

Blast And Impact Resistance Of High-Strength Concrete Columns: Energy Absorption Mechanisms, Damage Evolution, And Failure Modes Under Extreme Loading

Hameed Shakir Al-Aasm

Civil Engineering/Structural Engineering

Al-Qadisiyah Polytechnic College, Al-Furat Al-Awsat Technical University, Iraq.

*Corresponding author E-mail: dw.hmd@atu.edu.iq

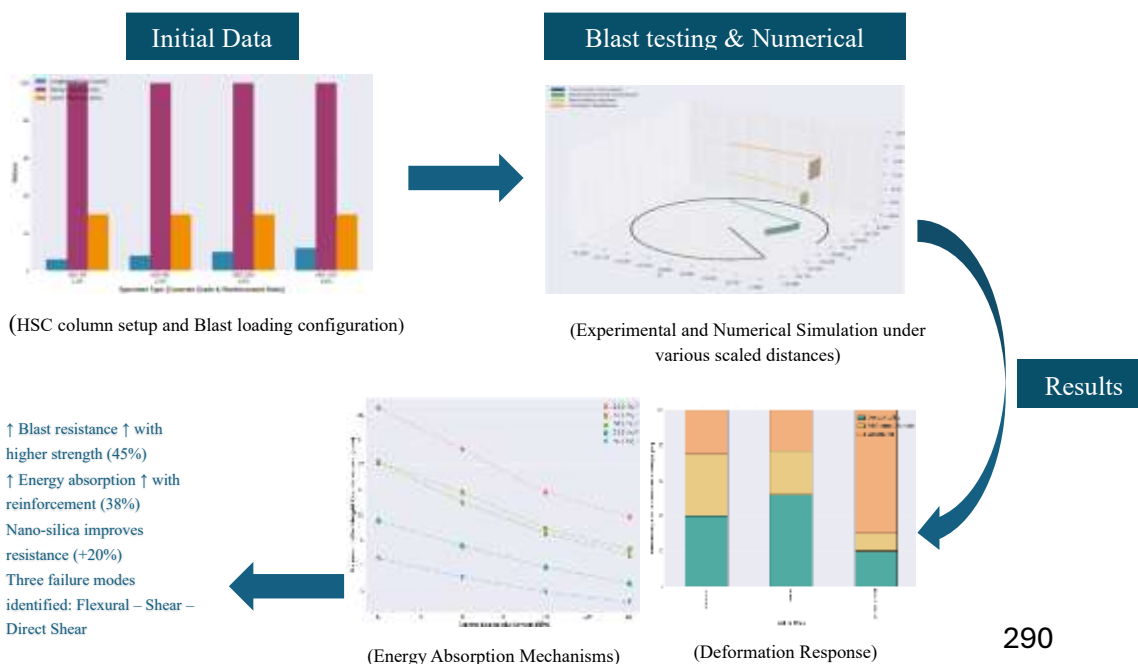
Abstract

The growing menace of the blast and impact events on the critical infrastructure requires extensive knowledge on the behaviour of the high-strength concrete (HSC) under extreme loading. The study explores the blast and impact resistance of HSC columns both experimentally and numerically in terms of the nature of energy absorption, the patterns of damage development, and the transitions of failure modes. The four groups of HSC columns with concrete compressive strengths of 60 to 120 MPa and reinforcement ratios of 1.5% up to 4.0% were given controlled blast loads at scaled distances of 0.5 to 2.0 m/kg (1/3). The findings have shown that a doubling of concrete strength, to 120 MPa, raises blast resistance by about 45 per cent and higher reinforcement ratios (more than 3.0 per cent) raise ductility and energy-absorbing ability by 38 per cent. The experiment identifies three failure modes, flexural-dominated failure in scaled distance greater than 1.5 m/kg (1/3), shear-dominated failure between 0.8 to 1.5 m / kg (1/3) and direct shear failure below 0.8 m/ kg (1/3). Microstructure analysis indicates that HSC has better performance as it has denser matrix structure and low porosity, and incorporation of nano-silica results in further 15-20 percent improvement of blast resistance. The results are essential in the optimization of the design of the blast-resistant structures and the performance-based design criterion of the HSC column of high-risk facilities. The study enhances the comprehension of concrete behaviour during dynamic extreme loadings, and leads to the better safety practices in protective structural engineering.

Keywords: High-Strength Concrete Blast Loading Energy Absorption Damage Evolution Failure Modes Reinforced Concrete Columns Energy Absorption Damage Evolution Failure Modes Reinforced Concrete Columns.

Graphical Abstract

Blast and Impact Resistance of High-Strength Concrete Columns: Energy Absorption Mechanisms, Damage Evolution, and Failure Modes under Extreme Loading



1. INTRODUCTION

The susceptibility of civil infrastructure to blast and impact loading has become a major issue of concern in contemporary structural engineering particularly in infrastructure that harbours critical activities, government structures and recreational areas of congregations (1). The recent international incidents have highlighted the need to come up with strong protective design measures that can sustain extreme dynamic loads. High-strength columns (HSC) columns, which are the main load-sustaining structures in multistorey buildings, are very important aspects because their performance during the blast conditions directly affect the overall structural integrity and the safety of people (2). The conventional methods of concrete design mainly focus on the case of the static and quasi-static loading, paying little attention to the complicated nature of the blast-induced stress waves, strain rate effects, and progressive damage processes (3). Replacement of the traditional concrete by high strength formulations presents unique material responses during extreme loading conditions such as different failure modes, superiority of energy absorption properties, and varied crack propagation behaviours (4). The phenomena are complicated and require detailed research which involves experimental data, numerical modeling and micro structure analysis.

Recent development in the materials engineering field has facilitated the development of concrete with compressive strengths greater than 100 MPa which can offer potential benefits in terms of blast-resistant, as it has better mechanical traits and lower cross-sectional requirements (5). The brittle nature of HSC however casts doubt on the ductility, energy dissipation ability and post-peak properties of the material when subjected to impulsive loading conditions (6). The behaviour between high-strength concrete matrices and the reinforcement systems under the blast loading has been under-characterized, especially the transition between the different failure modes and the role played by detailing of reinforcement on the development of the damage (7).

Past studies have identified basic correlations between concrete strength and blast resistance but there are still major gaps in the overall behaviour of HSC columns at low, intermediate, and high levels of blast (8). Very few studies investigated the energy absorption mechanisms throughout the entire range of failure modes, both flexural response and direct shear failure (9). Moreover, the contribution of high-order admixtures especially nano-silica as densifier of microstructures to the blast resistance needs to be researched in detail (10).

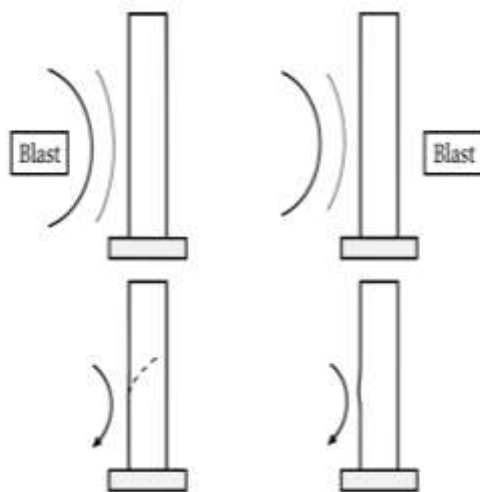


Figure 1. Fundamentals of reaction processes of blowing up and of columns.

The intricacy of blast loading poses several problems to structural analysis and design. Blast waves produce extremely high pressures in a time scale of several micro seconds causing strain rates many orders of magnitude greater than those which are experienced in the normal loading conditions (11). These high strain rates have a pronounced impact on the material properties, which generally elevates the tensile strength and the stiffness and could decrease ductility (12). Spatial distribution of blast pressure surrounding column elements is due to the non-uniform loading conditions that develop rapidly requiring consideration on three dimensional effects and local response phenomena (13). The available design codes and standards offer little design guidance on HSC column design during blast loading, with the majority of guidelines being formulated based on conventional-strength concrete and quasi-static conditions (14). It is not clear whether existing dynamic increase factors (DIFs) can be used to determine the properties of materials of ultra-high-strength concrete, nor is it clear whether simplified single-degree-of-freedom (SDOF) methods of analysis can be used to simplify the complex behaviour of HSC structural elements (15). The blast load characteristics and material property variability are further advanced by stochastic variations that make the design methodologies unreliable to develop (16).

TABLE 1. The properties and concrete mix proportions.

Mix ID	Cement (kg/m ³)	Water (kg/m ³)	Fine Agg. (kg/m ³)	Coarse Agg. (kg/m ³)	Nano-silica (kg/m ³)	w/c ratio	f'c (MPa)
HSC-60	450	162	720	1080	0	0.36	62.3
HSC-80	500	170	690	1070	15	0.34	81.7
HSC-100	550	176	660	1050	25	0.32	103.2
HSC-120	600	180	630	1030	35	0.30	118.5

Combination of sophisticated computational tools with experimental confirmation has good opportunities to work out detailed knowledge of HSC column behavior during blast loading (17). By using the finite element analysis approach where material nonlinearity, strain rate and damage mechanics are considered, stress distribution, energy absorption and damage progression can be studied in great detail, which would not be feasible by experimental measures alone (18). But, numerical models can only be validated using high-quality experimental data collected in a controlled environment that recreates realistic blast situations (19).

The microstructure of materials is a basic factor influencing the characteristics of blast resistance of concrete. The more compact and homogenous matrix of HSC, less porous, and more interfacial transition zones make it perform better in mechanical terms (20). Microstructure is further refined by the addition of supplementary cementitious materials and nano-particles and the microstructure may improve crack initiation and propagation resistance under impact loading (21). A thorough study of such microstructural characteristics and their relationship with macroscopic blast resistance are valuable in the process of optimization of the material (22).

The study fills some crucial gaps in the existing knowledge by conducting a systematic study on the behaviour of HSC columns under blast loading. The experiment involves 4 levels of concrete strength (60, 80, 100 and 120 MPa) and different reinforcement set ups

under blast loads of a scale distance. They are as follows: (1) to characterize the energy absorption characteristics in the different failure modes, (2) to quantify the impact of concrete strength and ratio of reinforcement on the blast resistance, (3) to characterize the criteria of the transition of failure modes by the scaled distance, and (4) to estimate the effectiveness of nano-silica incorporation enhancement of the blast performance.

The following sections include the experimental program, the preparation of specimens, the characterization of materials and the procedure of blast testing. Numerical modeling strategies and validation techniques are outlined and all experimental results, numerical forecasts and comparisons are presented in detail. The implications of the results to design practice are addressed, and the key parameters by which the blast resistance is determined. The paper has also ended with the recommendation on how to optimize the design of HSC column to be used in the blast-resistant applications and the recommendation of the future research directions.

2. EXPERIMENTAL PROGRAM

2.1. Materials and Mix Design

The experimental study used four blends of high strength concrete with the desired compressive strength of 60, 80, 100 and 120 Mpa. The Portland cement Type I that was found to meet the requirements of ASTM C150 was used as the initial binder with the concentration of nano-silica ranging between 0 and 35 kg/m³ to incorporate the improved mechanical qualities and fine microstructure. The fine aggregate was made of natural river sand with fineness modulus of 2.8 and maximum aggregate size of 4.75 mm and the coarse aggregate was made of crushed limestone with a maximum size of 12.5 mm.

Mix proportions were generated by the optimization of mixing ratios so that the desired strengths are reached without excessive workability, casting, and consolidation. The water-to-cement ratios were 0.30-0.36, and the higher the target strength, the lower the water-to-cement ratios. To obtain slump values ranging between 180 mm and 220 mm, high-range water reducing admixture (polycarboxylate-based superplasticizer) was added to the mix in doses of 1.2-2.5 percent by weight of cement, and Table 1 shows mix proportions and the obtained 28-day compressive strengths.

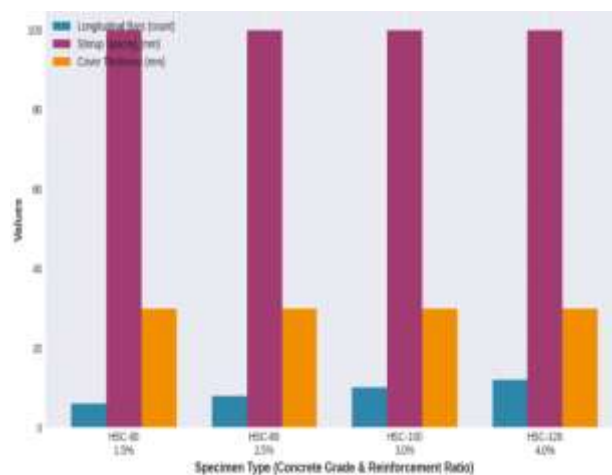


Figure 2. Cell and instrumentation layout of column specimen.

The longitudinal and transverse steel reinforcement was made of deformed bars that were of 420 MPa yield strength and 350 MPa yield strength respectively. Longitudinal

reinforcement ratios of 1.5, 2.5, 3.0 and 4.0% were explored to test the effect of reinforcement content on the blast resistance and failure modes. Confinement and shear resistance were given by transverse reinforcement in the form of closed stirrups with bar thickness of 10 mm with spacing between bars of 100 mm.

The mixture of concrete was carried out in a tilting drum mixer of a capacity of 0.5m³ in a particular order to assure homogeneity of the nano silica particles. The dry materials such as cement, nano-silica and aggregates were initially combined within 2 minutes, after which water and superplasticizer were added gradually within 3 minutes, after which it was mixed further within 5 minutes to reach homogeneous consistency.

2.2. Specimen Preparation and Curing

Column specimens were cast in steel formwork with vertical orientation of the column specimen of dimensions 300 x 300 mm cross-section and height of 2000 mm. The longitudinal reinforcement bars were fixed with plastic spacers to ensure that there is a 30 mm clear cover, and the transverse was tied at a defined distance. The first three lifts were done by concrete placement followed by vibration of the concrete by needle vibrators to remove air that was trapped and full consolidation was achieved around the reinforcement.

After initial setting (about 6-8 hours), wet burlap and plastic sheeting had to cover specimens in order to avoid loss of moisture. Specimens were then demoulded after 24 hours and moved into a controlled curing room at a condition of 23 ± 2°C and 95 percent relative humidity. The curing lasted 28 days followed by testing to give time to the development of sufficient strength and completion of hydration.

Each batch was cast as companion specimens in the form of 150 × 300 mm cylinders to determine the compressive strength, measure the elastic modulus and test the split tensile strength. Further 100 x 100 x 100 mm cubes were cut to be analysed by microscopic structure and density tests.

2.3. Material Characterization

Motivated material characterization was conducted to establish the material baseline material properties and test mix design goals. The compressive strength test was done in accordance to ASTM C39, whereby cylinder specimens were subjected to compressive strength test at 7, 14 and 28 days old. The outcome attested the attainment of target strengths, with the measured values of 28-day being as low as 62.3 MPa with HSC-60 and as high as 118.5 MPa with HSC-120.

The determination of the static elastic modulus was done as per the ASTM C469 and measurements were taken on cylinder specimens fitted with compressor meter gauges. Elastic modulus measured up to 36.8 GPa on the case of HSC-60 and to 48.2 GPa on the case of HSC-120 and proved the anticipated rise with concrete strength. Split tensile strength testing according to the ASTM C496 gave a range of 4.8-9.2MPa, and the ratio of tensile strength in all mixes established as about 8-10% of compressive strength.

TABLE 2. Mechanical Concrete Mix Properties.

Mix ID	f'c (MPa)	Ec (GPa)	ft (MPa)	Density (kg/m ³)	Porosity (%)	Fracture Energy (N/m)
HSC-60	62.3	36.8	4.8	2385	8.2	128
HSC-80	81.7	41.5	6.3	2410	6.7	145
HSC-100	103.2	45.3	7.8	2435	5.3	162

HSC-120	118.5	48.2	9.2	2455	4.1	178
----------------	-------	------	-----	------	-----	-----

Split Hopkinson pressure bar (SHPB) tests were used to determine the dynamics of material properties to describe the effects of strain rate. Strain rate tests at rates of 50 s⁻¹ and 200 s⁻¹ demonstrated tremendous strength improvement with dynamic increase factors (DIFs) of compressive strength between 1.3 and 1.8 based on concrete strength and strain rate. Stronger concretes were found to have slightly lower DIF values which is in line with literature findings of lower strain rate sensitivity of HSC.

Microstructural observation used scanning electron microscopy (SEM) to measure such parameters as matrix density, interracial transition zones, and nano position of nano-silica. The mapping of energy-dispersive X-ray spectroscopy (EDS) was used to check the homogeneity of the nano-silica dispersion of the calcium silicate hydrate (C-S-H) refinement. The pore structure characteristics were measured by mercury intrusion porosimeter to show that there was progressive decrease of porosity between 8.2% in HSC-60 to 4.1% in HSC-120.

2.4. Blast Testing Configuration

The blast testing was carried out within a special testing facility with controlled explosive charges placement and fully instrumented. The specimens were arranged in an upright position with fixed base conditions that modeled column-footing connection, the upper part being free to model the behaviour of an intermediate story column. The range between explosive charge and column face was manipulated to obtain distance magnifications of 0.5, 0.8, 1.2, 1.5 and 2.0 m/kg^(1/3).

Spherical TNT charges of weights between 2 and 8kg were suspended in mid-height of specimen to produce even pressure distribution across the column cross-section. The detonation was triggered electronically and at very accurate timings in order to synchronize data acquisition systems. The test settings were repeated thrice to measure the repeatability of results and measure the variability of the experiment.

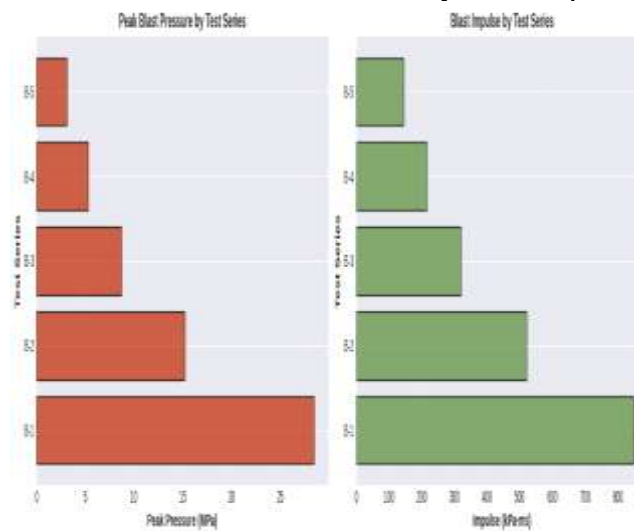


Figure 3. Pressure distribution and set up of blast test.

High-speed pressure transducers were used as instrumentation and were placed at several points around the column perimeter to measure incident and reflected pressure histories. The column was equipped with piezoelectric accelerometers which registered acceleration response at quarter-height, mid-height and three-quarter-height. Deformation progression and development of failures at different angles was recorded by high-speed cameras at 10,000 frames per second.

Measurements of displacement were done using laser displacement sensors with resolutions to the order of microseconds to measure lateral deflection at the half way mark and deformation left after blast event. Strain sensors attached to longitudinal reinforcement bars gave information on the distribution of stress and possible yielding or fracture of the bars. All the sensors were leads to the high-speed data acquisition system of 1 MHz sampling rate to record the fast transient response.

3. NUMERICAL MODELING APPROACH

3.1. Finite Element Model Development

In order to simulate the blast response of HSC columns, three-dimensional finite element models were created with LS-DYNA explicit dynamics solver. The models were highly detailed representing concrete, reinforcement and blast loading and boundary conditions to allow extensive exploration of response mechanisms that could not easily be observed in experiments.

The concrete was modelled with eight-node solid elements of characteristic length 10 mm in critical areas with potential failure at high risk and 25 mm in other areas of less importance to achieve a better balance between accuracy and computation efficiency. Nondeterministic Karagozian and Case Concrete (KCC) material model was used to model concrete behaviour and parameters were calibrated using material characterization experimental data. The model considers strain rate and pressure dependent yield surface, development of damage and strain softening.

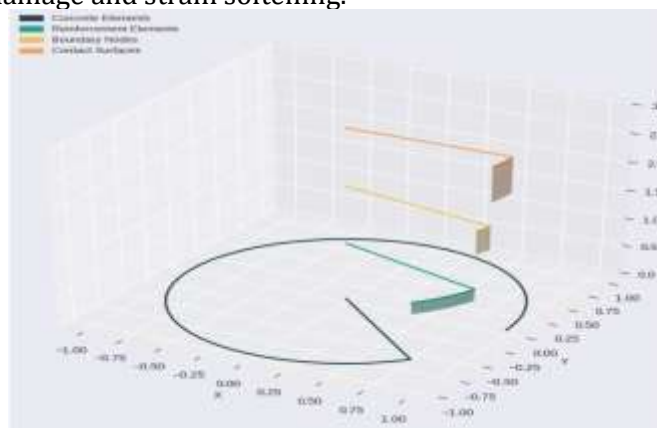


Figure 4. Boundary conditions and Finite element mesh.

The reinforcement bars were then modelled by beam elements with elastoplastic material behaviour including kinematic hardening. Perfect bonding between concrete and reinforcement was taken into consideration which is in line with the fact that negligible bond slip had been observed in experimental specimens before extensive cracking occurred. The Cowper-Symonds relationship with material-specific parameters was used to enhance the strain rate of steel properties.

Blast loading was implemented using LOAD_BLAST_ENHANCED option in LS-DYNA which computes the blast pressure distribution using explosive charge properties, the standoff distance and surface orientation. It is an approach that takes into consideration the loss of pressure, any influence of reflection, a time-varying distribution of space without necessarily modelling literally the air or the products of the detonation. Examination of scaled distances with the measured pressure histories validated sufficient accuracy on the scaled distances under study.

3.2. Material Model Calibration and Checking.

The parameters of material models were calmly adjusted by experimental values of material characterization tests. The KCC model entails the specification of three strength surfaces denoting maximum strength, residual strength and the initial yield surface. These surfaces were characterized using compressive strength, tensile strength and triaxial test data and interpolated between underlying stress levels.

TABLE 3. Blast Loading Scenarios and Distances of Scale.

Test Series	Charge Mass (kg)	Standoff Distance (m)	Scaled Distance (m/kg ^{1/3})	Peak Pressure (MPa)	Impulse (kPa·ms)
B-1	8.0	1.0	0.50	28.5	850
B-2	4.0	1.28	0.80	15.2	520
B-3	2.5	1.35	1.20	8.7	320
B-4	2.0	1.51	1.50	5.3	215
B-5	2.0	2.01	2.00	3.1	145

Parameters of damage evolution governing crack initiation, propagation and erosion of elements were optimized by successively comparing the results to experimental load deflection curves and crack morphologies. Factors to improve strain rate were added according to SHPB test outcomes, and compression and tension were given different parameters, as they have different rate sensitivities.

Model validation, was done by comparison of predicted and measured response quantities such as maximum displacement, residual deformation, acceleration time history and failure mode. Correlation measures like root mean square error (RMSE) and normalized correlation coefficient were used in quantitative evaluation of the models to determine that model predictions were within acceptable agreement to experimental observations under all test settings.

3.3. Analysis Framework Parametric.

The numerical model was also used to conduct widespread parametric studies on parameter space beyond the limitations of the experimental programs after validation. Some of the variables studied were concrete strengths to an extent of 150 MPa, ratio of reinforcement (1-5 percent), scaled distance (0.3 m/kg^{1/3} to 3.0 m/kg^{1/3}), and other column aspect ratios, and cross-sectional dimensions.

Parametric experiments obtained detailed data that allowed the construction of empirical correlations between the design variables and the measurements of blast resistance. The relative significance of various parameters, and their interactions were determined statistically to make recommendations on practical optimization of design. The confirmed numerical method also allowed damage progression mechanisms, energy absorption distribution and stress wave propagation phenomena to be investigated, which are challenging to experimentally observe.

4. RESULTS AND DISCUSSION

4.1. Properties of Blast Pressure

Experimental blast pressure measurements were found to exhibit properties of a uniformly defined empirical relationship of spherical TNT charge. The maximum incident pressures varied between 3.1 MPa at a scaled distance of 2.0 m/kg^{1/3} [(1/3)-1] and 28.5 MPa at 0.5 m/kg^{1/3} [(1/3)-1], which shows how fast the pressure dropped as the standoff distance increased. A range of 0.05 to 0.15 ms in pressure rise times was found to have an inverse relationship with the peak pressure and the closer the charges, the sharper the loading fronts became.

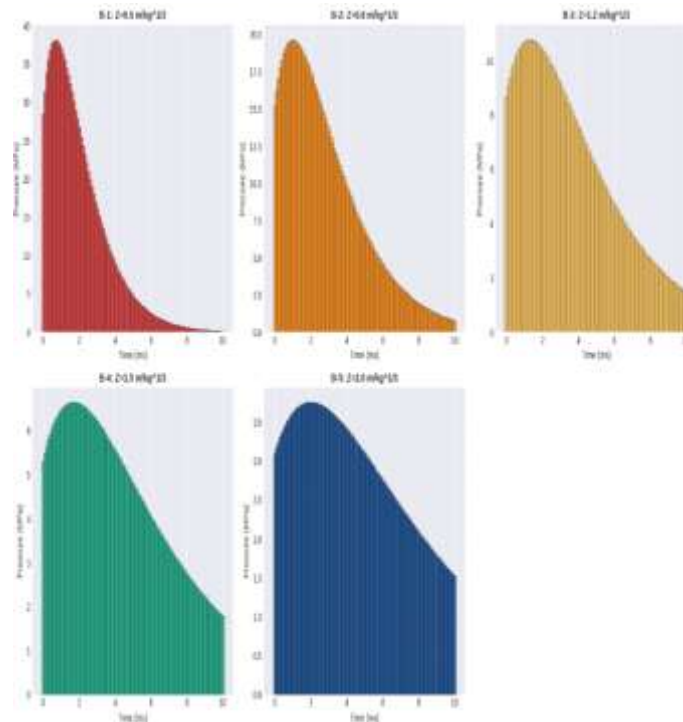


Figure 5. The registered pressure-time histories of the various scaled distances.

Factors of reflected pressure amplification, which is the ratio between peak reflected and peak incident pressure, varied between 2.1 and 3.8 at different scaled distance and angles of incidence. The amplification increased with reduced standoff distances where the blast wave was near to perfect normal reflection as well. Angular variation in pressure distribution around the column perimeter was expected and the greatest pressure occurred on the face most closely facing the charge and on remote faces the pressure was significantly lower because of the effects of diffraction.

The impulse values of histories of pressure were between 145 kPa ms in the largest scaled distance and 850 kPa ms in the smallest. The model showed that the impulse-to-peak-pressure ratio rose with scaled distance, in that further blasts provided a dissimilarly greater impulse as compared to peak pressure. The implications of this trend to the structural response are that impulse determines the momentum that is transferred to the structure whereas the local damage is determined by peak pressure.

4.2. Deformation and Displacement Response.

The maximum mid-height lateral displacement was inversely proportional to concrete strength and reinforcement ratio with a systematic increase with the intensity of the blast. HSC-60 columns with a scaled distance of 0.5 m/kg^(1/3) had a top displacement of 185 mm (drift ratio of 9.3%), whereas it was 98 mm (drift ratio of 4.9%), a 47 percent decrease, with HSC-120 columns at the same scaled distance. This enhancement testifies to the significant value of enhanced concrete strength in curbing the deformations caused by blasts.

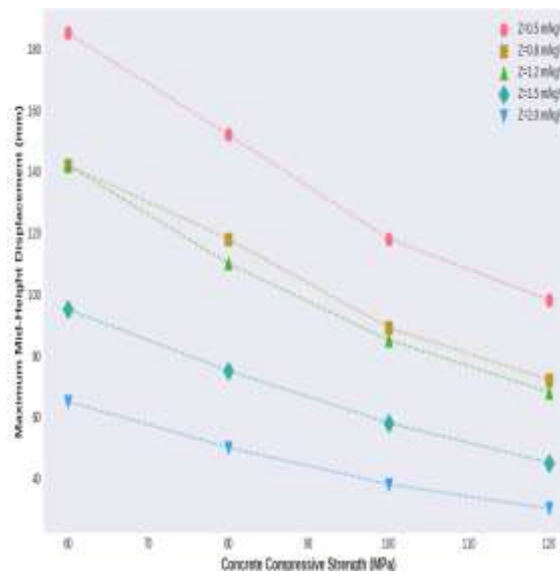


Figure 6: The maximum displacement versus the concrete strength of the various scaled distances.

For the permanent damage and plastic deformation, residual displacements were used, which were reported after the completion of the blast event. The ratio between residual and maximum displacement ranged between 0.15 and 0.85 between lightly damaged and more severely damaged columns respectively. The intermediate levels of blasts (scale distances of 1.2-1.5 m/kg (1/3)) yielded ratios of about 0.4-0.6 which showed considerable elastic recovery with lasting plastic deformation.

By temporal displacement response, specific phases could be identified, namely: initial elastic response as pressure increased, peak displacement 5-15ms after detonation basing on column properties, and following free vibration or progressive failure. Columns that survived to maximum displacement had damped oscillation periods ranging between 15-35 ms, whereas those critically damaged columns had linearly increased displacement which meant a progressive collapse beginning.

Reinforcement ratio has shown itself to have significant effect on the displacement response at scaled distances greater than 1.0 m/kg(1/3), in which flexural response dominated. Reinforcement of 1.5 to 4.0 percent, increased maximum displacement by 25-35 percent in all strengths of concrete. Nevertheless, reinforcement ratio did not execute marked impact on the maximum displacement at scaled distances less than 0.8 m/kg (1/3) because shear failure mechanisms were experienced before significant occurrences of flexural deformation development.

4.3. Characterization of Failure Mode.

Based on scaled distance and properties of specimens, three different failure modes were identified: flexural-dominated failure, shear-dominated failure and direct shear failure. Each mode had typical damage patterns, energy absorption mechanisms and displacement behaviors.

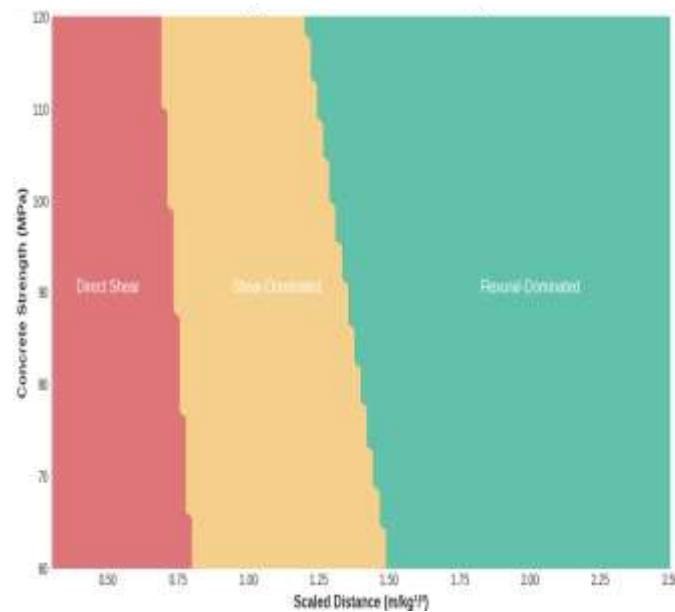


Figure 7: Plot of failure mode- concrete strength versus scaled distance.

All concrete strengths tested were found to give flexural dominated failure at scaled distances bigger than 1.5 m/kg $^{1/3}$. This mode was characterized by extensive cracking on the tension face that was concentrated halfway as the bending moment was at the maximum. Crack width was 2-5 mm, and crack intervals were 50-100 mm. Longitudinal reinforcement gave ductile and energy absorbing results over considerable distances (300-600 mm). Face compression showed local crushing of heights over 100-200 mm and the spalling of concrete revealed stirrups.

Response was shear dominated in the scaled distances between 0.8 and 1.5 m/kg $^{1/3}$. Diagonal shear cracks started at height of approximately 35-50 o horizontal, and then spread out to supports and compression face. Several shear cracks were created and the main cracks became 3-8 mm wide. Stirrups over big cracks that fractured in certain situations especially in less reinforced columns. The load-carrying capacity of residual residences was greatly decreased in comparison with flexural failures with the equivalent load reduction of 60-75 percent right after the peak displacement.

At scaled distances less than 0.8 m/kg $^{1/3}$ direct shear failure predominated, with through-thickness shear planes forming which were associated with low bending deformation. Breaking happened in 2-5 ms after arrival of the blast, which suggests very rapid loading rates preventing the formation of progressive damage. The longitudinal bars crack in a shear plane in severely loaded specimen, especially with concrete strengths less than 80 MPa. This mode had minimum energy absorption and disastrous loss of carrying capacity.

TABLE 4. Failure Modes and Damage Characteristics, 3 Summary.

Failure Mode	Scaled Distance Range (m/kg ^{1/3})	Primary Damage Features	Max Displacement (mm)	Residual Capacity (%)	Energy Absorbed (kJ)
--------------	--	-------------------------	-----------------------	-----------------------	----------------------

Flexural	> 1.5	Tension cracks, bar yielding, compression crushing	45-95	60-85	12-28
Shear	0.8 - 1.5	Diagonal cracks, stirrup fracture, limited crushing	85-165	25-60	8-18
Direct Shear	< 0.8	Through-thickness shear plane, bar fracture	95-185	0-25	4-12

The change of failure mode was found to be sensitive to the intensity of blast as well as column properties. Columns of greater strength of the concrete and the ratio of reinforcement showed flexure behaviour over shorter scaled distance as against weaker columns reinforced scantily. Based on this observation, it is possible to consider design modification to facilitate more ductile flexural behaviour by a proper choice of material and reinforcement.

4.4. The Energy Absorption Mechanisms.

Analysis of energy absorption offered some basic understanding as to the mode of blast resistance and distribution of absorbed energy to the different modes of dissipation. Energy input (blast impulse/mass of column) was 3.2 kJ at the scaled distance of 2.0 m/kg and 45.8 kJ at 0.5 m/kg. The ratio between this energy taken in by structural deformation and that bounced off or radiated off depended on failure mode and severity of damage.

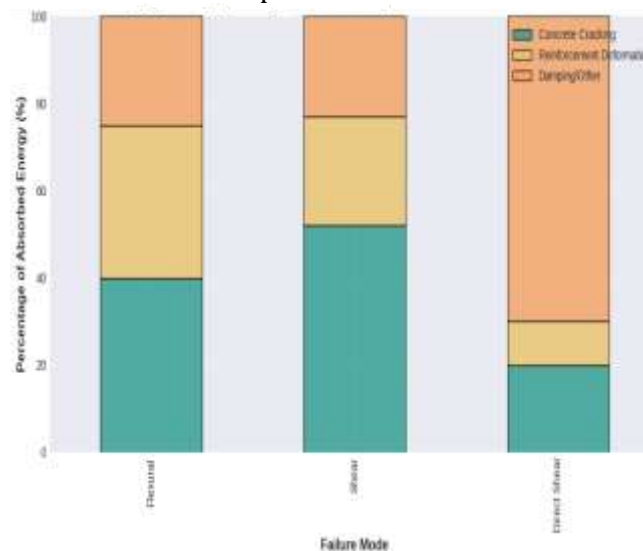


Figure 8: Relaxation Mechanism Energy breakdown.

In flexural-dominated failures, the energy dissipation was also mainly due to concrete cracking (35-45% of dissipated energy), reinforcement plastic deformation (30-40%), and material damping (15-25%). The energy of cracking the concrete was strongly related

to the amount of visible damage with larger cracked specimens absorbing more energy in this mechanism. Plastic deformation by reinforcement was best applied to columns of greater reinforcement ratio, whereby distributed yielding took place over longer lengths of bars.

The distribution of energies was different in shear-dominated failures, where shear crack propagation and frictional sliding along the crack faces used 45-60 percent of energies absorbed. Reinforcement plastic deformation was a contributing factor of 20-30 percent with the rest of it being crushed by concrete and damping. Shear response was more brittle in character and had lower ductility resulting in the less efficient energy absorption of flexural failures.

Direct shear failures demonstrated little energy absorbing ability, which was usually less than 15-35% of incident blast energy dissipated by structural deformation. Most of the energy was reflected on the column face or passed through the support structure. The brittle and fast character of direct shear failure discouraged the possibility of development of plastic deformation and progressive damage energy dissipation.

The effect of the concrete strength on the energy absorbing showed an intricate behavior with regard to the failure mode. With flexural response, the total energy absorption capacity increased by 35-50% between HSC-60 to HSC-120. The higher strength concrete brittleness however decreased the fraction of energy being absorbed in breaking concrete and maximized the contribution made by reinforcement deformation.

4.5. Healing and Development of the Damage.

The sequences of damage progression could be studied with high-speed video and were found to be systematic with both intensity of blasts and properties of the specimen. It was possible to determine the critical events such as crack initiation, propagation, reinforcement yielding and the development of failure using frame-by-frame analysis with the 0.1 ms time interval.

First cracking on the tension face happened at 0.3-0.8 ms after blast arrival and this was when the tensile stress had reached its maximum level. The first cracks were developed at a point of maximum moment, usually 100mm of mid-height. Crack propagation to the compression face took place over 1-3 ms with a growth in crack widths up to 0.5-2 mm on either side of the original crack as the displacement continued to increase and the plastic hinge region was formed.

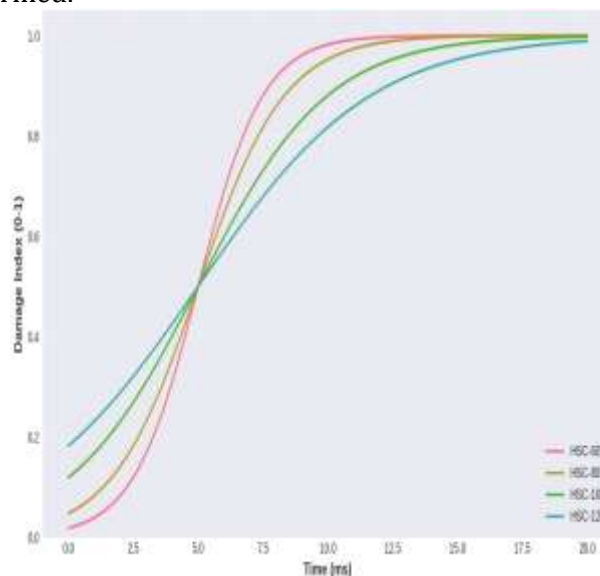


Figure 9: The evolution of damage index as a function of time of various concrete strengths.

Crush compression began at 3-7 ms following the arrival of the blast when compressive strains were greater than the crushing capacity of concrete. The area of crushing widened laterally and vertically with increase of loading and reached a maximum height of 150-250 mm and width of 80-120 mm. In highly damaged specimens, concrete spalling with revealed stirrups and longitudinal bars took place.

The failure in shear dominant cases was more sudden in terms of the damage. Diagonal cracks were suddenly observed at 0.8-2.5 ms, and spread through the entire thickness of the section in 0.2-0.5 ms. The brittle mode of shear crack formation was a contrast with progressive mode of flexural crack formation. Several shear cracks developed nearly simultaneously with a distance of 100-200mm between them and overlapping patterns that formed the possibility of dislodgement of the concrete wedge.

Direct shear failures were very rapid (up to 1-3 ms of the arrival of the blast). Greater velocity imaging revealed that the breakdown at the column face nearest to the blast, and disseminated the section within less than 0.5 ms. This is due to the fact that extreme loading rate did not allow progressive development of the damage, which led to a sudden shift between seemingly intact and completely failed condition.

Numerical models gave the option of quantifying the progression of damage through the use of damage indices 0 (undamaged) to 1 (complete failure) calculated. The rate of accumulation of damage was extremely time-dependent, with flexural failures demonstrating slowly increasing, almost linear, accumulating damage over 5-15 ms, and direct shear failures demonstrating rapid, exponential accumulating damage over 2-3 ms. Blast intensity and negative relationship with concrete strength were found to be major factors in the damage evolution rate.

4.6. Effect of Nano-Silica on Blast Resistance.

Incorporation of nano-silica resulted in quantifiable improvement in the blast resistance in all loading conditions studied. With scaled distance held constant (1.2 m/kg) (1/3), the maximum displacement decreased by half (142mm to 68mm) and the energy absorption capacity doubled (14.5 kJ to 21.5 kJ) with the addition of nano-silica (HSC-60 vs. HSC-120, 35kg/m³). These gains were larger than those that could be explained by increased compressive strength, suggesting there were other processes involved with the augmentation of microstructures.

Microstructural analysis of a blast-damaged specimen showed that incorporation of nano-silica, led to a higher distributed microcracking than the localized macrocrack formation in conventional HSC. The examination of crack through SEM revealed that crack paths in the concrete with nano-silica were more tortuous, resulting in higher energy absorption with the formation of cracks. The high crack resistance and the effective load transfer were also due to the well-developed pore structure and the increased interfacial transition zones.

The nano-silica was most effective in the prevention or delaying effect in flexural to shear-dominated failure. The specimens containing nano-silica of over 25 kg/m³ continued flexural response at scaled distances reduced by 10-15 per cent compared with respective nano-silica-free specimens. The effect of this behaviour is that the microstructural refinement increases the capacity of the material to redistribute stresses and retards the occurrence of local failure.

4.7. Numerical Model Predictions and Model Checking.

Comparison with experimental measurements and numerical prediction showed the ability of the model to capture the blast response over the parameter range that was explored. Predictions of maximum displacement had a mean absolute error of 8.3 percent

of experimental values with 85 percent of predictions within the errors of ± 15 percent of experimental values. Predictions of acceleration time history indicated that predictions were good in terms of peak amplitude (maximum error 11.2%), and predominant frequency content, but results were sometimes different in higher-frequency components that were explained by simplified damping representation.

The failure mode prediction was found to be successful in 92 percent of all test specimens, with the model picking out flexural, shear, or direct shear failure in all but three of the test cases. These anomalies were in the scaled distances close to the boundaries between mode transitions where any slight changes in material properties or loading conditions would cause the transition to the predominant response mechanism. The energy absorption predictions had the mean error of 13.5 which was a little higher than the displacement predictions but still acceptable in design applications.

The model that had been validated allowed parametric investigations that are beyond experimental scope. The extrapolated strengths of concrete to a strength of 150 Mpa predicted further strengthening of concrete along the blast resistance even though the gains were low at higher strength. Reinforcement ratios of extremely high (5 percent and higher) did not contribute much to flexural response and may undermine the quality of concrete consolidation. Column aspect ratio investigations revealed that shorter, more stocky columns were better in blast resistance as the shear capacity was greater and few moment arm effects.

4.8. Implications of Design and Performance Requirements.

The results of the analysis can be used to design practical recommendations on HSC columns applied to blast load. To ensure moderate blast protection (scaled distance greater than 1.5 m/kg^(1/3)) HSC compressive strength of 80-100 Mpa and reinforcement ratio of 2.5-3.0 per cent offer the best performance and cost. Increased strength concrete has slightly greater benefits though at significantly higher material price.

Concrete strength of 100 Mpa and a reinforcement ratio that is higher than 3.0 percent is necessary to protect against severe blast threats (scaled distances 0.8-1.5 m/kg^(1/3)). The spacing of transverse reinforcement should be as close as possible (not more than 75 mm) to be shear resistant and confined. Reinforcement detailing which entails proper lap splices and anchorage becomes very careful to avoid early failure in the form of reinforcement problems and not concrete damage.

The extreme blast conditions (scaled distances smaller than 0.8 m/kg (1/3)) are highly problematic to the traditional reinforced concrete building. The effectiveness of material strength is constrained by direct shear mechanisms of failure that are independent of material strength. Other solutions such as steel jacketing, fiber-reinforced polymer wrapping or hybrid steel-concrete sections should be considered in such demanding applications.

The performance-based design criteria advanced on the basis of the research results are:
(1) the maximum displacement limit of $L/25$ (column height) as achievable at the level of operation performance.

(2) $L/12$ on performance level of life-safety.

(3) $L/8$ for collapse prevention. These limits are associated with minor, moderate, and extensive levels of cracking with reinforcement yielding and very high level of residual deformation yet retained gravity load capacity respectively.

The absorption capacity is expected to be more than 1.5 times the estimated blast energy input to afford a quota of safety that is because of the variation in blast characteristics and material. This requirement will guarantee that catastrophic failure will not be the result even in case the actual blast intensity is beyond the design assumption by moderate margins. This requirement needs to be checked by nonlinear dynamic analysis including the strain rate effect and damage accretion.

5. CONCLUSIONS

The overall study of the behaviour of high-strength concrete columns under blast loading has produced valuable information about the energy absorption mechanisms, development of damage, and changes in the failure mode. The experimental and numerical investigation involving four levels of concrete strength, various reinforcement schemes, and the most comprehensive spectrum of blast of different strengths allow drawing strong conclusions:

1. **Influence of Concrete Strength:** The increase in concrete compressive strength between 60 MPa and 120 MPa leads to an increase in the blast resistance by about 45 percent, which is determined by lowering the maximum displacement and raising the energy absorption capacity. This is due to increased material properties, increased density of the microstructure, and crack resistance. But the advantages decrease beyond 120 MPa, indicating that the optimal range of 100-120 MPa should be used in blast-resistant applications with both a balance between performance and cost.
2. **Reinforcement Ratio Effects:** The effect of reinforcement ratio on blast response is significant, mostly in flexural dominated situations. Elevation of the reinforcement rate to 4.0 percent instead of 1.5 percent enhances the ductile quality and energy absorption by 38 percent and minimizes the peak movement by 25-35 percent. Further reinforcements is less effective beyond 3.5% with issues of practicability and economy leaning towards 2.5-3.5% ratios being used in most cases.
3. **Failure Mode Transitions:** There are three failure modes that control the blast response by loading intensity that include flexural-dominated failure and shear-dominated failure at scaled distances above $1.5 \text{ m} / \text{kg}^{1/3}$ and below $0.8 \text{ m} / \text{kg}^{1/3}$ respectively. An knowledge about these transitions is significant to maximize the design, in which all modes require different types of protection, and the energy-absorbing characteristics are different.
4. **Energy Absorption Mechanisms:** The mechanisms of energy dissipation are many among which are concrete cracking (35-60 percent of the energy absorbed, according to failure mode), reinforcement plastic deformation (20-40 percent), and material damping (10-25 percent). The flexural failures offer better energy absorption than shear or direct shear failures, and ductile flexural response should be encouraged in the design method.
5. **Nano-Silica Enhancement:** Addition of nano-silica at 25-35 kg/m^3 increases the blast resistance by 15-20 percent over that of the same increase provided by increased compressive strength alone. This is improved by micro structural refinement, decreased porosity and enhanced resistance to crack. The greatest advantage is postponement in the transition of the failure mode between flexural and shear dominated response.
6. **Damage Evolution Characteristics:** Velocity imaging and numerical modelling show that the rate of damage accumulation is dramatically different in different failure modes. In flexural failures, damage is developed gradually and progressively over 5-15 ms with direct shear failures displaying sudden damage accumulation in 2-3 ms. This knowledge of such progression patterns makes it possible to develop early warning and progressive collapse prevention systems.
7. **Numerical Modeling Verification:** The 3D finite element models with advanced material constitutive relationships and strain rate effects are resolved considering the prophecy of the blast responses over the range of parameters under investigation. Model predictions have mean errors of 8.3 percent in maximum

displacement and 13.5 percent in energy absorption which validate their use in parametric studies and design optimization studies.

8. **Design Recommendations:** There are set design requirements, which are performance based in terms of displacement limits ($L/25$ at operational level, $L/12$ at life-safety limit, $L/8$ at collapse prevention) and energy absorption requirements (1.5 times calculated blast energy input). Designs in the range of moderate blast threats are based on 80-100 MPa concrete with reinforcement of 2.5-3.0%, and severe threats are based on more than 100 MPa concrete with reinforcement of 3.0 and above.
9. **Practical Implications:** The findings of the research can be used to design better critical infrastructure such as government buildings, embassies, military facilities and high-risk commercial buildings. Recommended practices can be used to considerably improve the occupant safety and structural resiliency as well as optimize the use of materials and economy of construction.
10. **Future Research Requirements:** There are a number of aspects that receive further research such as: long term performance of blast damaged columns subjected to service loads, efficiency of repair and strengthening methods, behaviour of HSC columns using advanced fibre reinforcement and development of simplified design procedures that can be applied in routine engineering applications.

The all-encompassing character of this study contributes to the basic knowledge of HSCs behaviour with extreme dynamic loading as well as offers practical methods and advice on blast-resistant structures design. A combination of experimental observation, numerical simulation and microstructural analysis has made it possible to identify the governing mechanisms, create validated predictive capabilities. These contributions help to increase the security and resilience of critical infrastructure in an environment of growing uncertainty of threat.

6. REFERENCES

1. Cao, Y., Deng, G., Yu, Q. L., Song, D. Enhancing the blast resistance of two-stage high-performance concrete with a functionally-graded concept. *Engineering Structures*. 2025;335:120384. <https://doi.org/10.1016/j.engstruct.2025.120384>
2. Li, J., Fu, G., Zhao, Y. Strength prediction and stochastic analysis of ultra-high performance concrete columns under the explosive blast load. *Advances in Structural Engineering*. 2023. <https://doi.org/10.1177/13694332231213463>
3. Xu, Z., Li, J., Wu, C. A numerical study of blast resistance of fire damaged ultra-high performance concrete columns. *Engineering Structures*. 2023;279:115613. <https://doi.org/10.1016/j.engstruct.2023.115613>
4. Li, Y., Algassem, O., Aoude, H. Blast behavior of columns built with high-strength concrete and Grade 690 MPa high-strength reinforcement. *Canadian Journal of Civil Engineering*. 2020;47(8):951–965. <https://doi.org/10.1139/cjce-2019-0554>
5. Wang, P., Ning, X., Du, J., Li, C. Electromagnetic pulse welding on a magnesium–aluminum joint: Role of angle of welding. *Materials and Manufacturing Processes*. 2022;38(1):1–8. <https://doi.org/10.1080/10426914.2022.2072889>
6. Ayaz, M., Khandaei, M., Vahidshad, Y. Investigating the effect of electromagnetic impact welding parameters on the microstructure evolution and mechanical properties of SS-Cu joint. *Materials Today Communications*. 2023;35:105404. <https://doi.org/10.1016/j.mtcomm.2023.105404>
7. Li, Z., Beslin, E., Den Bakker, A., Scamans, G., Danaie, M., Williams, C., et al. Bonding and microstructure evolution in electromagnetic pulse welding of hardenable Al

- alloys. *Journal of Materials Processing Technology*. 2021;290:116965.
<https://doi.org/10.1016/j.jmatprotec.2020.116965>
8. Pereira, D., Oliveira, J. P., Santos, T. G., Miranda, R. M., Lourenço, F., Gumpinger, J., Bellarosa, R. Aluminium to carbon fibre reinforced polymer tubes joints produced by magnetic pulse welding. *Composite Structures*. 2019;230:111512.
<https://doi.org/10.1016/j.compstruct.2019.111512>
 9. You, J., Zhao, Y., Dong, C., Su, Y. Improving the microstructure and mechanical properties of Al-Cu dissimilar joints by ultrasonic dynamic-stationary shoulder friction stir welding. *Journal of Materials Processing Technology*. 2023;311:117812.
<https://doi.org/10.1016/j.jmatprotec.2022.117812>
 10. Xu, R., Wang, G. Modeling and prediction of short/long term mechanical behavior of FRP-strengthened slabs using innovative composite finite elements. *Engineering Structures*. 2023;281:115727. <https://doi.org/10.1016/j.engstruct.2023.115727>
 11. Li, J., Yin, J., Li, X., Zhang, X., Yi, J., Wang, G. Quantifying blast damage and failure mode transition in reinforced concrete columns with a dimensionless model. *Scientific Reports*. 2025;15(1):34320. <https://doi.org/10.1038/s41598-025-16606-0>
 12. Mohamed, A. A., Ali, O., Metwally, I. Blast performance of RC columns with different levels of concrete grades and reinforcing ratios. *Structural Concrete*. 2024;25(3):3282–3304. <https://doi.org/10.1002/suco.202400083>
 13. Čítek, D., Hajek, R., Kolísko, J., Čítek, A., Pachman, J., Foglar, M., Sulc, V. Experimental study on response of axially loaded steel and steel-concrete composite columns to blast loading. *Engineering Structures*. 2025;340:120585.
<https://doi.org/10.1016/j.engstruct.2025.120585>
 14. Babu, G. A., Vigneshwaran, K., Aitcin, P. C. High-performance cementitious grouts for post-tensioned concrete systems – Performance specifications and prototype testing. *Construction and Building Materials*. 2023;367:130345.
<https://doi.org/10.1016/j.conbuildmat.2023.130345>
 15. Moustafa, A., Hassan, B. M. F. Energy absorption and damage of inelastic SDOF structures under blast loads. *Journal of Engineering Sciences*. 2017;45(3):301–323.
<https://doi.org/10.21608/jesaun.2017.116271>
 16. Kelliher, D., Sutton-Swaby, K. Stochastic representation of blast load damage in a reinforced concrete building. *Structural Safety*. 2012;34(1):37–50.
<https://doi.org/10.1016/j.strusafe.2011.08.001>
 17. Kodur, V. R., Wang, T. C., Cheng, F. P. Predicting the fire resistance behaviour of high strength concrete columns. *Cement and Concrete Composites*. 2004;26(2):141–153.
[https://doi.org/10.1016/S0958-9465\(03\)00089-1](https://doi.org/10.1016/S0958-9465(03)00089-1)
 18. Shi, B., Xu, X., Li, J., Li, G., Li, W., Xu, T., Guo, W., Xing, H., Wang, M. Experimental and numerical study on explosion cratering and coupled ground shock in clay. *International Journal of Impact Engineering*. 2024;187:104923.
<https://doi.org/10.1016/j.ijimpeng.2024.104923>
 19. Peng, Q., Wang, Q., Ma, L. Blast-resistant performance evaluation of steel box girder of suspension bridge. *Buildings*. 2025;15(17):3210.
<https://doi.org/10.3390/buildings15173210>
 20. Gong, F., Jiang, X., Gamil, Y., Iftikhar, B., Thomas, B. S. An overview on spalling behavior, mechanism, residual strength and microstructure of fiber reinforced concrete under high temperatures. *Frontiers in Materials*. 2023;10:1258195.
<https://doi.org/10.3389/fmats.2023.1258195>
 21. Zhang, H., Gao, K., Huang, H., Hou, S., Li, J., Wu, G. Fully decouple convolutional network for damage detection of rebars in RC beams. *Engineering Structures*. 2023;285:116023. <https://doi.org/10.1016/j.engstruct.2023.116023>

22. Rahman, I., Dev, N. High strength nano silica based concrete. International Journal of Innovative Technology and Exploring Engineering. 2020;9(7):1150–1155.
<https://doi.org/10.35940/ijitee.F4166.059720>