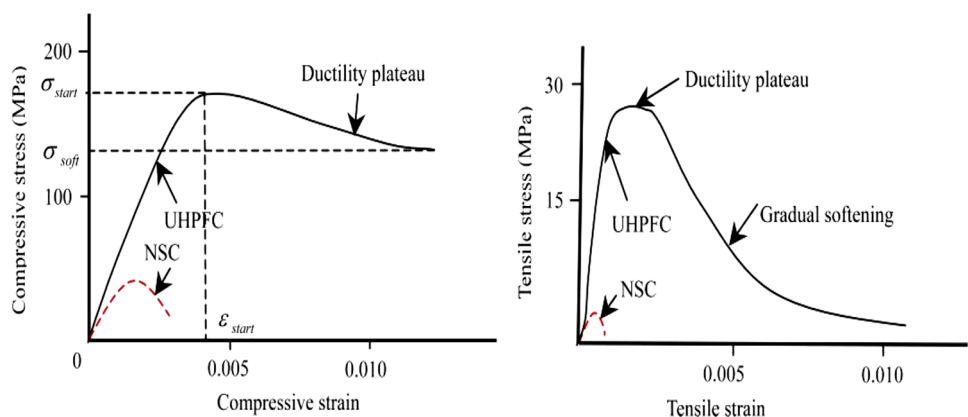**Fig. 1** Behaviour of UHPFC and NSC specimen subjected to **a** compression and **b** tension [42]

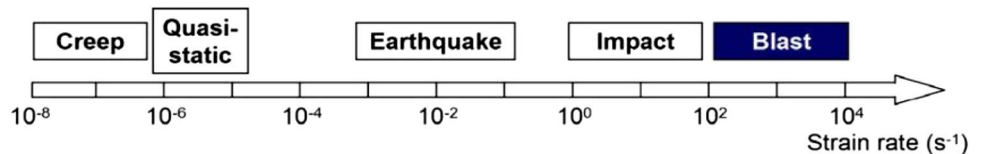**Fig. 2** Strain rate ranges for various loading types [44]
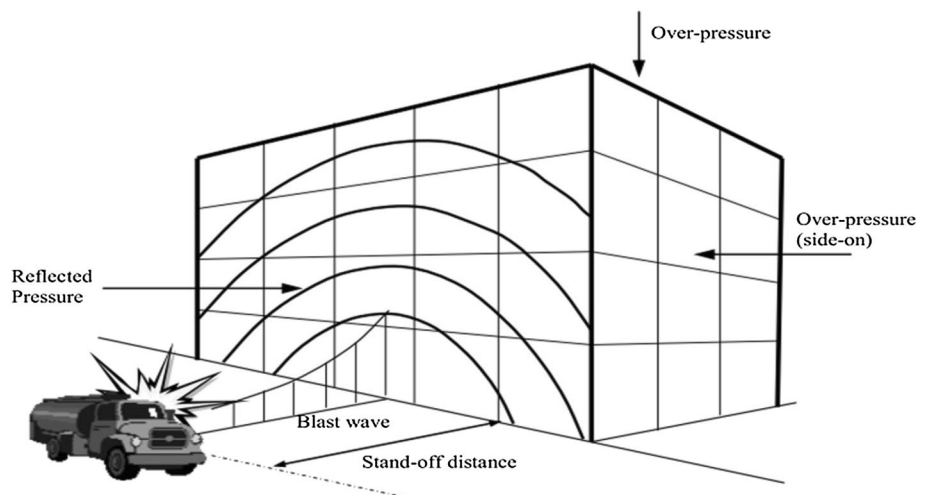

Fig. 3 Building subjected to blast loading [26]
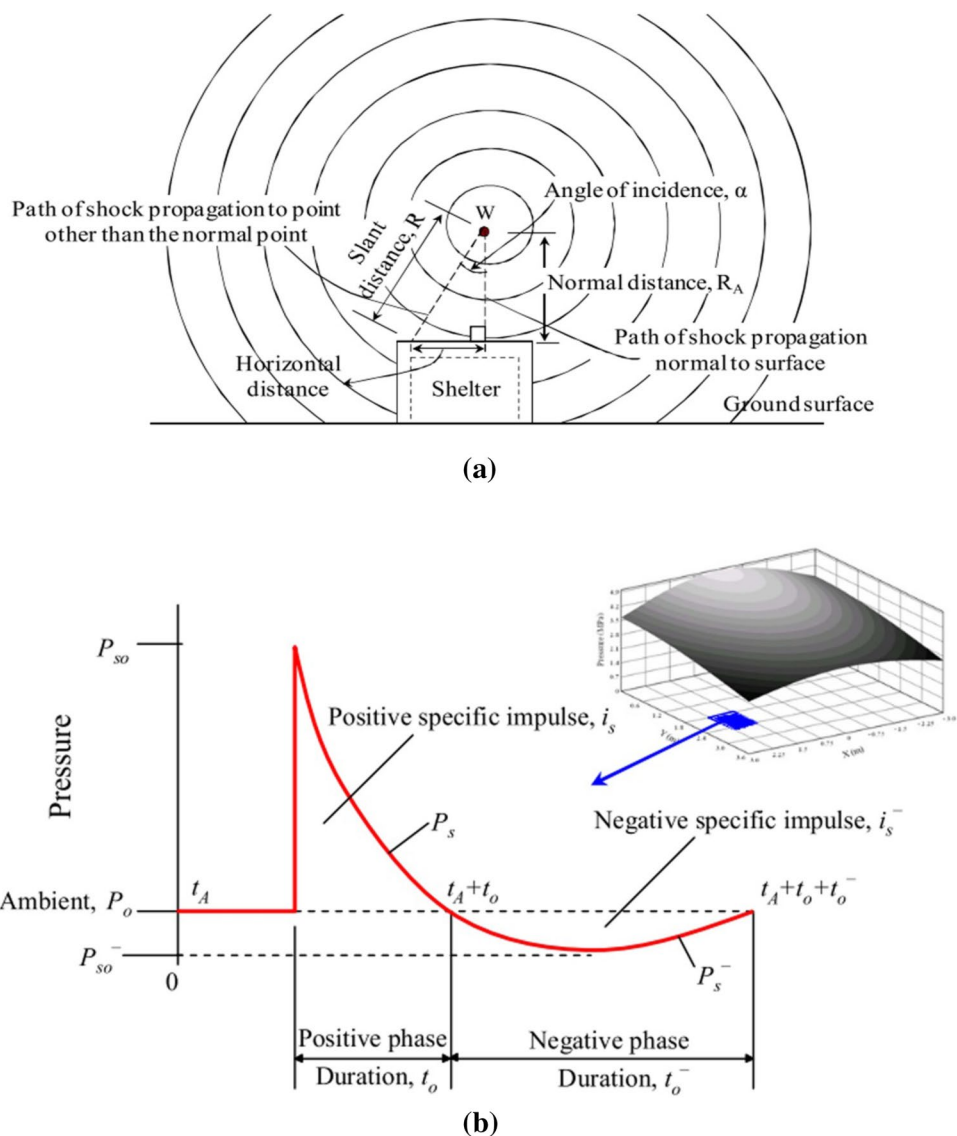
Fig. 4 **a** Spherical free air blast and 4 **b** Pressure–time history [14]

(a)

(b)

as peak overpressure or side on peak pressure or incident peak overpressure. The peak pressure value and the velocity in the shock wave decreases with increase of the scale distance. The pressure at the peak value decreases exponentially until the ambient pressure reaches $t_A + t_0$, t_0 is called positive phase duration. From the pressure–time graph, the pressure becomes so small than ambient value for negative phase. P_{so}—denotes the negative overpressure- and t_o—is called a negative duration. After the blast on a structure, the glass fragments on the exterior to the buildings as compared to interior [36] (Fig. 4).

When blast occurs, the ambient pressure increases and then decreases forming triangular overpressure. Brode [5] proposed expression for peak overpressure p_s in case of close in contact condition as,

$$p_{s0} = \frac{6.7}{Z^3} + 1 \quad (p_s > 10 \text{ bar}) \tag{1}$$

and
$$p_{s0} = \frac{0.975}{Z} + \frac{1.455}{Z^2} + \frac{5.85}{Z^3} - 0.019 \text{ bar } (0.1 < p_s < 10 \text{ bar}) \tag{2}$$

Based on the experimental data, an expression for peak positive overpressure was given by Henrych [10] as

$$p_{s0} = \frac{14.072}{Z} + \frac{5.54}{Z^2} - \frac{0.357}{Z^3} + \frac{0.00625}{Z^4} \text{ bar } (0.05 < Z < 0.3) \tag{3}$$

$$p_{s0} = \frac{6.194}{Z} - \frac{0.326}{Z^2} + \frac{2.132}{Z^3} \text{ bar } (0.3 < Z < 1) \tag{4}$$

and

$$p_{s0} = \frac{0.662}{Z} + \frac{4.05}{Z^2} + \frac{3.228}{Z^3} \text{ bar } (0.3 \leq Z \leq 1) \tag{5}$$

Based on the data of explosion, the peak overpressure p_{s0} may then be evaluated by [13] as,

$$p_{s0} = 2\frac{W^{2/3}}{R^2} \text{ (MPa)} \tag{6}$$

Graham and Kinney [10] suggested an equation to calculate peak overpressure 'ρ_{so}' as

$$p_{s0} = \frac{808\left[1 + \left(\frac{Z}{4.5}\right)^2\right]}{\sqrt{\left[1 + \left(\frac{Z}{0.048}\right)^2\right]} x \sqrt{\left[1 + \left(\frac{Z}{0.32}\right)^2\right]} x \sqrt{\left[1 + \left(\frac{Z}{1.35}\right)^2\right]}} \text{ (bar)} \tag{7}$$

Sadovskiy [10] presented another expression peak overpressure 'ρ_{so}, based on experimental data as,

$$p_{s0} = 0.0.85\frac{W^{1/3}}{R} + 0.3\left(\frac{W^{1/3}}{R}\right)^2 + 0.8\left(\frac{W^{1/3}}{R}\right) \text{ (MPa)} \tag{8}$$

Based on the modification of Sadovskiy equation, Bajic [10] presented a new equation to compute peak positive overpressure 'ρ_{so} as,

$$p_{s0} = 1.02\frac{W^{1/3}}{R} + 4.36\frac{W^{2/3}}{R^2} + 14\frac{W}{R^3} \text{ (bar)} \tag{9}$$

Newmark [10] proposed an equation for computing peak overpressure, pso for surface blast as,

$$p_{s0} = 6784\frac{W}{R^3} + 93\left(\frac{W}{R^3}\right)^{1/2} \text{ (bar)} \tag{10}$$

Mills [10] introduced an expression to compute peak overpressure ρ_{so} as,

$$p_{s0} = \frac{1772}{Z^3} - \frac{114}{Z^2} + \frac{108}{Z}\text{(kPa)} \tag{11}$$

where, Z is the scale distance in meter and W is the charge weight (kg) as defined by,

$$Z = \frac{R}{W^{1/3}} \left(\text{m/kg}^{1/3}\right) \tag{12}$$

All the above models for peak positive reflected overpressure are critically examined by [3].

5 Published literature

The critical examination has led to research on evaluating strength parameters of cementitious materials from RC, NSC, and HPC under blast loading. It has been seen that the slab panels having 2% fiber volume indicates improved blast performance. It has likewise been accounted for that no huge improvement in blast performance is accomplished with increased fibre contents from 2 to 3%. It was also seen that the composition of composite matrix and type of fiber play a vital role in improving blast resistance. In the present paper, an attempt has been made for contemplating influence of different parameters mentioned below that affect the behavior of UHPFRC under blast loading.

5.1 Standoff distance

Ngo et al. [25] experimented the panels with varying reinforcement and thicknesses. Test was conducted underneath a 6 t TNT equal explosion with standoff distances as 30 and 40 m. The observed data for the specimens included deflections and blast pressures of the panels. From the test, it was observed that the panels were capable to resist enormous deflection under high loading rate. Further, the panels were able to resist the blast loading and do not break into fragments.

Barnett et al. [4] tested several UHPFRC panels of size 3500*1300*100 mm under 100 kg of TNT equivalent explosive loading at standoff distance of 9 and 7 m, respectively. The variables investigated consist of type and amount of fiber reinforcement, reinforcement and standoff distance of the explosive rate. From the test, it was concluded that the UHPFRC materials had been used in the safety of civil and defence purposes.

Wu et al. [41] found that aluminium foams are a recently created portable and lightweight material with magnificent energy absorption capacities. The researchers utilized two kinds of aluminium foams to shield RC panels of slab and led several trials to study the behavior of aluminium foam shield RC panels of slab subjected to blast loadings. The displacements, acceleration, performance of samples, maximum and permanent deflections, etc. were studied. The response occurred from foam shield slabs are superior to that of the non-protected slabs. Williams and Williamson [40] discussed the loads which are acting in outrageous cases, for example, impacts and blast effects, particularly on the RC bridge columns. They found that the results obtained after numerical models are utilized to understand the mechanisms to this prompting response. With the capacity to assess the degree of spalling damage that can happen for a threat like situation, engineers can guarantee that the column design have satisfactory capacity to withstand dead loads followed by the damage due to explosive loading. Foglar et al. [9] investigated the effects of low tensile strength waste fibers of steel with low ductility and their mixture, with fibers made of polypropylene, on the blast-related phenomena of concrete.

The combination of blast effects of different compressive strength is additionally studied. The experiments were carried out on the precast slabs for 25 kg of TNT at a standoff distance of 1.675 m from the panels of slab. Steel fibers from waste incorporated in concrete mixture had insignificant effects on the blast phenomena of FRC. Low-quality fibers and low ductility incorporated into the concrete matrix had minimal effects on the blast behavior of FRC and its fracture energy value. De Carufel et al. [7] studied columns, built with traditional concrete and UHPC, have been examined under blast loading using a shock tube. The parameters taken into consideration to examine the results consist of type of concrete, amount of fiber, strength, transverse reinforcement, and longitudinal reinforcement ratio. The influence of increasing amount of fibre from 2 to 4% in UHPC gives better performance against failure.

Qu et al. [30] examined performance of samples made of UHPFRC columns under distinct explosive loadings at a standoff distance of 1.5 m. Blast tests were conducted on high strength reinforced concrete (HSRC) compression column with a similar size and reinforcement as in UHPFRC columns to investigate the behavior having identical loading conditions. The post-blast crack pattern, deflections, and different dimensions of damage demonstrated that UHPFRC compression elements exhibited better performance under blast loading when compared with HSRC compression elements. The effects of axial load on compression elements exposed to blast loads has been examined. The typical values demonstrated that the samples have lesser deflections for UHPFRC elements.

5.2 Magnitude of charge weight

Kim et al. [14] investigated influence of ultra-high strength concrete (UHSC) and reactive powder concrete (RPC). It was found that these can be developed to improve concrete strength significantly. It was found that the use of RPC and UHSC improve member size, concrete strength, weight reduction, and workability. Further, HSC usages in improved resistance to earthquake and increase height of building and span of bridges. Repair materials, blast resistance, and retrofitted structure were evaluated to study response of UHSC and RPC under blast wave pressure. The pattern of distress in UHSC and RPC illustrated that the materials have much higher resistance under blast loading as these materials also possess higher blast resistance capacity when compared with NSC.

Ha et al. [11] studied strengthening of RC infrastructures using the fiber-reinforced polymer (FRP), as it is being increasingly used nowadays. The application of FRPs for strengthening structures against an impact accident or blast terror is of paramount interest from specialists view point in retrofitting and strengthening area. The test data pertaining to free field incident, reflected blast pressures, steel and concrete strains and maximum and residual displacements, etc. are measured. It was concluded that the maximum displacement of hybrid fibre, polyurea, and CFRP specimens have retrofitting effect of 37.4, 15.7, and 21.4% respectively when compared with NSC.

Mao et al [21] examined numerically influence on the UHPFRC subjected to blast loads using a concrete model. The reliability of analytical modelling was confirmed by differentiating analytical results obtained in the modelling to the data with the information from relating full-scale blast tests. They also examined the impact of fibers and reinforcement in enhancing UHPFRC capacity under blast loading. The damage model of concrete was utilized to demonstrate the performance of UHPFRC panels subjected to blast loads. The typical results showed that blast impulse and peak blast pressure may be assessed with great precision. The prediction of damage can be enhanced by demonstrating the fiber unambiguously in the model of concrete so that the fiber effect can be communicated. It was also noticed that in case of field blast loading, reinforcement bar and fibers have similar effect on UHPFRC slabs. At the point when exposed to close in blast explosions, the UHPFRC slabs can have increased resistance altogether with steel reinforcement. Qasrawi et al. [29] studied the benefits of encasing RC members with glass fibrous polymer (GFP) tube exposed to close in blast loads. The concrete-filled fiber-reinforced polymer (CFFT) samples performed essentially superior to conventional concrete samples, demonstrating more prominent robustness and decreased localized damage but decreased residual displacement. They demonstrated that the inclusion of GFRP tube to a RC members enhanced monotonic load capacity and displacement at extreme load by 112% as well as increase in its monotonic energy absorption capacity by 488% primarily because of confinement of concrete.

Zhang et al. [48] examined potential application for base isolation to shield from explosive loading and for improving the reaction of base-isolated infrastructure during blasts without any settling earthquake-related protection. The authors researched the minimization of damage due to small and large standoff distance blasts on infrastructures by way of base isolation. The advantageous properties of utilizing base isolation to reduce inter-story drifts and total story accelerations demonstrated in seismic loading were observed under blast loading. The proposed supplemental control instruments had the capacity to uphold base isolation performance under small excitations while limiting large base isolation displacements under higher excitations. The base-level tuned mass damper (TMD) displayed reduction in root mean square values for displacement at the base, inter-story

drift, and story absolute accelerations as well. Luccioni et al. [19] examined the inclusion of different content of 60 mm long type hooked steel fibers in an 114 MPa concrete on blast tests and static response. Blast behavior is found to be enhanced by the fiber addition. Permanent deflections, spalling zone dimensions, flexural crack width, etc. are decreased with increase of fiber content. Fibers addition in HSC may also change the kind of damage, blast response, slab failure, and conserving their integrity. In contact type of blast loads, incorporation of as low as 0.5% fibers is sufficient for changing the failure mode and avoiding flexure kind of failure. In case of contact blast load, scaled distance, which causes flexural failure, diminishes with increase in fiber content. This may be because of increment of toughness and flexural strength which was noticed under stationary test conditions.

5.3 Types of blast loading

Shen et al. [34] investigated numerically the curve-shaped sandwich type of panels having aluminium face plates as well as aluminium foam, which are subjected to air blast loadings. The LS-DYNA software was utilized for modelling the physical processes, and finite element (FE) model was approved by the data obtained by experimental study. The typical results obtained experimentally demonstrated that the blast load intensity and sheet thickness were important parameters liable for the final deflection of the curved sandwich type of panels. They acquired, from computational fluid dynamics, models of blast loads acting against circle and square bridge columns. Yi et al. [45] verified the simulated results of blast loadings in LS-DYNA by using accessible blast tests on two different beams. They simulated results obtained after blast loading effects on the concrete members having element size of 25 mm. It was observed from the simulated results from the blast around 3.048 m from the piers of the bridge that detailed modeling of rebars is significantly important for the simulation of blast loading effects on concrete structures.

Mao et al. [22] experimentally examined the UHPFRC elements under close-in explosive loading. The UHPFRC panels were cast with different volume and fiber types. Static tests were conducted to examine the influence of fibers on the performance of UHPFRC samples. The experimental results demonstrated that distribution and orientation of fibers influence the behavior of UHPFRC. FE modeling was also used to study the UHPFRC slab panels subjected to blasts. No spalling was detected on the back of the slab, and the cracks occurred on the front face of the slab. From static test of UHPFRC samples, it was seen that the most extreme pressure increases with increases of fiber volume in the samples. Zhang et al. [49] examined double-skin concrete filled tubes (DSCFT) comprising two concentrically steel tubes. They also studied the performance of UHPC filled with double skin steel cylindrical columns after close-in blast loading. The axial load capacities of unimpaired round and square DSCFT samples were fundamentally the same as and were 4000 kN and 4025 kN, respectively. The damage index of all DSCFT samples were under 0.4, showing that the DSCFT samples had the capacity to hold over 60% of its axially loading capacity even after extreme blast load.

Ma et al. [20] investigated the Johnson–Cook constitutive type of model to distinguish various failure modes of the dome. The relationship among static/dynamic and collapse loads were also achieved. The results showed that single-layer reticulated domes, with huge initial stresses, may fall at dynamic loads lower than projected load. The numerical results showed that the counter institutive behavior is in existence for single-layer reticulated domes under specific conditions. They proposed that the static preloading may be limited to keep away from collapse for blast resistant design of single-layer reticulated domes. Qu et al. [30] focused on locations, charge weights, depth of initial cracks and width, and places of explosive charges, in addition to reinforcement proportions on the dynamic behavior of RC beams having cracks under air blast loading. The simulated results demonstrate comparison between beams with RC beam in terms of increase of maximum deflection, velocity at node at mid-span, stresses of concrete in compressive zone, etc. Qasrawi et al. [28] discussed the analytical study to foresee the reaction of concrete-filled FRP tubes (CFFTs) and RC members in the case of close in test and the factors affecting their reaction. The models were checked against drop weight impact lab estimation and ODOF. They demonstrated that the displacement response at peak was in reverse proportion to all the parameters. They showed experimentally improved strength and stiffness for the case of blast resistant applications. They additionally validated the experimental results obtained under impact as well as blast testing. The maximum deflection were found to be 16% of the laboratory results. They suggested that the maximum value of allowable displacement rise from 0.211 to 0.261 m in case of CFFTs to represent their added energy-absorbing capability.

Remennikov et al. [31] studied the detonation of nitromethane spherical charges under blast load over steel plates. The effectiveness of different protective elucidations were also investigated. In the study, plates of high strength steel, mild steel, and stainless steel were tested under explosive blast loading. It was observed that in stainless steel plates, peak deformations are reduced by 26% when compared with mild steel plates.

Nam et al. [24] examined blast capacity of fiber-reinforced cement concrete composite (FRCCC) elements, with

fiber content by volume of 2%, exposed to blasts test utilizing an emulsion. The cracks obtained on rear face of the micro- synthetic fibrous concrete panel because of contact blasts were significantly reduced compared to hooked end steel fiber reinforced element. In any case, the blast capacity of large hooked steel fibrous reinforced element was enhanced by hybrid micro synthetic fibers. The fracture energy of FRCCs is higher than corresponding value for high strength concrete and reinforced cement composites (RCC) without fibers. The fibers of FRCC elements altogether reduce the damage diameter and is a measure of superficial damage when contrasted with the depth of local damage. Zhang et al. [49] discussed the UHPC filled DSCFTs exposed to close-in blast loads with square section for outer and inner steel tubes. They proposed DSCFT column had the capacity to sustain large explosive load without any significant failure. Therefore, it can be utilized in structures as well as infrastructures. The analytical model of the DSCFT column was calibrated and approved against the blast tests. Contrasted with NSC, the utilization of UHPC filler in the DSCFT specimen minimized the residual deflection while the decrease in the most extreme deflection was significantly less

5.4 Strength of UHPFRC

Wu et al. [42] conducted several tests to study blast resistances of UHPFRC and reinforced ultra-high performance fiber concrete (RUHPFC) slab panels reinforced with wrapped with externally bonded (EB) fiber-reinforced polymer (FRP). It was found that RUHPFC slabs performed well and superior as compared to other slabs of other types.

Schleyer et al. [33] studied dynamic increment factor (DIF) subjected to both shear and flexural loading on UHP-FRC members under blast loading. The outcomes demonstrated that the factor should not be incorporated to enhance shear strength under high loading rates. Under flexural loading conditions, high strain rates of 1.0 s^{-1} or more may be assumed under large standoff blast wave. Yi et al. [45] evaluated properties of UHSC and RPC subjected to static loads. It was observed that both UHSC and RPC illustrate adequate workability for construction purpose. The higher compressive and split tensile strength values of UHSC and RPC specimens, obtained as 202.1 and 202.9 MPa and 9.2 and 21.4 MPa, respectively, illustrated that UHSC and RPC, are found adequate to withstand blasts, also because of increased shear capacities. Failure pattern of UHSC and RPC also demonstrated higher resistance of UHSC and RPC to blast loading compared to NSC.

Astarlioglu and Krauthammer [2] compared the behavior of the UHPFRC and NSC column having similar measurements and reinforcing details and exposed to same loading conditions. The UHPFRC columns suffered 27 and 30% lesser deformation compared with NSC columns with supported ends, and all the ends are fixed. Likewise, in case of impulse loads, the UHPFRC compression columns can continue to take 400% higher than the impulse which may affect the NSC columns to fail. The UHPFRC and NSC showed different behaviors when quasi-static loads were applied. In case of NSC, the maximum reflected pressure values for quasi-static loads demonstrated by horizontal asymptote on the load impulse diagram, were fundamentally the same as for supported and fixed edge conditions, respectively.

Aoude et al. [1] studied performance of UHPFRC columns subjected to blast loading. The influence of fibre content, concrete type, fibre properties, spacing of transverse reinforcement, and ratio of longitudinal reinforcement was investigated. It was revealed that UHPFRC columns demonstrate improved blast resistance due to reduced residual and maximum displacements, enhanced damage tolerance and elimination of fragments of secondary nature.

Nicolaides et al. [27] studied mechanical properties, rheological characteristics, as well as the effect of a few specifications on the strength improvement of the material. The fiber content utilized was equivalent to 6%. The average specific fracture energy and compressive strength acquired for this mixture were around 26,000 N/m and 175 MPa, respectively. All the essential criterion influencing UHPFRCCs behaviour were analysed experimentally. Based on research, another class of material was developed and assigned as UHPFRC. Su et al. [35] modelled the solid framework, and the straight round steel fibers are thought to be scattered randomly with Hopkinson pressure bar (SHPB) split tensile test, static split tensile tests. The behaviour of UHPC material under both extreme dynamic loading and static were studied. In view of the proposed model, static split tensile test is simulated. It was observed that the proposed model gives great material behaviour prediction under static load.

Yoo and Yoon [47] studied the behaviour of UHPFRC structures subjected to shear, flexure torsion, and blasts. The performance of UHPFRC and reinforcements under bond, which is an essential requirement for the performance of RC structures, was also examined. It was observed that the addition of 2% fibres resulted in improved post- cracking load capacity and stiffness of reinforced UHPFRC beams.

Wang et al. [39] studied clay brick masonry unit walls reinforced with polyuria under dynamic load condition. The failure modes, failure mechanisms, and peak pressure damage of spray-on polyurea reinforced clay brick masonry walls under blast loading were investigated. The polyuria layer was found to improve resistance against blast loads significantly.

Yoo and Banthia 2017 [46] examined the blast and impact resistance of UHPFRC by considering about different factors. They found that the UHPFRC can disperse a lot of energy by impact when compared with normal strength concrete having no fibers and with steel fibers. The utilization of long and straight type of steel fibers are found to be successful in enhancing the resistance of UHPFRC under impact loading contrasted with that of deformed fibers at large fiber contents. The orientation of fibers influences the impacts of UHPFRC when additional fibers are adjusted in the direction of tensile load. Additionally, improved impact resistance is accomplished.

Cadoni et al. [6] investigated direct strength at higher strain rate of UHPFRC mix design of 150, 170, and 210 MPa with the variation of fibres. The result obtained for the hardening behaviour of UHPFRC against energy dissipation. The peak behaviour were not change due to different fibre volume content.

Turker et al. [38] studied the behaviour of UHPFRC beams with hybrid fibres experimentally and analytically. Beams have been cast with exceptional reinforcement ratios. The result shows that the UHPFRC beams with better reinforcement ratio were better flexural performance, ductility, flexural capacity, and stiffness. Use of hybrid fibres in UHPFRC resulted extra efficiency in terms of flexural behaviour. The details of the parametric study of blast loading are presented in Table 2 below.

The DIF versus strain-rate relationship is, however, found to be insignificant. UHPFRC is therefore advised for its application in blast-resistant compression members instead of NSC and SCC because it bears more force for the same dimensions and reinforcing detailing. Karagozian & Case (K and C) concrete model, also known as concrete damage model, has been used to analyse concrete response to blast loading due to its simplicity in implementation. Figure 5 illustrates the stress–strain behaviour of UHPFRC. In order to investigate capacity of the K and C model to describe the behaviour of UHPFRC, this stress strain has been used [21]. The compressive and tensile values may be obtained from the quasi-static load tests. $f_d t$, $\varepsilon_{t,l}$, ε_{tp} and ε_{tu} represent tensile strain, maximum linear strain, limiting tensile strain and maximum tensile strain, respectively.

Further, σ_{cp}, $\varepsilon_{c,l}$, ε_{cp}, and ε_{cu} correspond to compressive strength, maximum linear strain, limiting compressive strain, maximum compressive strain, respectively.

It is pertinent to mention that the blast loading plays vital role, especially in strategic civil engineering structures. The behaviour of UHPFRC exposed to high strain loading is unique in relation to that under low strain rate and static

Table 2 Parametric study of blast loading

S. No	Authors	Parameters studied			
		Standoff distance (m)	Characteristics strength (MPa)	Type of loading	Magnitude of charge weight (kg)
1.	Turker et al. [38]	–	150	Surface blast	–
2.	Su et al. [35]	1.5	–	Surface blast	1, 17.5, 35
3.	Ngo et al. [25]	30, 40	–	Surface blast	6000
4.	Barnett et al. [4]	7, 9	–	Surface blast	–
5.	Foglar et al. [9]	1.675	–	Surface blast	–
6.	Qu et al. [30]	1.5	–	Surface blast	25

Fig. 5 Stress–strain relationship of UHPFRC [21]
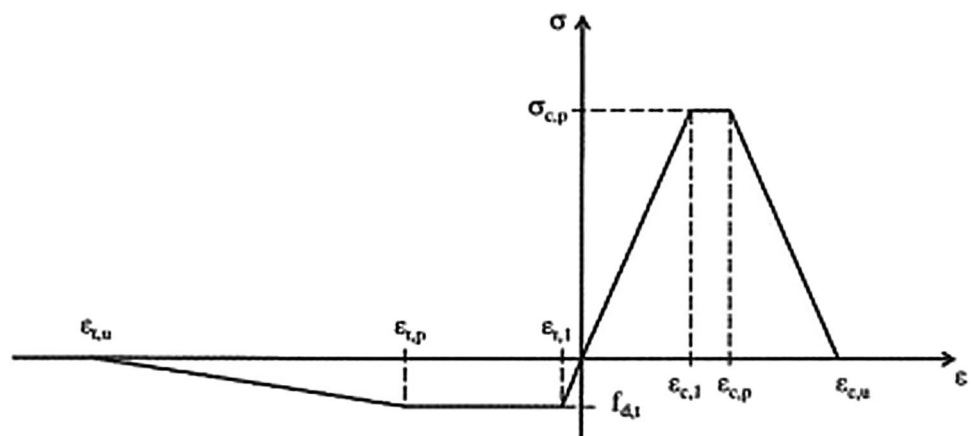
loading. With the increasing terrorism threat all over the world, more consideration is required in case of structures subjected to blast loading, which is an intricate issue as it includes material as well as geometric non-linearity, time-based deformation phenomenon, and rate of loading based material properties.

The exhaustive review of the published work conducted both experimentally as well as analytically, demonstrated that most of the investigators have made studies on NSC, HSC, and HPC with and without fibers in varying fiber content. Further, investigations have been conducted to study behaviour of beams, columns, and slab elements under the condition of below ground, on ground, and above ground blast loading conditions. Few investigators have also attempted UHPFRC to study behavior of the material under blast loading. It was observed that the influence of standoff distance, magnitude of charge weight, types of blast loading and strength was studied in the existing published literature. The impact of standoff distance, magnitude of charge weight, types of blast loading and strength of UHPFRC, however, was not studied by any investigator.

It is noteworthy to mention that the influence of parameters like standoff distance, magnitude of charge weight, types of blast loading and strength of UHPFRC structures is of paramount importance in view of present scenario of world over terrorism and war like situation across the countries. UHPFRC also possess higher resistance against high strain rates compared to NSC which is evident from full scale testing. Structural design of strategic importance using UHPFRCs subjected to severe blast loadings necessitates knowledge of material properties that govern the structural response. However, despite recent studies, several questions are yet to be answered which require extensive investigation analytically, experimentally and as specific design standards. The influence of effects of fibre volume content, type, aspect ratio, geometry, etc. of fibre reinforcement on strain rate on mechanical characteristics are still not completely understood.

On the basis of mechanical properties, UHPFRC has been found to be advantageous in case of strategic and security-related structures. The critical analysis has been used to identify the gap areas in the available research work for better understanding and to carry forward the research. The guidelines on extreme loading conditions and provisions pertaining to progressive collapse prevention need to be incorporated in the building design standards.

6 Conclusions

The influence of standoff distance, charge weight, type of blast loading with varying compressive characteristic strength has been discussed to study structural characteristics and mechanical behaviour of UHPFRC elements. Based on present study, following conclusions are drawn.

1. Shear failure has been observed as one of the dominant modes in UHPFRC under blast loading at close standoff.
2. The dynamic amplification factor and strain-rate relationship has been found to be insignificant. UHPFRC is therefore favoured for use in blast-resistant structural members.
3. UHPFRC possesses increased capacity to disseminate large amount of energy during blast loading and demonstrates improved performance after blast damage contrasted with NSC and HSC. Thus, UHPFRC can be advantageously used for blast resistant structures as it bearded more than 400% the force for same size and reinforcement.
4. Rate of sensitivity of straight steel fibres in UHPFRC increases with the decrease of diameter of fibres.
5. Inclusion of fibres to UHPFRC can change type of damage, failure pattern, and blast response without compromising on integrity of the structure. Low Strength and low ductility fibres added to UHPFRC illustrates minimal influence on the blast performance and fracture energy.
6. Detailing in UHPFRC structural elements under seismic condition offers better blast performance.

Compliance with ethical standards

Conflict of interest The author(s) declare that they have no competing interests.

References

1. Aoude H, Dagenais FP, Burrell RP, Saatcioglu M (2015) Behavior of ultra-high performance fiber reinforced concrete columns under blast loading. Int J Impact Eng 80:185–202. https://doi.org/10.1016/j.ijimpeng.2015.02.006
2. Astarlioglu S, Krauthammer T (2014) Response of normal-strength and ultra-high-performance fiber-reinforced concrete columns to idealized blast loads. Eng Struct 61:1–12. https://doi.org/10.1016/j.engstruct.2014.01.015
3. Badshah E, Naseer A, Ashraf M, Shah F, Akhtar K (2017) Review of blast loading models, masonry response, and mitigation. Shock Vib. https://doi.org/10.1155/2017/6708341
4. Barnett SJ, Millard SG, Schleyer GK, Tyas A (2010) Briefing: blast tests of fibre-reinforced concrete panels. Proc Inst Civ Eng Constr Mater 163:127–129. https://doi.org/10.1680/coma.900017
5. Brode HL (1955) Numerical solutions of spherical blast waves. J Appl Phys 26:766–775. https://doi.org/10.1063/1.1722085
6. Cadoni E, Forni D, Bonnet E, Dobrusky S (2019) Experimental study on direct tensile behaviour of UHPFRC under high

strain-rates. Constr Build Mater 218:667–680. https://doi.org/10.1016/j.conbuildmat.2019.05.152

7. De Carufel S, Dagenais F, Melançon C, Aoude H (2016) Effect of design parameters on the blast response of ultra-high performance concrete columns. In: Proceedings of the first international interactive symposium on UHPC, Iowa State University, Ames, pp 1–8. https://doi.org/10.21838/uhpc.2016.43

8. Dynamics S (1988) The spall strength of condensed. J Mech Phys Solids 36(3):353–384

9. Foglar M, Hajek R, Kovar M, Štoller J (2015) Blast performance of RC panels with waste steel fibers. Constr Build Mater 94:536–546. https://doi.org/10.1016/j.conbuildmat.2015.07.082

10. Goel M, Vasant M, Gupta A (2012) An abridged review of blast wave parameters. Def Sci J 62:300–306. https://doi.org/10.14429/dsj.62.1149

11. Ha JH, Yi NH, Choi JK, Kim JHJ (2011) Experimental study on hybrid CFRP-PU strengthening effect on RC panels under blast loading. Compos Struct 93:2070–2082. https://doi.org/10.1016/j.compstruct.2011.02.014

12. Hassan AMT, Jones SW, Mahmud GH (2012) Experimental test methods to determine the uniaxial tensile and compressive behaviour of ultra high performance fibre reinforced concrete (UHPFRC). Constr Build Mater 37:874–882. https://doi.org/10.1016/j.conbuildmat.2012.04.030

13. Held M (1983) Blast waves in free air. propellants. Propellants Explos Pyrotech 8:1–7. https://doi.org/10.1002/prep.19830080102

14. Kim JHJ, Yi NH, Oh IS, Lee HS (2010) Blast loading response of ultra high performance concrete and reactive powder concrete slabs. In: Proceedings of FraMCos-7. pp 1715–1722

15. Kratz RD (2001) A philosophy for blast resistant design. Struct Mech Comput 2:1051–1059

16. Li J, Wu C, Hao H (2015) An experimental and numerical study of reinforced ultra-high performance concrete slabs under blast loads. Mater Des 82:64–76. https://doi.org/10.1016/j.matdes.2015.05.045

17. Li J, Wu C, Hao H, Su Y (2015) Investigation of ultra-high performance concrete under static and blast loads. Int J Prot Struct 6:217–234. https://doi.org/10.1260/2041-4196.6.2.217

18. Li J, Wu C, Su Y, Li Z-X (2017) A study of concrete slabs with steel wire mesh reinforcement under close-in explosive loads. Int J Impact Eng 110:242–252. https://doi.org/10.1016/j.ijimpeng.2017.01.016

19. Luccioni B, Isla F, Codina R, Ambrosini D, Zerbino R, Giaccio G, Torrijos MC (2017) Effect of steel fibers on static and blast response of high strength concrete. Int J Impact Eng 107:23–37. https://doi.org/10.1016/j.ijimpeng.2017.04.027

20. Ma J, Fan F, Wu C, Zhi X (2015) Counter-intuitive collapse of single-layer reticulated domes subject to interior blast loading. Thin Walled Struct 96:130–138. https://doi.org/10.1016/j.tws.2015.08.001

21. Mao L, Barnett S, Begg D, Scheleyer G, Wight G (2014) Numerical simulation of ultra high performance fibre reinforced concrete panel subjected to blast loading. Int J Impact Eng 64:91–100. https://doi.org/10.1016/j.ijimpeng.2013.10.003

22. Mao L, Barnett SJ, Tyas A, Warren J, Schleyer GK, Zaini SS (2015) Response of small scale ultra high performance fibre reinforced concrete slabs to blast loading. Constr Build Mater 93:822–830. https://doi.org/10.1016/j.conbuildmat.2015.05.085

23. Mcvay MK (1988) Spall damage of concrete structures. US Army Corps Eng 1

24. Nam J, Kim H, Kim G (2017) Experimental investigation on the blast resistance of fiber-reinforced cementitious composite panels subjected to contact explosions. Int J Concr Struct Mater 11:29–43. https://doi.org/10.1007/s40069-016-0179-y

25. Ngo T, Mendis P, Krauthammer T (2007) Behavior of ultrahigh-strength prestressed concrete panels subjected to blast loading. J Struct Eng 133:1582–1590. https://doi.org/10.1061/(ASCE)0733-9445(2007)133:11(1582)

26. Ngo T, Mendis P, Gupta A, Ramsay J (2007) Blast loading and blast effects on structures—an overview. EJSE Spec Issue Load Struct 7:76–91

27. Nicolaides D, Kanellopoulos A, Petrou M, Savva P, Mina A (2015) Development of a new ultra high performance fibre reinforced cementitious composite (UHPFRCC) for impact and blast protection of structures. Constr Build Mater 95:667–674. https://doi.org/10.1016/j.conbuildmat.2015.07.136

28. Qasrawi Y, Heffernan PJ, Fam A, ASCE AM (2016) Numerical modeling of concrete-filled FRP tubes' dynamic behavior under blast and impact loading. J Struct Eng 142(2):04015106. https://doi.org/10.1061/(asce)st.1943-541x.0001370

29. Qasrawi Y, Heffernan PJ, Fam A, ASCE M (2015) Performance of concrete-filled FRP tubes under field close-in blast loading. J Compos for Constr 19(4):04014067. https://doi.org/10.1061/(asce)cc.1943-5614.0000502

30. Qu Y, Li X, Kong X, Zhang W, Wang X (2016) Numerical simulation on dynamic behavior of reinforced concrete beam with initial cracks subjected to air blast loading. Eng Struct 128:96–110. https://doi.org/10.1016/j.engstruct.2016.09.032

31. Remennikov A, Ngo T, Mohotti D, Uy B, Netherton M (2017) Experimental investigation and simplified modeling of response of steel plates subjected to close-in blast loading from spherical liquid explosive charges. Int J Impact Eng 101:78–89. https://doi.org/10.1016/j.ijimpeng.2017.03.024

32. Roller C, Mayrhofer C, Riedel W, Thoma K (2013) Residual load capacity of exposed and hardened concrete columns under explosion loads. Eng Struct 55:66–72. https://doi.org/10.1016/j.engstruct.2011.12.004

33. Schleyer GK, Barnett SJ, Millard SG, Wight G (2010) Modelling the response of UHPFRC panels to explosive loading. Struct Under Shock Impact XI 113:173–184. https://doi.org/10.2495/SU100151

34. Shen J, Lu G, Zhao L, Qu Z (2011) Response of curved sandwich panels subjected to blast loading. J Perform Constr Facil 25:382–393. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000234

35. Su Y, Li J, Wu C, Wu P, Tao M, Li X (2017) Mesoscale study of steel fibre-reinforced ultra-high performance concrete under static and dynamic loads. Mater Des 116:340–351. https://doi.org/10.1016/j.matdes.2016.12.027

36. TM 5-1300 (1990) Structures to resist the effects of accidental explosions. Joint Departments of the Army, Air Force and Navy Washington, DC

37. Tayeh BA, Bakar BHA, Johari MAM, Voo YL (2013) Utilization of ultra-high performance fibre concrete(UHPFC) for rehabilitation—a review. Procedia Eng 54:525–538. https://doi.org/10.1016/j.proeng.2013.03.048

38. Turker K, Hasgul U, Birol T, Yavas A, Yazici H (2019) Hybrid fiber use on flexural behavior of ultra high performance fiber reinforced concrete beams. Compos Struct 229:111400. https://doi.org/10.1016/j.compstruct.2019.111400

39. Wang F, Kong Y, Wan M, Chong K, Lim H, Lim M (2008) Reinforced concrete slab subjected to close-in explosion. LS-DYNA Anewnderforum, Bamgerg, pp 21–28

40. Williams GD, Williamson EB, M ASCE (2011) Response of reinforced concrete bridge columns subjected to blast loads. J Struct Eng 137:903–913. https://doi.org/10.1061/(ASCE)ST.1943-541X.0000440

41. Wu C, Huang L, Oehlers DJ (2011) Blast testing of aluminum foam-protected reinforced concrete slabs. J Perform Constr Facil

25:464–474. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000163

42. Wu C, Oehlers DJ, Rebentrost M, Leach J, Whittaker AS (2009) Blast testing of ultra-high performance fibre and FRP-retrofitted concrete slabs. Eng Struct 31:2060–2069. https://doi.org/10.1016/j.engstruct.2009.03.020

43. Xu J, Wu C, Xiang H, Su Y, Li Z-X, Fang Q, Hao H, Liu Z, Zhang Y, Li J (2016) Behaviour of ultra high performance fibre reinforced concrete columns subjected to blast loading. Eng Struct 118:97–107. https://doi.org/10.1016/j.engstruct.2016.03.048

44. Yi N-H, Kim J-HJ, Han T-S, Cho Y-G, Lee JH (2012) Blast-resistant characteristics of ultra-high strength concrete and reactive powder concrete. Constr Build Mater 28:694–707. https://doi.org/10.1016/j.conbuildmat.2011.09.014

45. Yi Z, Agrawal AK, Ettouney M, Alampalli S, ASCE F (2014) Blast load effects on highway bridges i: modeling and blast load effects. J Bridg Eng 19(4):04013023(1–17). https://doi.org/10.1061/(asce)be.1943-5592.0000547

46. Yoo D-Y, Banthia N (2017) Mechanical and structural behaviors of ultra-high-performance fiber-reinforced concrete subjected to impact and blast. Constr Build Mater 149:416–431. https://doi.org/10.1016/j.conbuildmat.2017.05.136

47. Yoo D, Yoon Y (2016) A review on structural behavior, design, and application of ultra-high-performance fiber-reinforced concrete. Int J Concr Struct Mater 10:125–142. https://doi.org/10.1007/s40069-016-0143-x

48. Zhang F, Wu C, Li Z-X, Zhao X-L (2015) Residual axial capacity of CFDST columns infilled with UHPFRC after close-range blast loading. Thin Walled Struct 96:314–327. https://doi.org/10.1016/j.tws.2015.08.020

49. Zhang F, Wu C, Zhao X-L, Heidarpour A, Li Z (2017) Experimental and numerical study of blast resistance of square CFDST columns with steel-fibre reinforced concrete. Eng Struct 149:50–63. https://doi.org/10.1016/j.engstruct.2016.06.022

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.