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A Concise Overview of Numerical Simulation Tools and Techniques for Anti-Explosion Response Prediction of Infrastructures and Facilities

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Abstract. In the wake of recent devastating explosions, like the tragic blast in Lebanon's Beirut City, there has been a growing recognition of the need for blast-resistant design. Previously, this type of design was mainly reserved for critical infrastructures such as embassies and military facilities. However, the destructive power unleashed by these incidents has highlighted the importance of implementing blast-resistant measures in a wider range of buildings and infrastructure. The focus is now shifting towards incorporating blast-resistant features into various types of structures to enhance public safety and minimize the devastating impact of future explosive events. Collapse of infrastructures in the surrounding area of the explosion and the potential damage to buildings located at significant distances has raised serious concerns among structural engineers regarding the safety of infrastructures and facilities when subjected to explosive detonations. The level of devastation caused by the explosion can differ, spanning from reparable damage to total structural failure, leading to loss of life. Some engineers propose that buildings in areas prone to vulnerability or affected by war should be constructed with the ability to withstand explosive detonations, in order to prioritize the safety of human lives and preserve the integrity of the infrastructure. This article provides a concise overview of the latest advancements in numerical simulation tools and methodologies for predicting the response of infrastructures and facilities to explosions. It covers topics such as structural responses, pressure-impulse diagrams, existing design methods, and various numerical simulation tools and methodologies. The article also delves into the challenges faced in modeling blast scenarios and analyzing structural responses using different numerical methods. Additionally, it offers recommendations for overcoming these difficulties.

1. Introduction

Throughout history, the examination of the repercussions of explosions on buildings, crucial structural elements, and individuals has primarily been a concern for the military or industrial sectors. This is due to the considerable risks involved and the stringent regulations regarding the handling and detonation of explosive products [1-3]. In modern times, the need for research and development in impact resistance and blast mitigation for engineering structures has become crucial due to various incidents such as accidental explosions, deliberate blasts, and detonations that occur in both civilian and military environments. The primary objective is to safeguard individuals and infrastructure from the intense dynamic loading caused by blast and shock waves [1]. As a result, there has been a significant increase in curiosity surrounding the development of innovative strategies for safeguarding structures and advancing armor technology. This has sparked a growing demand for adaptable and highly intelligent solutions in the field.

Such interests become more apparent when considering the casualties and the level of destruction associated with certain acts of terrorism [1]. These acts often involve the use of vehicle bombs or suicide bombers to target crowded

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city centers and vulnerable infrastructure and facilities. Examples of such attacks include the bombing of the Alfred P. Murrah building in Oklahoma City in 1995, the attacks on the US embassies in Kenya and Tanzania in 1998, the Hilton Hotel attack in Egypt in 2004, the train bombing in Madrid in 2004, the attack on the office of the Prime Minister in Oslo in 2011, as well as the bombings in Brussels in 2016 and Sri Lanka in 2019 [1].

Reinforced concrete (RC) is a widely used construction material in the building of civil and military structures [3-5]. It is a key component in the construction industry, known for its strength and durability [3]. RC merges the durability of concrete with the resilience of steel reinforcement (r/f), resulting in a substance that has the ability to endure substantial loads and prevent the occurrence of cracks. Its versatility and cost-effectiveness make it a preferred choice for a range of applications, from bridges and high-rise buildings to dams and tunnels [3]. The use of RC in construction has revolutionized the industry, providing a reliable and efficient solution for creating robust and long-lasting structures. Throughout their lifespan, these building structures may encounter various threat scenarios, as mentioned earlier, where the structure is exposed to an exceptionally high-intensity load that surpasses the intended design load. Such circumstances can lead to significant damage [1, 3].

The focus on protecting structures from blast detonations has gained significant attention in recent times, primarily due to the rise in accidental explosions and acts of terrorism targeting critical government and civilian establishments [5]. Blast loads, characterized by their brief duration but intense impact, elicit unique structural responses that differ from those caused by static or less severe dynamic loads, such as earthquakes, waves, and wind [1, 5]. Hence, the methods used for designing and analyzing infrastructures that are exposed to static and low-rate dynamic loads cannot be directly utilized for infrastructures that experience explosive detonations. In addition, the response of infrastructures and the characteristics of materials when subjected to explosive forces usually exhibit nonlinearity. This is because they involve intricate stress conditions caused by the propagation of stress waves within the structure. Furthermore, these responses are also time-dependent, which means that certain simplified methods commonly employed in design practices may not always result in accurate predictions of structural reactions.

In order to ensure the reliability of the design and analysis of infrastructures under explosive detonations, it is crucial to have a deep understanding of the blast load characteristics and the dynamic material properties involved [4, 5-11]. Most design practices currently rely heavily on simplifying the analysis to single-degree-of-freedom (SDOF) systems. In addition to the simplified methods outlined in different guidelines, it is often necessary to conduct experimental tests and numerical simulations to accurately assess the structural responses. These additional measures provide a more reliable means of quantifying the behavior of the structures [4, 12]. Experimental testing is a direct method used to study the behavior of structures or structural components. This approach involves conducting both field and laboratory tests. By utilizing experimental testing, researchers can gather valuable insights into how structures perform under different conditions. These tests provide first-hand data that can be analyzed to enhance our understanding of structural behavior and inform future design and construction practices. Field tests involve examining structures in real-world settings, while laboratory tests allow for controlled conditions to isolate specific variables [1, 12]. Together, these testing methods contribute to advancing the field of structural engineering. The results obtained from physical testing not only provide a clear demonstration of the actual structural behaviors but also serve as a means to validate the accuracy of numerical models. However, conducting physical tests can be challenging for several reasons. Firstly, safety concerns often impose restrictions on the feasibility of such tests. Moreover, the costly nature of the necessary equipment and instrumentation, along with the need for specialized expertise, adds to the challenges of capturing and documenting rapid blast loading and structural responses. Despite these challenges, physical testing remains an invaluable tool in understanding and analyzing structural performance. The progress of computer technology and computational mechanics techniques has led to the creation of various commercial software programs that are extensively utilized for performing numerical simulations of infrastructures exposed to explosive detonations [1, 12]. Nowadays, it has become commonplace to employ validated high-fidelity numerical simulations for anticipating the responses of structures under blast loads. These simulation outcomes can complement the data obtained from physical testing, which can be challenging to acquire. Moreover, they enable more meticulous observations and documentation of the structural responses and damages, which are not possible in actual experiments. However, it is imperative to ensure the reliability of the predictions by verifying the model before utilizing numerical simulations.

In certain developing countries, weak political systems and inadequate governance have created an environment reminiscent of war, with buildings and structures being destroyed by explosions and bombs. There is also a prevalence of industrial accidents caused by insufficient knowledge and mishandling. Recent accidental explosions, such as the one in Beirut Port, Lebanon in August 2020, and the ammunition depot blast on the outskirts of Ryazan City, Russia in November 2020, raise concerns about the safety of nearby buildings and their occupants. These powerful detonations often result in structural damage, leading to either disproportionate or progressive collapse. Hence, it is of utmost importance to possess a comprehensive comprehension of the explosion phenomenon and the immense forces it generates, along with the structural reactions to detonations caused by explosives.

Blast engineering is a highly specialized area within the field of structural engineering, and many structural engineers have limited knowledge about the dynamics of blasts, blast loading, and how structures respond to such events. This study aims to provide a brief summary of numerical simulation tools and techniques that can be employed to predict the response of infrastructures and facilities to explosions. The information presented here will be valuable for structural engineers and committee members involved in developing blast design standards. The focus is on equipping these professionals with the necessary knowledge and resources to effectively address and mitigate the impact of blasts on structures.

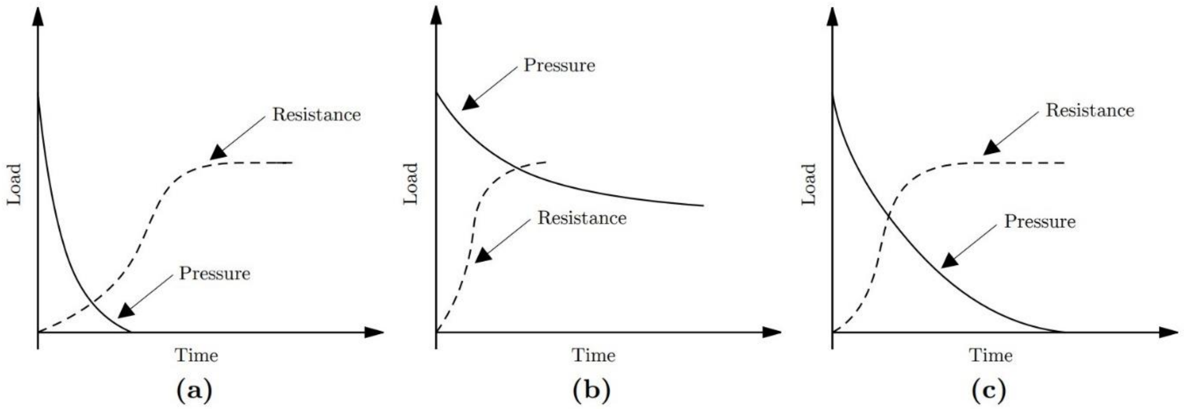


Fig. 1. A diagrammatic depiction of time reactions for various categories of loading: (a) sudden, (b) nearly constant, and (c) energetic loading.

2. Structural Response

The response of an infrastructure element or a building is greatly affected by the ratio of the load duration to the fundamental frequency of the element or a building structure [13]. This ratio determines the type of loading that the structure will experience, and there are three possible types [13].

- *Impulsive loading* is characterized by a scenario where the load's duration is short in comparison to the system's response time. In Figure 1(a), we can see a schematic representation of such a scenario, where a load is applied to a structure but quickly removed before any significant deformation can occur. The maximum displacement experienced by the structure is determined by factors such as the impulse, stiffness, and mass of the structure [13]. This form of loading often happens when a building is exposed to the explosion of a bomb.
- *Quasi-static loading* refers to a situation where the duration of load application is longer than the maximum response time of the load. Essentially, this means that the applied load has minimal dissipation before reaching maximum deformation. This can be visualized in Figure 1(b). In such cases, the resistance history or response of the system is solely determined by the peak load and the structural stiffness of the system.
- *Dynamic loading* refers to a scenario where the load and system response time share a similar magnitude, as depicted in Figure 1(c). In this case, the load-time profile plays a crucial role in determining the system's response. One example of such a situation is when a structure is subjected to a blast from a nuclear device or a detonation of a substantial quantity of high explosive from a long distance. These types of loads are commonly referred to as long-duration blast loads.

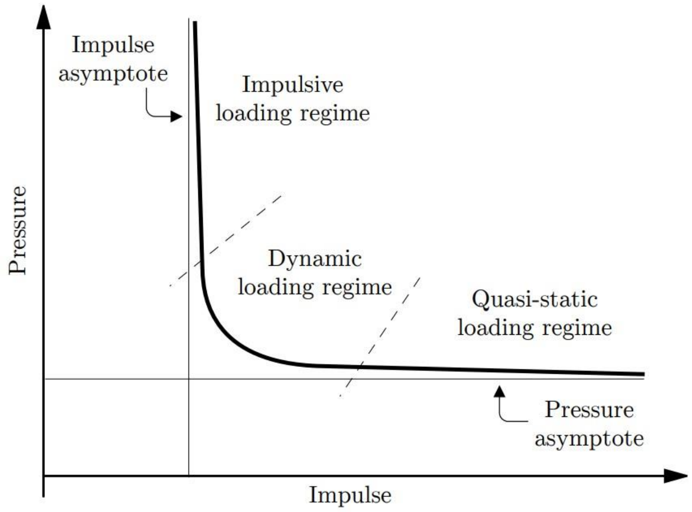


Fig. 2. A diagram that represents pressure and impulse in a typical manner.

3. Diagrams Depicting Pressure and Impulse

When evaluating the anti-explosion response of a structure, the primary design consideration is frequently determining the final deformation state [1, 12]. The utmost displacement that a structure can endure before collapsing holds greater significance than having a thorough understanding of the structure's displacement over time, as stated by Hetherington and Smith [14].

Previous studies have revealed a significant connection between the structural reaction and the proportion of load duration to the natural period of the building. This relationship gives rise to three distinct loading regimes: impulsive, quasi-static, and dynamic [15]. Response spectra, which plot the maximum peak response against this load duration to natural period ratio, provide a simplified approach to designing structural systems [13, 16]. In certain applications, such as blast-loaded structures, it is more practical to represent the response spectra in terms of pressure and impulse. By delineating distinct sets of axes, the response spectra for a specific system can be represented using pressure and impulse instead. This allows for a more relevant representation of the load, given that pressure and impulse are the typical parameters used in such cases.

Iso-damage curves, also known as pressure-impulse (P-I) diagrams, were initially developed during the Second World War in the United Kingdom to evaluate the damage sustained by structures [17]. These diagrams provide a straightforward means of assessing the structural response to a particular load. Each data point on the P-I curve corresponds to a unique combination of pressure and impulse, leading to a distinct level of failure or damage. In the field of blast-resistant design for structures, P-I curves are widely utilized to establish response limits for different blast loading scenarios. These limits can be observed qualitatively or measured quantitatively using parameters such as displacements, ductility ratios, support rotations, and so on.

The key components of a P-I diagram can be observed in Figure 2. As depicted in the diagram, there are distinct vertical and horizontal asymptotes that respectively represent the impulsive and quasi-static phases. The former signifies the minimum force required to achieve a specific level of damage, while the latter indicates the minimum peak pressure required to reach the same level of damage. The transitional phase between the impulsive and quasi-static asymptotes is known as the dynamic phase, where the structural response is influenced by both pressure and force. In addition, the curve displayed on the diagram separates the space of pressure-impulse into two distinct areas: the area located above and to the right of the curve indicates situations where the predetermined threshold for structural damage is surpassed, whereas the region below and to the left indicates response levels that fall below the specified threshold, which is deemed as the "safe side".

Numerous research studies have been conducted to create P-I diagrams by utilizing analytical and numerical approaches, in addition to experimental data for generating pressure-impulse curves [12-13, 15, 18]. When considering analytical methods, the response spectrum of a SDOF system can be derived from its corresponding response history functions, allowing for the determination of the vertical and horizontal asymptotes of the P-I curve, as demonstrated by [19]. These investigations have contributed significantly to the development of P-I diagrams, offering valuable insights into the behavior of structures subjected to pressure and impulse loads. By combining experimental evidence with analytical and numerical solutions, researchers have expanded our understanding of how pressure and impulse interact with different structural systems. This comprehensive approach enhances our ability to predict and evaluate the response of structures under various loading conditions, ultimately improving their design and safety. A more commonly used approach to determine the asymptotes of the P-I diagram is through the utilization of an energy balance method [12]. One way to obtain the impulse asymptote is by assuming that, in this particular regime, the initial energy supplied to the system is solely in the form of kinetic energy, which is entirely converted into strain energy at its final state. On the other hand, by assuming a constant load throughout the deformation process and equating the work performed by this load to the strain energy acquired, it is possible to derive the quasi-static asymptote of the P-I curve [19].

4. Existing Design Methodologies and Strategies

Designing structures to mitigate the effects of blast loads usually involves two primary factors: designing the structural elements to withstand blasts and designing the structures to retain their integrity following an explosion, thereby preventing a progressive collapse [1, 12]. Structural components located near the explosion are susceptible to damage from blast loads of a certain magnitude and distribution. These components can be reinforced to resist the specific blast loads. However, in practical applications, accurately predicting the location of an explosion and the magnitude and distribution of blast loads is often impossible. Hence, it is not feasible or economical to create every essential structural element with blast resistance in mind. In these situations, the design of structures should prioritize meeting integrity standards by incorporating ample strength and redundancy. By adopting this method, it ensures that the breakdown of one or a small number of elements does not result in a disproportionate collapse of the whole framework [12]. By focusing on maintaining overall structural integrity, even if individual components are damaged, the structure as a whole remains stable. Considering the unpredictable nature of blast events, it is crucial to adopt a holistic approach when designing structures for blast resistance. This approach involves considering potential blast scenarios and their effects on different structural elements. By implementing adequate measures to enhance structural resilience, the potential impact of blast loads can be minimized, reducing the risk of catastrophic failure.

In the realm of blast-resistant design analysis, there exist three commonly utilized methodologies: equivalent static loads (ESLs), the single-degree-of-freedom (SDOF) method, and numerical simulations. The ESL approach simplifies the dynamic analysis by treating it as an equivalent static one. This technique is convenient to implement and straightforward [20], but it does not explicitly consider the dynamic or inertial effects. Thus, the ESL approach is only appropriate in situations where the duration of the blast loading exceeds the fundamental period of the structure, enabling the response to be approximated as quasi-static. Advanced techniques have been created to accurately forecast the reactions and harm caused to structures. However, despite the advancements in computer technology, simulating the structural response to explosive forces remains a time-consuming and resource-intensive task. This is primarily due to the brief yet intense nature of blast loads. In addition, the accuracy of these simulations depends greatly on the presence of extensive dynamic material models, which may not always be readily available. It also requires a profound grasp of computational mechanics, damage mechanics, and structural dynamics. Detailed explanations regarding the numerical methods employed to handle dynamic structural response to blast loads can be found in the subsequent sections of this article.

5. Computational Modeling of Explosive Product Detonations and the Resulting Structural Response

The process of predicting blasts involves two main procedures: determining the load and determining the response. There are two main categories of procedures that can be classified: first-principle methods (FPMs) and semi-empirical methods (SEMs). FPMs involve the solution of motion equations using the fundamental laws of physics. In contrast, SEMs rely on extensive data from previous experiments, which makes them less computationally demanding. However, the limited availability of past experimental results and the restricted distribution of most semi-empirical numerical tools have resulted in structural engineers and researchers relying more on FPMs to address these challenges.

Over the past few decades, advancements in computational fluid dynamics (CFD), computational structural dynamics (CSD), and computer processing power have led to the development of numerical tools. These tools employ a combination of first-principle or coupled semi-empirical and first-principle methodologies to forecast the impact of explosions and the subsequent structural reaction when subjected to blast forces. In this portion, we will explore the qualities, restrictions, and applications of different sophisticated modeling methods.

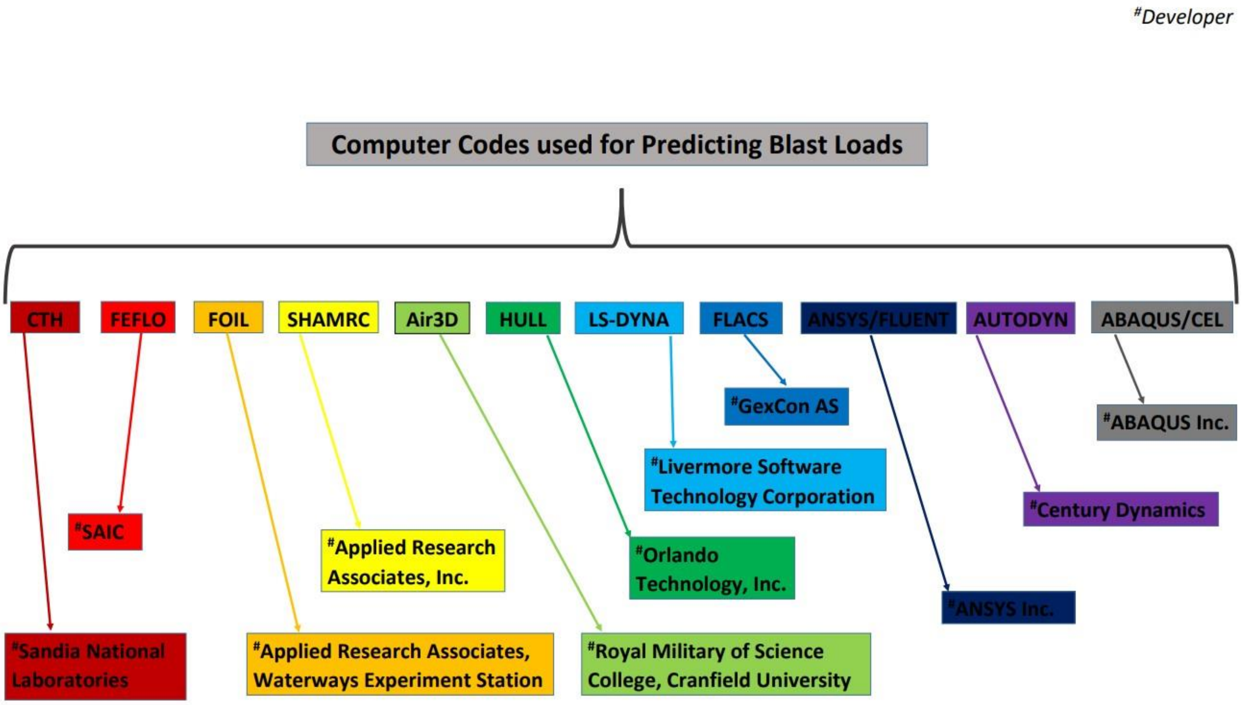


Fig. 3. Computational algorithms employed for explosive detonation simulations.

- **Implicit and Explicit Platforms**

For anti-explosion response prediction of infrastructures and elements, there are two main platforms that can be used to solve the equation of motion for the structural system: an implicit platform or an explicit platform. Each platform has its own set of advantages and disadvantages, making them suitable for various simulation scenarios.

The implicit platform/algorithm addresses the motion equation by examining the balance of external, internal, and inertial forces within the structural system at regular intervals of time. This results in stable solutions and typically yields highly accurate results. Nevertheless, employing implicit platforms requires calculating the inverse of the stiffness matrix at regular time intervals. This results in a significant prolongation of the computational time needed to analyze the structural reaction to blast incidents. This is particularly true when dealing with nonlinear material and structural behavior, as the stiffness of the elements changes over time. In contrast, explicit solution methods do not necessitate the calculation of the inverse of the stiffness matrix at every time interval. Instead, they directly solve the equation of motion using an explicit integration scheme. This approach is more computationally efficient for cases where the stiffness matrix is changing rapidly or where nonlinear effects dominate. However, explicit platforms can be less stable and may produce less accurate results compared to implicit ones.

Explicit platforms, unlike implicit ones, compute the response at each time interval by taking into account the equilibrium at the previous interval. This implies that explicit methods do not necessitate the calculation of the inverse of the stiffness matrix for every interval. Nevertheless, since equilibrium is not perfectly satisfied at every interval, explicit solutions can experience numerical instability if the intervals are not adequately small.

Historically, explicit platforms have been widely chosen for executing blast simulation studies. One of the main reasons for this is the benefit of not having to calculate the inverse of the stiffness matrix in every time step, which is more significant than the need for smaller time steps. In addition, explicit computational codes provide the ability to easily integrate the failure and removal of elements into the analysis. However, incorporating these algorithms into implicit codes still presents a computational difficulty.

- **Numerical Modeling of the Propagation of a Blast/Shock-wave**

The numerical modeling of detonations encompasses the simulation of the detonation event, as well as the propagation of the ensuing shockwave through the surrounding area, and ultimately, the interaction between the shockwave and buildings or other structures. This process involves accurately representing the detonation phenomenon, analyzing how the blast wave travels, and understanding its effects on the environment and objects in its path. By employing numerical methods, researchers can gain insights into the behavior of detonations and their impact on structures, aiding in the development of safety measures and mitigation strategies. Figure 3 provides a list of first-principle CFD codes that are used for blast modeling. Although many of these codes are not available to the public, the following section introduces some commercially available and commonly used codes, such as LS-DYNA, AUTODYN, ABAQUS/CEL, and Air3D. These codes play a crucial role in accurately analyzing and understanding detonation phenomena.

1. *Modelling explosions in the Air3D software*. Air3D is a CFD code called Eulerian code, which was developed by [21]. This code enables users to enter values for mass, initial energy, and explosives density in order to simulate them as high-pressure and high-temperature balloons. Air3D has the capability to compute pressure timelines at user-defined locations. It has the capability to model problems in 1D (with radial symmetry), 2D (using Cartesian coordinates), and 3D space. Additionally, it has remapping capabilities. Air3D approaches the modeling of structures by considering them as solid blocks and flawless reflectors. One of the main advantages of using Air3D for detonation modeling is its user-friendly interface and minimal input requirements. However, it should be noted that Air3D is not suitable for modeling overpressure in close proximity to the explosive or for handling fluid-structure interaction.
2. *Blast simulation in LS-DYNA*. LS-DYNA is widely recognized as the go-to computer code for addressing high strain rate problems, particularly those involving explosions, low-velocity and high-velocity impacts. When it comes to simulating detonation problems with shock wave propagation, LS-DYNA offers a variety of modeling options. In this discussion, we will focus on three major implementations, which encompass both FPMs and SEMs.

   One method to consider is the utilization of multi-material arbitrary Lagrangian-Eulerian (ALE) formulations to simulate both the explosive and air components. This particular formulation is ideal for carrying out simulations of air blasts due to its ability to incorporate different substances, such as air and the explosive gases produced by the explosion, into an element. By utilizing this modeling technique, it has become possible to accurately represent the interaction between the blast and structures, as well as the transmission of waves through a medium like air.

   The alternate method to simulate an explosion in this software revolves around constructing a unique mesh solely dedicated to the air region. In order to incorporate the explosive substance within the air mesh, the user can designate an initial percentage of the explosive using LS-DYNA's default keycard. This functionality operates in conjunction with the ALE multi-material composition. The shape of the explosive can be designated as a spherical, cylindrical, or a simple cube, granting the user the autonomy to select both the detonation site and timing.

   The third approach employed is a semi-empirical technique called CONWEP, which LS-DYNA incorporates to produce pressure records. The CONWEP algorithm relies on empirical information gathered by [22]. This approach is effective for simulating air blasts from a spherical explosive product and surface blasts from a hemispherical explosive product. Nevertheless, it lacks the ability to accurately forecast nearby detonation processes, shock wave expansion, or interactions with structures.
3. *Simulating explosions using AUTODYN.* AUTODYN is a sophisticated 3D software program designed for the numerical analysis of nonlinear dynamic problems. It is specifically developed to tackle complex scenarios involving solids, fluids, and gases. The program encompasses both a Lagrangian solver, which is used for modeling structures, and an Eulerian solver, which is used for modeling fluids and solids undergoing significant deformations. One of the key features of AUTODYN is its remapping technique. This method enables the precise rendering of the initial explosion phase to be reconfigured and employed as the starting parameters for subsequent computations. By utilizing this approach, it becomes feasible to simulate the detonation process with superior grid resolution without imposing a substantial burden on computational resources. AUTODYN stands apart as the sole CFD software that can simulate the post-combustion impact of a detonation. By integrating the energy from afterburning into the numerical simulations, this program facilitates the rapid expansion of gases, leading to notably elevated temperatures. The research conducted by

[21] has thoroughly documented this phenomenon. Moreover, the phenomenon of afterburning also influences the properties of the explosion. It diminishes the maximum pressure in the immediate vicinity and augments the force exerted in the distant area. These aspects underscore the significance of considering afterburning when examining and replicating detonation incidents.

4. *Modelling of explosions using ABAQUS/CEL*. The addition of the Coupled Eulerian-Lagrangian (CEL) capability to ABAQUS/Explicit is a recent development. The function of this feature is to utilize an Eulerian mesh to depict the air and include the blast wave (pressure) as a boundary condition within this mesh. Consequently, the stress wave moves through the structure by means of a Lagrangian mesh. It is possible to adjust the positioning of the Lagrangian structure within the Eulerian domain in order to attain a desired angle of incidence [23]. With the implementation of this innovative approach, there is no longer a requirement to calculate the reflected pressures for oblique surfaces. Although this approach still requires validation against test data, the preliminary results show promise [24].

- **Difficulties and Recommendations in Explosive Product Detonation Effect Modeling**

Despite the presence of multiple CFD and semi-empirical software programs used to simulate blast detonation, propagation, and interactions with structures, structural engineers and researchers continue to face difficulties in verifying the accuracy of their simulation outcomes for design and guidance purposes.

As mentioned earlier, semi-empirical codes are formulated using a comprehensive set of test data. Therefore, their modeling results are highly regarded because they incorporate verified empirical data. However, the application of semi-empirical modeling is limited to blast scenarios that closely resemble the test data utilized in the code's development. It lacks the capability to address complex geometrical challenges.

CFD codes, also referred to as first-principle models, are employed for solving the physics equations that govern the process of detonation. These codes have a broader range of applications in comparison to semi-empirical codes. Nevertheless, it is crucial to validate the outcomes obtained from CFD simulations by comparing them with existing test data. Furthermore, a dependable CFD simulation should effectively address the following considerations:

1. The precision of CFD outcomes relies heavily on a range of factors, including the size of the elements, the time step used, and the specific coupling algorithm employed. It is crucial to perform sensitivity analyses, specifically convergence tests, to ensure accurate results.
2. Material models and EOS (Equation of State) must adequately represent the real explosive and medium being simulated. In certain scenarios, such as when performing a CFD analysis involving a substantial amount of explosive material or examining detonations that occur in close proximity, the temperatures surrounding the explosive can be considerably higher than the standard value for an ideal gas. Furthermore, it would be inaccurate to presume a consistent value for the ratio of specific heats pertaining to air within this specific area.
3. When conducting simulations for non-spherical explosives in scenarios where the range is close, it is crucial to take into account the impact of the shape and orientation of the explosive product. The shape of the explosive product plays a significant role in determining how the overpressure is distributed in the nearby areas. In comparison to a spherical explosive product, a cylindrical product produces significantly higher pressures and impulses. Neglecting these effects during analysis can lead to a potential risk of underestimating the impact of the explosion.

These considerations are essential in ensuring accurate and reliable CFD simulations of detonation processes. By addressing these concerns, researchers and engineers can obtain trustworthy results that can be applied in various applications related to explosives and their effects.

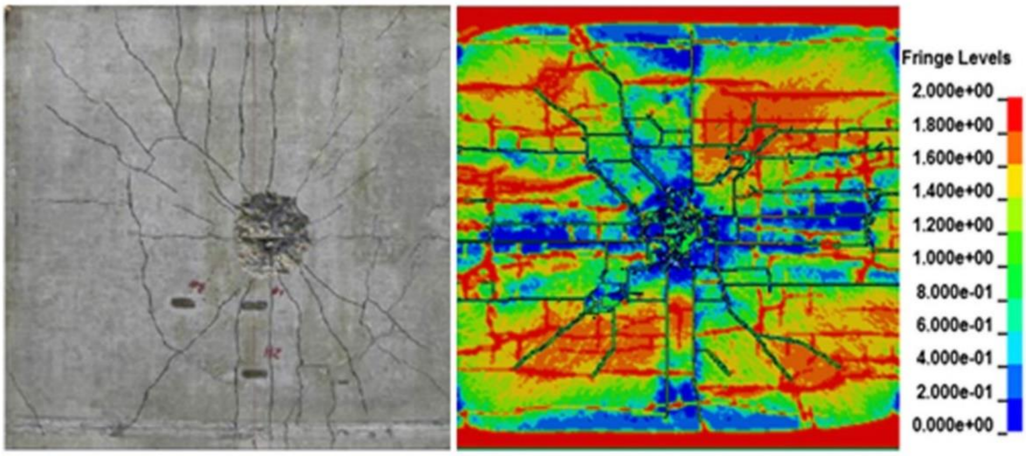
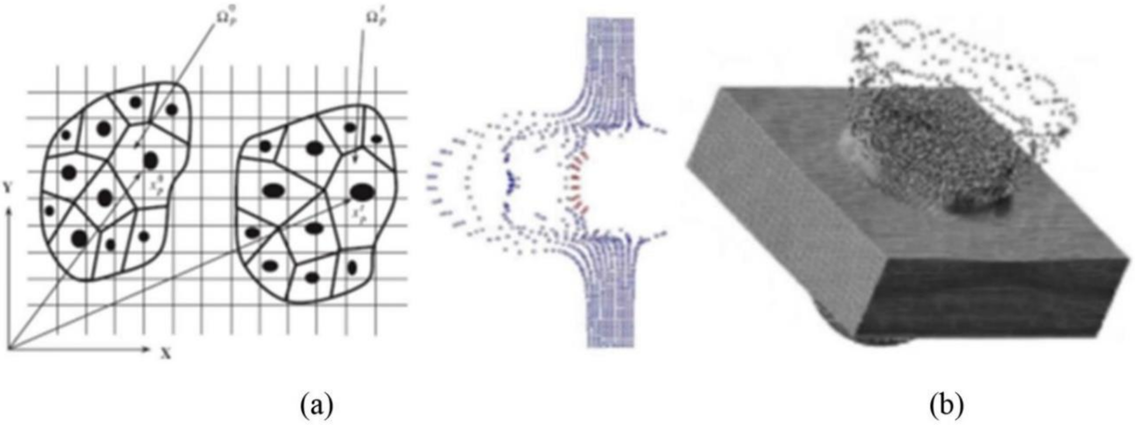


Fig. 4. An examination of numerical analysis conducted on a concrete slab in comparison to the results from testing.



(a)

(b)

Fig. 5. (a) outcomes of MPM mesh and simulation; and (b) results obtained from SPH simulation.

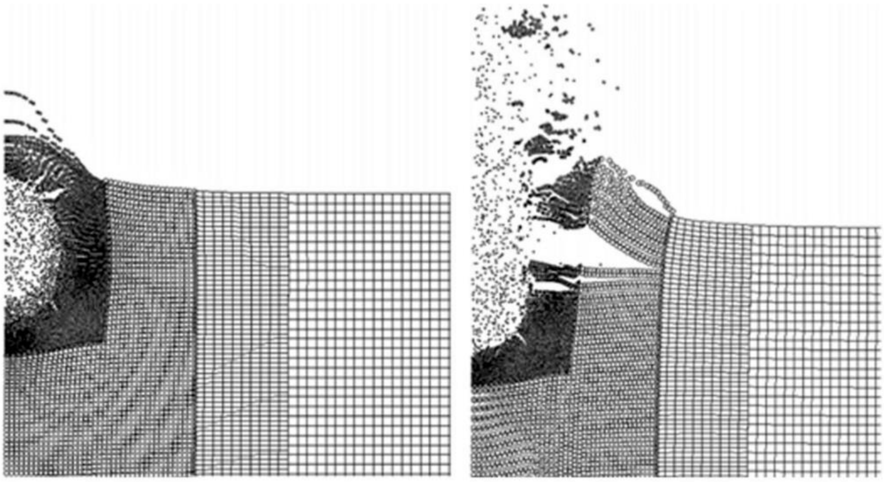


Fig. 6. A simulation model called SPH-FE utilized to replicate the processes of cratering and element disintegration.

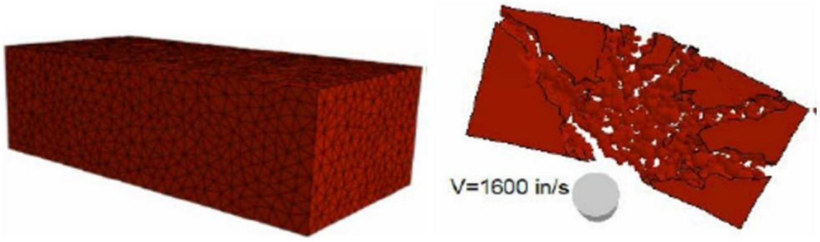


Fig. 7. LPDM simulation.

- **Analyzing Structural Responses using Numerical/Computational Techniques**

During explosive detonations situations, the response of the infrastructure or elements goes through a rapid and temporary phase in which various factors come into play, including high strain rates, nonlinear material properties, and time-dependent deformations. Infrastructure elements can fail for two reasons: material fracture resulting from stress wave effects in close-range detonations, or significant structural deformations in far-range detonations. In addition to these uncertainties, accurately predicting the distribution of blast loads on a deforming structure further complicates the analysis of its response.

Hydro-codes employ two different types of analysis: coupled analysis and uncoupled analysis. In an uncoupled analysis, blast loads are determined by assuming a blast wave impacting a rigid surface. The calculated blast loads are then imposed on a flexible structural model. It is clear that in an uncoupled analysis, the program tends to overestimate the blast loads, particularly when the target structure undergoes rapid deformation. In contrast, a coupled analysis involves the interconnection of blast load simulation and structural response. This entails simultaneously solving the prediction of blast load through CFD and the structural response obtained from Computational Structural Dynamics (CSD). This coupled analysis accommodates structural deformation and failure, which ultimately leads to a more accurate prediction of the acting blast pressure. There are three noteworthy software packages that have the ability to combine blast pressures with structural response: AUTODYN, ABAQUS/Explicit, and LS-DYNA. These software packages are known for their capability to analyze the effects of blast pressures on structures. AUTODYN, ABAQUS/Explicit, and LS-DYNA are widely recognized and utilized in various industries for their expertise in simulating and predicting the behavior of structures under blast loading conditions. By employing coupled analysis, accurate predictions can be made, enhancing the safety and performance of structures in blast-related events. The techniques employed to examine the structural response to explosive forces can be categorized into distinct groups, which will be explored in the subsequent sections. Each of these methodologies possesses its own distinctive characteristics and is capable of effectively addressing diverse scenarios with varying degrees of precision.

1. *Conventional FEM*. The method known as Finite Element (FE) is extensively utilized in the analysis of how structures respond to explosive products detonations. Its widespread adoption can be attributed to not only its accessibility but also its versatility, as it allows for integration with a fluid solver. This integration enables a more realistic depiction of the loading environment.

   Traditionally, FE models incorporating damage mechanics have been employed to simulate the structural response to blast loads. This approach necessitates the use of small time steps and element sizes to ensure stability and accuracy in the simulations. Moreover, while first-principle CFD and CSD methods are developed based on solving physical equations, their results are typically deemed reliable only when validated against existing experimental data.

   One of the primary obstacles encountered by the Lagrangian grid-based finite element (FE) model when handling structures subjected to powerful blast loads is the substantial distortion of elements. This distortion has the potential to produce singular Jacobi matrices, which can lead to a notable degree of inaccuracy and, ultimately, trigger computational overflow. To address this issue, a solution known as the "erosion algorithm" is implemented, where elements are removed once a predefined failure criterion is met. This method has been effectively integrated into commercial hydro-codes such as LS-DYNA and ABAQUS, and has been extensively employed by many researchers. Figure 4 demonstrates an instance of modeling concrete slabs subjected to blast loads, showcasing the ability to accurately and reliably simulate concrete cracks through the implementation of an effective strain-based element erosion technique.

While the ease of use is a notable advantage, it is important to highlight that the erosion algorithm lacks a solid foundation in physics. Furthermore, the deletion of a large number of elements violates the principle of mass conservation. In a study conducted by [25], a detailed discussion on the erosion limit for concrete is presented. In order to tackle the problem of element removal and maintain mass conservation, [26] introduced interfacial elements in their finite element (FE) model to simulate the process of fragmentation. They extended this approach by including non-zero thickness elements along weak connections in the structure, as demonstrated by [27]. These methods prevent the removal of elements in a conventional FE model. However, a disadvantage is that the pre-established components at the interface limit the ultimate fracture pattern and the dispersion of fragment dimensions. Camacho and Ortiz [28] devised a technique for adaptive meshing in two-dimensional space using a cohesive law. This revolutionary method removes the requirement to beforehand establish the vulnerable surface, leading to enhanced precision in forecasting the progression of cracks in concrete and the processes of fragmentation. In a subsequent study, Ortiz and Pandolfi [29] proposed a fully three-dimensional finite element model that incorporates cohesive fracture surfaces, enabling the tracking of three-dimensional crack propagation and interaction. In recent times, there has been an increasing use of cohesive finite elements to replicate the dynamic fragmentation of structural elements [30]. Although this approach offers the benefits of accurately modeling cracks and fragmentation, it is marred by its computational inefficiency, which requires frequent remeshing. This is especially pronounced when dealing with infrastructures of concrete subjected to explosive detonations, which tend to break into numerous small fragments.

2. *Alternative techniques for numerical simulations that do not rely on mesh-based discretization, such as mesh-free methods*. Numerous techniques that do not rely on mesh have been created to tackle the computational difficulties related to mesh distortion in Lagrangian solvers, particularly in cases involving significant deformations. These methods include the interfacial element approach. In 1994, Belytschko et al. [31] introduced the element-free Galerkin (EFG) method and applied it to the analysis of dynamic fracture in concrete. Rabczuk and Belytschko [32] also utilized the EFG method to investigate hard impact effects on concrete infrastructure elements. Another modeling technique that can handle mesh issues during large deformations is the material point method (MPM), as proposed by [33]. Over time, the MPM technique has evolved to effectively handle significant distortions and a variety of materials, including the interaction between fluids and structures. It is worth mentioning that there have been only a few investigations conducted on the adjustment of MPM for simulating concrete structures that experience impulsive and blast loads.

   The smooth particle hydrodynamics (SPH) technique, initially introduced by [34], is widely utilized as a meshless method. In contrast to the conventional finite element (FE) grid method, SPH permits the tracking of material deformation and time-dependent behavior. Additionally, the SPH model can accommodate intricate material models commonly employed in traditional FE models. A demonstration of the application of the MPM and SPH methods in modeling concrete slabs under blast loads is depicted in Figure 5. The outstanding performance of SPH has resulted in its integration into the solvers of commercial software such as AUTODYN and LS-DYNA, thereby facilitating its extensive usage.

   Johnson et al. [35] developed a generalized particle algorithm (GPA), which initially models the structure using continuum FE. When certain conditions for failure or erosion are satisfied, the components undergo a transformation into particles without a mesh structure. However, similar to the MPM and SPH methods, the GPA method is unable to accurately predict fragment size distributions because they are dependent on the predefined particle size.

3. *Methods that combine elements of both finite element (FE) and mesh-free techniques*. Although the meshless method has been widely used and has shown good performance, it does have some limitations. One of these limitations is the higher computational cost compared to the conventional FE method when dealing with meshless particles. However, the Smoothed Particle Hydrodynamics (SPH) approach, which is a Lagrangian formulation, allows for a connection between meshless methods and standard FE models. Over time, several methods have been developed to couple mesh-free methods with FEs, and Rabczuk et al. [36] provides a comprehensive overview of these methods.

   One of the initial methods for coupling involves the interaction between fluid and structures. In this method, the fluid is depicted using a meshless technique, while the structure is depicted using FEs. During the computations, forces are evaluated to avoid the particles from penetrating the surfaces of the elements, referred to as the master-slave coupling. The approach utilizes a mesh-free technique to represent the fluid and employs finite elements to represent the structure. Throughout the calculations, forces are determined to ensure that the particles do not penetrate the surfaces of the elements, which is known as the master-slave coupling.

A different approach to connecting particles and FEs is through the utilization of mixed interpolation functions in the transitional zone. This method offers an alternative way of coupling the two components. One example is the implementation of a sliding interface to couple SPH particles with FEs. When an SPH particle is linked to an FE, its motion equation is defined by the forces applied by the neighboring SPH particles and FE elements. If there is no linkage between the SPH particles and FEs, the particles will glide across the surface of the FEs. In these situations, a dedicated algorithm for a sliding interface becomes essential [37]. The simulation presented in Figure 6 employed a combined SPH-FE model to replicate fragments.

A new approach was developed and utilized by [38] called the coupling method, which employs Lagrange multipliers. This method can be used with or without an overlapping zone. Researchers have discovered that when compared to alternative methods of coupling, this particular approach exhibits a highly desirable rate of convergence. In their study, Caleyron et al. [39] employed this method in analyzing the response of a reinforced concrete (RC) slab subjected to impact. In their analysis, the concrete was represented using particles, while the r/f was modeled using beam elements. The findings suggest that this approach holds promise for accurately predicting the behavior of RC structures under dynamic loading conditions. By utilizing particle-based modeling for the concrete and beam elements for the r/f, the researchers were able to achieve a favorable convergence rate, thereby enhancing the accuracy and efficiency of their analysis. This research contributes to advancing our understanding of the impact response of RC slabs and paves the way for further investigations in the field of structural dynamics.

In contrast to the aforementioned methods, Johnson and Stryk [40] proposed a different technique to address the issue of finite element (FE) mesh distortion. They introduced a combined SPH and FE method. In the process of dynamic response, the technique employed here transforms severely distorted components into particles that do not require a mesh. This approach is especially well-suited for addressing issues that involve localized distortion, such as the structural response caused by contact detonation. In these cases, the distorted elements can have a significant impact on the overall structure. By converting them into particles and using appropriate contact algorithms, this effect can be accurately captured and preserved [41].

4. *Alternative approaches*. In addition to the previously mentioned approaches, an alternative method called the discrete element method (DEM) has been proposed by [42] and utilized for simulating damage and fragmentation under extreme loading rates [43]. This method, which is also a mesh-free Galerkin method, is recognized as a more advanced option for examining the mechanical behaviors of fractured masses. By precisely defining the failure of materials, the Discrete Element Method (DEM) has the capability to simulate the dissipation of energy that occurs during the process of fracture. It can also analyze the kinetic energy of each individual cell involved. Nevertheless, it is crucial to acknowledge that this approach does have its limitations, especially in relation to the computational expenses involved. Furthermore, it may not accurately predict the initiation and spread of cracks in concrete, since these factors are influenced by the chosen discretization model.

The Lattice Discrete Particle Model (LDPM) is a three-dimensional model of the meso-structure of concrete that was developed by [44]. This model has been extensively calibrated and validated through various quasi-static and dynamic loading conditions. It has consistently demonstrated its ability to accurately predict both the qualitative and quantitative behaviors of concrete. The LDPM has become widely used in simulating fiber-reinforced concrete under dynamic loading scenarios. Figure 7 showcases the typical LDPM and provides predictions of fragmentations in structures subjected to impact loads. In this particular approach, it is crucial to acknowledge that the formation and spread of cracks are impacted by both the predetermined size of particles and the unpredictable arrangement of said particles. It is worth emphasizing that the size of particles is predetermined, meaning that it has been established beforehand and is not subject to change. Additionally, the distribution of particles is random, implying that there is no specific pattern or order to how they are arranged. These two factors play a significant role in determining how cracks initiate and propagate within the given context.

Typically, there may be doubts about the reliability and effectiveness of continuum finite element (FE) models that utilize a Lagrangian mesh when it comes to predicting how structures will respond to blast loads. These models often require the adoption of erosion algorithms or the use of interfacial element models, which in turn necessitate a significant amount of "remeshing". On the other hand, meshless methods like SPH, MPM, GPA, DEM, and LDPM are capable of effectively handling element breaking. However, these techniques frequently prove inadequate in dealing with the initiation and spread of cracks in concrete, as well as the distribution of fragment sizes. Bonet and Kulasegaram [45], Rabczuk et al. [46], and Vignjevic et al. [47] have engaged in discussions on potential methods and adjustments to ensure that fractures occur solely due to physical factors. Nevertheless, there is still a need for more effective approaches in addressing these issues.

A new method has been introduced in a recent study that integrates the principles of continuum damage mechanics and the formation of micro-cracks to investigate a particular phenomenon [48]. This innovative two-step stochastic method has been introduced in order to analyze the phenomenon in greater detail. The main objective of the research was to gain a thorough comprehension of the procedure by integrating the concepts of continuum damage mechanics and the evolution of micro-cracks. By utilizing this method, researchers can gain insights into the underlying mechanisms and factors contributing to the phenomenon under investigation. The incorporation of these principles allows for a more accurate and detailed analysis, enhancing our knowledge and providing valuable information for further research in the field. The approach utilizes a straightforward algorithm to forecast the trajectory of fragments and the distance they are launched, taking into account factors such as the size of the fragments and their ejection velocity.

6. Conclusions

This article presents a comprehensive overview of the latest advancements in numerical simulation tools and methodologies used to predict how infrastructures and facilities respond to explosions. It discusses various topics including structural responses, pressure-impulse diagrams, existing design methods, and different numerical simulation tools and methodologies. Additionally, the article explores the challenges faced when modeling blast scenarios and analyzing structural responses using different numerical methods. After examining prominent publications on blast loading, it is clear that the study of this subject is still in its early stages. Therefore, before further growth can occur, it is crucial to compare and cross-reference the findings of the available works. Based on this review, several noteworthy points emerge.

- It is not unusual to encounter instances of extreme loadings on infrastructures as a result of intentional or unplanned explosions. The recent explosion of ammonium nitrate at Beirut seaport in Lebanon and the resulting devastation serve as a wake-up call. The danger presented by explosives has transformed from the utilization of high-powered weapons aimed at cities to the use of medium-range weapons that specifically target industrial hubs and military objectives with enhanced precision. Consequently, it is crucial to integrate adequate measures to resist the impact of explosions in the assessment and development of infrastructure and establishments.
- Ensuring the safety of infrastructures from unplanned explosions and intentional blasts is a matter of utmost importance. When a significant quantity of explosive substance is triggered in the air, the heated and highly compressed gases produced quickly displace the surrounding atmosphere, leading to the formation of an explosion wave. Furthermore, it is becoming increasingly important to ensure that essential elements have the ability to withstand blasts in order to avoid the occurrence of disproportionate or gradual collapse within the building. In order to prevent structural damage caused by progressive collapse, it is crucial to apply ductile design principles and integrate redundancy into the structural system. This approach is similar to the strategies used in earthquake-resistant design for infrastructures. By implementing these measures, the risk of structural failure can be significantly reduced.
- Numerous numerical tools and techniques have been accessible in the literature. Nevertheless, it remains uncertain which numerical approach should be regarded as the most superior or accurate one.
- Modern buildings are naturally sturdy in their construction, which is why the key to improving their ability to withstand blasts lies in preventing the blast from entering the building. This objective can be achieved by implementing a robust building facade that utilizes laminated glazing assemblies. Additionally, creating a significant distance between the blast source and the building can further enhance its performance against blasts. However, in densely populated cities, it may not be feasible to have a large standoff distance. Alternative methods

such as blast walls, sacrificial components, or barriers that provide a clear line of sight offer more effective ways to mitigate the risks associated with explosions in such situations.

- Numerical simulations have proven their efficacy in providing accurate results when analyzing explosions, with the most advanced methods being those based on CFD and neural networks. The use of numerical simulations offers a substantial improvement over simplistic empirical techniques in predicting blast parameters. Currently, CFD simulations can capture intricate flow-field behaviors with reasonable accuracy. Nevertheless, these models may still require further refinement to enhance their precision and are computationally demanding. The exact fidelity, features, and inputs necessary for these simulations to achieve satisfactory agreement with experimental measurements are not universally established. In fact, the lack of high-quality experimental data, comparable in sophistication and detail to numerical modeling approaches, is currently impeding progress in this field.
- Simulating the anti-explosion response of infrastructures can be effectively achieved through numerical simulation. However, to accurately replicate the response of the infrastructure, a high-quality numerical or analytical model is essential. This alternative methodology provides a reliable approach for analyzing the blast resistance of structures.
- The weather conditions, such as temperature, humidity, and wind, present at the test location can have an impact on the pressure and time history of a blast, consequently affecting the performance of the structure being tested. It is important to include information about the weather conditions when reporting on experimental studies and when conducting numerical or analytical research works.

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