Numerical Study of Blast-Induced Primary Injury in Mosques: Identifying High-Risk Zones and Structural Implications

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Abstract: The present study employed numerical simulations to investigate the impact of blast waves on people praying inside a mosque. The study also investigated the influence of the location and intensity of the explosion. The inviscid Euler equations were solved numerically using a finite volume method. Dynamic mesh adaptation to coarse initial cells has proven suitable for predicting qualitative and quantitative flow features. It was assumed that explosives of different TNT equivalent weights (1.5kg, 2.5kg, and 5kg) would be detonated deliberately in two locations in the mosque: at the front and in the center. This is the weight of a typical pipe bomb or suicide explosive belt that can be carried maliciously. The flow visualizations are analyzed using a schlieren image. The time history of overpressure is monitored at several locations inside the mosque. The results reveal that the impact of explosions on the eyes, lungs, and brain varies depending on the location of the mosque. Blast waves from confined-space explosions are intensified by reflective surfaces. Individuals praying at the front and center of the mosque are assumed to be the primary targets and are more susceptible to inevitable death. However, those praying close to the reflective walls, particularly near the corners of the mosque, are at risk of primary injury due to the repeated reflections of the blast waves. The current findings will prove invaluable in the design of effective safety measures to mitigate the impact of explosions on people.

Keywords: Blast-structure interaction, CFD, compressible flow, injury prediction, numerical analysis.

دراسة عددية للإصابات الأولية الناجمة عن الانفجارات في المساجد: تحديد المناطق عالية الخطورة والآثار البنيوية

الملخص: استخدمت الدراسة الحالية محاكاة عددية للتحقيق في تأثير موجات الانفجار على المصلين داخل المسجد. كما بحثت الدراسة في تأثير موقع وشدة الانفجار. تم حل معادلات أويلر غير اللزجة عدديًا باستخدام طريقة الحجم المحدود. أثبت التكيف الشبكي الديناميكي للخلايا الأولية الخشنة أنه مناسب للتنبؤ بخصائص التدفق النوعية والكمية. افترض أن المتفجرات ذات الأوزان المكافئة المختلفة لمادة تي إن تي (1.5 كجم، و2.5 كجم، و5 كجم) سيتم تفجيرها عمدًا في موقعين في المسجد: في المقدمة وفي المنتصف. هذا هو وزن قنبلة أنبوبية نموذجية أو حزام ناسف انتحاري يمكن حمله بخبث. يتم تحليل تصورات التدفق باستخدام صورة شليرين. يتم مراقبة التاريخ الزمني للضغط الزائد في عدة مواقع داخل المسجد. تكشف النتائج أن تأثير الانفجارات على العينين والرئتين والدماغ يختلف حسب موقع المسجد. يتم تكثيف موجات الانفجار من الانفجارات في الأماكن الضيقة بواسطة الأسطح العاكسة. يُفترض أن الأفراد الذين يصلون في مقدمة ووسط المسجد هم الأهداف الأساسية وهم أكثر عرضة للموت الحتمي. ومع ذلك، فإن أولئك الذين يصلون بالقرب من الجدران العاكسة، وخاصة بالقرب من زوايا المسجد، معرضون لخطر الإصابة الأولية بسبب الانعكاسات المتكررة لموجات الانفجار. ستثبت النتائج الحالية قيمتها في تصميم تدابير السلامة الفعالة للتخفيف من تأثير الانفجارات على الناس.

1. Introduction

When high-level explosions occur, a significant amount of energy is released and this triggers the propagation of a blast wave that spreads outward. The resulting overpressure, which is characterized by a positive pressure rise, is linked to the initial blast wave created by the explosion. As this blast wave continues to expand, the positive phase is eventually followed by a decrease in pressure and the emergence of a negative wave. The duration of the positive phase is dependent on the amount of energy released and the distance from the center of the explosion [1]. The global prevalence of terrorist attacks has increased from five thousand in 2007 to more than sixteen thousand in 2020 [2]. Mosques are the most vulnerable to suicide attacks by terrorist groups that pose a serious threat to human life, security, property, and buildings [3, 4].

When a blast wave interacts with surrounding structures, it creates a reflected wave that amplifies the overpressures [5, 6, 7]. This interaction between the blast and structure can significantly complicate the evolution of the blast wave [5, 6, 7, 8]. The confined explosion is a phenomenon that triggers a series of shock-focusing events. These events, known as regular and Mach reflections, occur due to interactions between two or more waves [5, 9]. As a result of these interactions, high-pressure zones are created, which can have significant implications for the surrounding environment [5]. These pressure zones can cause damage to structures and other objects in the vicinity and can be a safety concern. Therefore, understanding the mechanics of shock-focusing events is crucial for predicting the impact of confined explosions and mitigating any potential risks. It has been found that explosions that occur in proximity to structures can have devastating effects. The shock waves from the blast can reflect and increase the pressure near the structures by two to nine times [10]. Research has proven that explosions that are confined in a specific area cause greater loss of human lives and destruction compared to explosions that are out in the open [10-13].

In the unfortunate event of an explosion, the blast overpressure is felt by the human body. As the pressure wave reaches the body, it encounters resistance and some of it is reflected, whereas the rest is transmitted through the body. This causes a sudden and violent physical movement that can lead to the displacement, distortion, or even tearing of the medium, such as organs, and tissues. It is worth noting that these injuries occur without any visible blunt force injury or penetrating injury, making them even more dangerous and difficult to detect [14, 15]. Blast injury is a unique condition that has a high mortality and morbidity rate. There are different types of blast injuries, including primary, tertiary, secondary, and quaternary injuries [14, 15]. Primary blast injuries (PBIs) happen when the energy from a blast wave passes through the body and causes damage to the tissues. This damage can occur in tissues that have a significant density change, such as the lungs, brain, and ear canals, even if there are no external signs of injury [14-16]. PBIs can be caused by spallation, implosion, and shearing injury mechanisms [17]. PBIs can cause immediate or delayed effects, ranging from mild to life-threatening [17]. However, the severity of PBIs depends on factors such as the size of the explosive, duration of overpressure, and proximity to solid structures [14]. It is possible to sustain single or multiple blast injuries at once, depending on the intensity and duration of the explosion [17, 18]. For instance, the closer one is to the center of the explosion, the higher the chances of severe injuries. The distance from the center of the explosion also plays a role in the severity of injuries. A probe located three meters away from the explosion experiences nine times greater overpressure than a probe located six meters away [10].

It was found that terrorism-related explosions result in unique injuries and increased mortality compared to those caused by non-terrorism-related explosions [19]. It is essential to seek medical attention immediately after experiencing a blast injury, regardless of its severity. Delayed symptoms may manifest, such as respiratory distress, chest pain, and abdominal discomfort [17]. Timely medical intervention can improve the chances of recovery and minimize long-term complications.

When it comes to preventing primary blast injuries (PBIs), it is important to have accurate predictors of the minimum effective overpressures (thresholds) that can cause them. During the analysis, it is significant to observe limits to ensure that loading conditions are clinically relevant, realistic, and practical even though many experimental loading conditions are achievable [20]. Whereas multiple injury criteria have been used for this purpose, it is worth noting that the occurrence of PBIs can be influenced by other factors as well. Human orientation and proximity to solid structures, for example, can significantly impact PBI risk, resulting in injuries occurring at overpressures that are either below or above the expected threshold [20]. This information comes from a recent study by Denny *et al*. [11], which provides valuable insights into the complex nature of PBI risk. By considering these factors when assessing PBI risk and developing appropriate safety measures, one can better protect individuals from harm and reduce the risk of PBIs occurring in explosive events. It is imperative to consider the devastating impact of blast overpressure on the human body, particularly on the auditory system. Because the ear is the most sensitive organ, the most common injuries following exposure to blast overpressure are those affecting the ear [21]. Even a blast wave with a relatively low overpressure value of 35 kPa can rupture the eardrum and cause damage to the middle ear [21, 22]. This is a serious concern, as the eardrum is an essential component of the human ear, responsible for transmitting sound waves to the brain. Furthermore, it has been shown that exposure to overpressure levels of 103 kPa and 202 kPa respectively can increase the risk of eardrum rupture by up to 50% and 100% [21, 22].

When high explosives are detonated, primary blast lung injury is the most common cause of death, particularly, in confined spaces [16, 17]. When an explosion occurs, the overpressure can cause hemorrhage in the alveoli of the lungs, leading to a lack of oxygen and suffocation, which can ultimately result in acute respiratory distress syndrome [16, 23, 24]. Even a small 100-gram hand grenade can cause fatal lung injury [25]. A peak overpressure of 689 kPa-1,379 kPa is considered potentially lethal [11]. Practicing doctors have proposed a lung injury score to classify the severity of acute respiratory distress syndrome based on medical diagnosis [16]. The brain, being the most important organ in the human body, is particularly vulnerable to injury from exposure to excessive pressure. Such injuries can cause significant damage and lead to long-term cognitive and behavioral impairments, even resulting in death in some cases [18, 26] Therefore, it is crucial to ensure that the brain is adequately protected and not exposed to extreme pressure to avoid such severe consequences. Additionally, it is important to consider that the effects of blast overpressure are not solely physical. On the other hand, the organ of the gastrointestinal tract can suffer damage in the face of such an event [27]. Contusions and ruptures may harm the eyeball and lead to poor visual outcomes [28]. Furthermore, concussion can manifest even in the absence of obvious physical signs of head injury [29].

The task of determining the effect of strong blast waves on humans is a challenging one that requires laboratory experiments [7]. It is more feasible to achieve blast waves with positive phase durations of 2-10 ms experimentally; However, conducting such experiments is not always possible due to safety and ethical concerns that need to be addressed [20].

As a result, computational fluid mechanics (CFD) has emerged as a useful tool for evaluating the risk of blast injuries and mitigating their effects. This approach involves simulating the complex behavior of fluids and gases in response to explosive events. By analyzing these simulations, one can gain a better understanding of the physics underlying confined explosions, which are known to be particularly hazardous. By using CFD, one can make accurate predictions about the pressure and blast waves generated by explosive events, as well as their effects on the human body. This knowledge can pave the way for the development of more effective safety measures that can protect people from blast injuries and prevent catastrophic outcomes [23].

The present research addresses a critical research gap by focusing on the dynamics of confined explosions within mosque structures, which has received limited attention despite its relevance to public safety and counterterrorism efforts. Existing studies on blast effects primarily focus on open spaces or general urban environments, often neglecting the unique architectural and spatial characteristics of mosques. These structures, with their high levels of occupancy and reflective surfaces, pose distinct challenges in blast propagation and injury prediction. By employing CFD to simulate explosions and assess PBIs, this study provides essential insights into the heightened risks in confined spaces. The results of the study are of immense significance because they provide valuable insights into the intricate mechanisms that govern blast wave propagation and their impact on human bodies. Expanding the study emphasis on these distinctive contributions could enhance its significance to a broader audience, including architects, urban planners, public safety officials, and policymakers. Bridging this knowledge gap is crucial for informing targeted safety measures, architectural improvements, and emergency response strategies in vulnerable community spaces.

The following four main sections offer an in-depth analysis and detailed insights into the research process. The section on test case definition lays the foundation for the subsequent research, whereas the research methodology section provides a thorough overview of the methods used. The simulation results section presents data-driven insights and analysis, and the final section on conclusions and recommendations offers valuable suggestions for future research.

2. Problem definition

In the present study, a mosque building that covers an area of 600 m^2 (30 $m^2 \times$ 20 m^2) is considered. The confined building is shown in Fig. 1. It is important to note that there is only one entrance gate located in the middle of the back wall. Additionally, there are two emergency exit doors situated on the side walls. The gate and exit doors are treated as solid walls, as they remain closed at all times. The mosque is capable of accommodating up to 720 prayers that are distributed in 12 rows. The mosque has four columns with a diameter of 60 cm that are crucial to the structural integrity of the building. These columns provide necessary support to the mosque. However, in the model, these columns were not taken into account as their impact on the overall design was considered insignificant. As the building is symmetric around the y-axis, the simulation can be performed for half of the domain. Thus, the centerline is set as a symmetrical boundary whereas the other sides are set as wall conditions, as depicted in Fig. 1.

As mentioned previously, it is expected that the location and amount of explosions will cause varying damage. Explosives of different TNT equivalent weights, 1.5 kg, 2.5 kg, and 5 kg, are deliberately detonated in two locations in the mosque, in the front row of prayers, and in the middle of the mosque. The two explosion locations, indicated by a large circle in Fig. 1, are chosen based on previous suicide terrorist incidents that occurred in mosques [3].

The weight of 1.0 kg - 3.0 kg resembles to pipe bomb that can be carried maliciously in a carrying case [12, 30]. A TNT package weighing 5.0 kg is the typical weight of a suicide belt [30, 31]. It is worth mentioning that the energy released from one kilogram of TNT equivalent could demolish a small vehicle [30]. The blast wave parameters are estimated at a 0.5m stand-off distance using empirical formulas [1, 32]. The ambient conditions are 1.225 kg/m^3,1atm, and 20 ºC, for density, pressure, and temperature, respectively. Blast overpressure histories are monitored to estimate the PBIs at six probe locations (A, B, C, D, E, and F) around the mosque as presented in Fig. 1.

3. Computational methodology

The present study employs computational fluid dynamics (CFD) to simulate the explosion and the consequent transient blast wave propagation. The finite volume method using Ansys Fluent is used to solve Euler's equations, which can be written in matrix form and the two curvilinear co-ordinates, ξ and ζ, as:

$$\frac{\partial U}{\partial t}+\frac{\partial F_{\xi}}{\partial \xi}+\frac{\partial F_{\zeta}}{\partial \zeta}=0 \qquad (1)$$

where *F* represents the inviscid flux, *t* is time, and *U* is the conservative variables:

$$U=(\rho,\rho u,\rho v,e)^{T} \qquad (2)$$

where ρ is the density, *u* and *v* are the velocity components, and *e* is the total energy per unit volume. The pressure, *p*, is calculated by the ideal gas equation of state based on internal energy, *i*:

$$p=\rho(\gamma-1)i \qquad (3)$$

The explosion flow is simulated as an ideal gas, which has a specific heat ratio, γ , of 1.4 and a gas constant of 287 J/kg.K.

The rationale for using the two-dimensional (2D) model is that this approach captures the essential interactions of blast waves with reflective surfaces and structural boundaries, which are critical to understanding injury risks and overpressure patterns. The 2D model exploits the symmetry of the mosque layout, ensuring accurate results while reducing computational complexity. By using this simplified model, the study efficiently explores multiple blast scenarios and intensities, providing key insights into high-risk zones and structural vulnerabilities. Ultimately, while 3D models provide additional detail, the 2D approach is sufficient to identify broad patterns in blast dynamics and their implications [5, 6].

A second-order scheme is adopted to estimate the compressible spatial flow. An explicit first-order scheme is used to estimate the transient terms. A structured quadrilateral mesh with an initial size of 45,600 cells is used to solve the half-domain. Dynamic mesh adaptation is used to refine the mesh up to three times wherever the density gradients exceed 5% of the local normalized value.

On the other hand, the mesh becomes coarse where the density gradient is below 2%. By refining only in regions with significant density gradients, the approach captures critical phenomena such as shock focusing and wave interactions without overburdening computational resources.

Higher mesh refinements were also considered, but the triple mesh refinement ensures a precise balance between accuracy and computational efficiency. The results, which are not shown in the manuscript, clearly show that the resolution is independent of the mesh. Limiting the refinement to three levels avoids diminishing returns in accuracy while maintaining reliable results.

4. Results and discussion

A. *BLAST VISUALIZATION*

This section presents numerical schlieren snapshots that showcase the propagation of explosions inside a confined mosque building. These snapshots are based on the density gradient magnitude and depict the salient features of blast wave interactions and reflections. The intentional explosions took place in two locations, the front row of prayers and the center of the mosque. The explosives of varying weights of TNT equivalent (1.5 kg, 2.5 kg, and 5 kg) are detonated, which results in identical explosion patterns. However, there are differences in the time scale and intensity of the explosion. Therefore, only one numerical schlieren snapshot of each explosion location will be demonstrated. The numerical schlieren of a blast in the front row of prayers and the center of the mosque are illustrated in Figs. 2 and 3, respectively. These snapshots illustrate the evolution of explosion propagation, reflection, implosion, interaction, and diffraction.

The first snapshot of Fig. 2 reveals a striking phenomenon in the aftermath of the frontal explosion. As the primary incident wave, I, reaches the center of the mosque (probe B), it is followed by a series of pressure waves that explode in all directions. It is interesting to highlight the shock-focusing phenomenon. Of particular interest is the Mach reflection that causes the creation of a new Mach stem, M [5, 9]. This stem connects the triple intersection point, TP, of the incident wave segment, I, and the reflected wave segment, R, as displayed in Fig.2. The TP also connects with the contact surface, CS. What's noteworthy about the Mach stem wave, M, is that it has a higher pressure than the incident wave, I. As the blast progresses, it becomes evident that the front cavity of the mosque, where the leader of prayers (imam) usually stands, is filled with blast waves, as depicted in Fig.2. In the second snapshot, the Mach stem, M, grows and reaches probe D located next to the front corner of the mosque.

When the Mach stem, M, reflects off the sidewall, it creates shock focusing, a phenomenon that involves two-wave interactions known as regular reflection [5, 9]. The point where Mach stem, M, and reflected wave, R, converge moves along the sidewall towards the back wall whereas keeping the two waves together, as shown in the third frame of Fig. 2. The area where the regular reflection intersects is also a high-pressure zone [5].

It is important to note that when the explosion charge is larger, the regular reflection transforms into Mach reflection as it progresses along the solid structure [5, 9]. In this scenario, waves are being reflected and moving towards the center of a mosque. These reflected waves, R, are interacting with secondary waves, S, that are heading in the opposite direction.

This is shown in the third and fourth frames. In the fourth snapshot of Fig. 2, the crest of the incident blast wave reaches probe C at the closed main gate on the back wall. A compression wave, which accumulates secondary waves and reflected waves from the front wall or the cavity, moves behind the main incident wave. The last two snapshots of Fig. 2 depict the incident wave reflecting from the back wall and heading toward the frontal side of the mosque. Additionally, two waves reflected from the side wall head toward the center of the mosque. It can be observed that the reflected wave moves faster within the core of the explosion because of the higher sound speed in this region. It is worth noting that the last snapshot of Fig. 2 shows the creation of a new triple point, TP, for the two waves reflected from the back wall and the Mach stem, M, moving forward along the sidewalls.

Fig. 3 illustrates the development of the flow field resulting from the central explosion. Two cylindrical waves, caused by the incident and compression, exploded in a roughly symmetrical manner. These waves interacted with each other and with the low-density core of the explosion after reflecting from the solid walls of the mosque. The first snapshot of Fig. 3 shows the incident blast wave arriving at the location of probes A and C, which are positioned on the front and back walls, respectively.

The second snapshot depicts the arrival of the incident wave sidewalls followed by the explosive pressure waves. It can also be observed that the explosion almost filled the imam’s place in the front cavity of the mosque. The second snapshot of Fig. 3 also shows the reflected incident waves from the front and back walls. These waves nearly approach the center of the explosion in the third and fourth snapshots. Regarding the sidewalls, the incident wave segments reflected from them creep toward the center of the mosque, and the secondary waves head toward them as shown in Fig. 3. It is noteworthy that for a blast wave initiated at the center of the mosque, the shock focusing type is regular reflection. Therefore, the type of reflection of the shock-focusing events is dependent on the distance of the explosion charge from the solid structure [5, 9]. The closer the explosive charge is to the solid surface, the more the Mach stem dominates the entire incident wave [5].

Mosque-confined explosion configurations for structure-to-wave and wave-to-wave interactions are well-defined in the illustrated evolution of explosions. As expected, the flow field inside the mosque becomes increasingly complex over time. The cavity produces many wave interactions and reflections. There is a phenomenon that researchers have been interested in, which is the development of a complex flow structure around the sharp corners of the front cavity due to the diffraction of blast waves [33].

This phenomenon occurs for both blast locations. Moreover, bubbles of light-density air can be observed around the core of the explosions. The onset of Richtmyer-Meshkov instability is caused by the sudden acceleration of gases with varying densities, resulting in the continuous deformation that occurs in the core of the explosion [6].

In conclusion, this subsection highlights the complex dynamics of the propagation and reflection of the blast waves in the confined environment of the mosque. Both frontal and central explosions revealed shock-focusing phenomena, particularly at reflective surfaces and corners. In frontal explosions, Mach reflection led to the formation of high-pressure zones at corners, while central explosions displayed widespread regular reflections due to symmetrical wave interactions. These findings emphasize the need for structural designs that minimize sharp corners and reduce reflective surfaces to mitigate amplified pressure zones caused by these interactions.

B. DATA OF PROBES (OVERPRESSURES)

Table 1 provides a clear and concise overview of the recorded peak overpressure, P, and positive phase duration, D, at probes for varying blast intensities for the frontal and central explosions. The table serves as an informative reference for the given blast intensities. They are essential in understanding the nature and impact of the detonations on the risk of primary blast injuries (PBIs). It is noted that the peak overpressure increases with the increase in the intensity of the explosion, but the duration of the positive phase does not adhere to this rule, see Table 1. According to the data collected by the probes, the peak overpressures are ranked from most to least for both the frontal and central explosions. This information is indicated in Fig. 4, which provide a visual representation of the recorded data. For the front explosion, the highest peak overpressure is observed in the probes A, D, F, E, B, and C, whereas for the center explosion, it is observed in the probes B, D, F, C, E, and A, as presented in Fig. 4. Additionally, the data show that after the center of the explosion, the highest overpressure is recorded in the corners of the mosque for both frontal and central explosions.

The central explosion generates a significantly higher peak overpressure on the mosque corner probe D, as displayed in Fig. 4. Surprisingly, this effect remains true even though the explosion is farther away than the frontal one. This can be attributed to regular reflection which can have a significant impact on overpressure levels [5]. This indicates that the interaction of blast waves generates higher overpressure than a single traveling wave, even in cases where it is the Mach stem that generated the overpressure peak at the corner probe D in the frontal blast. This highlights the importance of understanding the complexities of blast waves and their interactions, which can have significant implications for safety and design considerations. It has been found that in the case of the mosque front explosion, the peak overpressure adjacent to the middle of the sidewall (probe E) surpasses probe B in the center of the mosque, even though probe E is nearly 8 meters further away from the center of the explosion than probe B. These findings are applicable to all blast intensities. A critical factor to consider is that placing the probe close to the sidewall exposes it to the high-pressure region of the moving Mach stem [5].

In conclusion, this subsection presents trends in peak overpressure and positive phase duration across multiple probe locations for varying blast intensities. The results show that peak overpressure increases with proximity to the blast epicenter and intensity of the explosion, but the duration of the positive phase varies with location and reflection dynamics. For frontal explosions, probes near corners (e.g., D and F) experienced high overpressure due to wave reflections, whereas central explosions exhibited a more uniform distribution of overpressure across the mosque. These trends are crucial for predicting injury severity, as areas with prolonged positive phases or amplified overpressure face higher risks of injuries.

C. *PRIMARY BLAST INJURIES (PBIs)*

Denny and his colleagues [11] created a graphical tool to estimate the likelihood of PBIs. The tool is visualized in Fig. 5 and displays the various zones of relevant blast loading conditions through solid and dashed lines. The graphical presentation provides a clear and comprehensive way to analyze and predict the risk of such injuries. The graph shows the threshold for lung blast injury for a 70 kg person standing close to a solid wall. It also displays the probability of death for 1%, 50%, and 99% based on previous studies by Bowen [23] and van der Voort *et al*. [25]. It has been shown that the severity of lung (pulmonary) injuries depends on the blast overpressure and the duration of the positive phase caused by an explosion [23, 25]. The dependency of lung injury risk on the duration of a blast decreases, as depicted in Fig. 5. Conversely, the occurrence of eardrum rupture [21, 22] and 50% mild brain hemorrhage [29] remains unaffected by the duration of the positive phase of the blast, as presented in Fig. 5. Notably, overpressure thresholds of 144 kPa can result in a 50% risk of mild brain hemorrhage [26].

The graphical representation provides a comprehensive and visually intuitive representation to assess the initial PBIs [11]. The graphical representation of predicted overpressures for different blast intensities within the mosque building is critical in assessing the risk of PBIs. The markers on the graph shown in Fig. 5 indicate the expected PBI risk for the predicted peak overpressure at each gauge location, which is calculated based on the simulations conducted in this study. Fig. 5 illustrates these results, providing a clear and concise visual representation of the data of probes A, B, C, D, E, and F. These findings will undoubtedly contribute to the development of effective measures that can help reduce the chances of PBIs and improve the safety of prayers in similar structures. The safety of prayers present in the mosque is of utmost importance. To ensure that, predicted risks of PBIs are carefully considered at two explosion locations, the first row of prayer and the center of the mosque. It is important to note that the peak overpressures for the front and center explosions are represented on the chart in Fig. 5 by the use of hollow and filled markers, respectively. This visual aid provides a quick and easy way to understand the data presented. Blast overpressure can have a severe impact on the human body.

It has been observed that the auditory system is susceptible to damage from blast overpressure, regardless of the duration of the positive phase. This is demonstrated by the eardrum rupture threshold of 35 kPa [21, 22]. This highlights the importance of protecting the auditory system during high-pressure situations. The onset of complete eardrum rupture occurs at approximately 205 kPa [23, 25]. The literature has not yet specified the blast overpressure threshold for brain hemorrhage. However, it is indicated a 50% risk of mild brain hemorrhage at approximately 145 kPa, as depicted in Fig. 5 [29].

To shed light on the PBIs resulting from a frontal explosion, it is alarming to note that even a less severe explosion of 1.5 kg could lead to certain death for those located near probes D and F, as shown in Fig. 5. The risk is higher for probe F, which is 7 meters away from the epicenter as compared to probe D. This is because of its location at the corner of the mosque, which makes it vulnerable to the interaction of two reflected shocks.

These reflected shocks increase the peak overpressure and pose a significant threat to human life. There are concerns about the safety of those who pray near probes A and E due to several PBIs, as displayed in Fig. 5. Several potential injuries include total eardrum rupture, 50% lethality from lung injury, and a 50% chance of mild brain hemorrhage for all blast intensities. It has been observed that probe E, located at a distance of 18.03 meters from the center of the explosion, experiences the same level of injuries as probe A, which is only 1.25 meters away from the center of the explosion. This can be attributed to the fact that probe E was subjected to a longer duration of the positive phase, which is more than 6 times longer than that at probe A, despite the peak overpressure at probe A being twice that of probe E, as presented in Fig. 5. Probes B and C indicate that the PBI risk is the lowest for explosives that weigh between 2.5 kg and 5.0 kg placed at the front of the mosque. Prayers, in this case, have a 50% risk of eardrum rupture and a 1% risk of death from lung injury. Fig. 5 illustrates that a low-intensity explosion weighing 1.5kg poses the same 50% risk of eardrum rupture as more intense explosions. However, in comparison, it poses less than 1% risk of death due to lung injury, as depicted in Fig. 5.

The blast at the center of the mosque results in the detection of primary blast injuries (PBIs). It is crucial to note that those who are praying at the location where probe B is situated are exposed to a deadly peak overpressure, regardless of the intensity of the explosion. Furthermore, individuals who are praying in the locations, where probes C, E, and F are located, are at serious risk of lung injury and death due to excessive peak overpressures, as presented in Fig. 5. The intensity of the blast has a different impact on the prayers at point E, as the explosions of weights 2.5 kg and 5.0 kg at the center of the mosque lead to 100% eardrum rupture, 50% lethality from a lung injury, and 50% mild brain hemorrhage. The peak overpressure from a 1.5 kg explosion can cause 50% mild brain damage, 50% ruptured eardrum, and 1% death due to lung injury, as displayed in Fig. 5.

The data clearly indicate that probe A is the safest location at 11.25 meters from the epicenter of the explosion. Whereas the higher two blasts can cause significant eardrum rupture and lung injuries, the minimum peak pressure of 1.5 kg has only a minor impact on prayers. However, probe C, located at the same distance as A, but near the back wall, suffered more serious injuries. This can be attributed to the location's proximity to the back wall, resulting in a higher peak overpressure. This highlights the importance of location in protecting oneself during such events. Based on the results, it is recommended that one should aim to avoid being close to any walls to minimize the risk of injury.

In conclusion, the subsection assesses the risk of PBIs based on the overpressure data at different probe locations for frontal and central explosions. In frontal explosions, probes near the epicenter (A) and reflective surfaces (D and F) had the highest injury risks, including lung rupture, eardrum rupture, and brain hemorrhage. Conversely, in central explosions, probe B at the detonation epicenter showed the most extreme overpressure, resulting in near-certain fatality regardless of blast intensity. Peripheral probes like E and C also faced significant injury risks due to prolonged positive phases. These findings stress the importance of identifying high-risk zones within confined spaces to guide safety protocols and evacuation planning.

D. *COMPARISON OF BLAST SCENARIOS: FRONTAL VS. CENTRAL EXPLOSIONS*

Two primary blast scenarios are investigated, frontal explosions (detonated in the front row of the mosque) and central explosions (detonated in the middle of the mosque). Each scenario exhibits distinct blast-wave propagation dynamics and injury risk profiles, influenced by the location of the detonation relative to structural boundaries and occupants. This section provides a detailed comparison of frontal and central blast scenarios. It explores the distribution patterns of the overpressure generated by each type of blast, examining how these patterns differ in terms of intensity and area affected. It also analyzes the dynamics of reflection in various environments are analyzed, highlighting how the direction and power of the blast interact with surrounding structures. Furthermore, the risk of PBI associated with each scenario is assessed, considering the potential injuries that could result from exposure to different levels of overpressure. Finally, the implications for safety measures that should be implemented in response to each type of blast are discussed.

In the frontal explosion scenario, the highest peak overpressure was recorded at probe A (1.25 meters from the explosion), with values up to 447 kPa for the 5.0 kg TNT equivalent. However, these effects were spatially localized due to the short positive phase duration (2.6 ms). High overpressure levels were also observed at probes D and F near the corners, driven by shock-wave reflections from solid walls. In contrast, the central explosion generated a more uniform distribution of overpressure across the mosque, with probe B at the epicenter experiencing an extreme overpressure of 6837 kPa (5.0 kg TNT equivalent). Corner probes D and F also recorded substantial overpressures (602–604 kPa), reflecting a more widespread impact due to wave interactions and prolonged positive phases.

Frontal explosions primarily endangered individuals close to the detonation and reflective surfaces. For example, probe A experienced the highest risk of PBIs due to the proximity to the explosion, including lung and eardrum injuries, although the short positive phase provided some mitigating effects. Corners D and F saw amplified injury risks due to Mach stem formation and wave reflections. Central explosions posed more widespread threats, with probe B indicating certain fatality risks for individuals at the epicenter, regardless of blast intensity. Peripheral probes such as E and C also showed increased risks due to prolonged wave interactions and higher overpressures compared to their counterparts in the frontal explosion scenario.

The differences in outcomes underscore critical considerations for safety planning. Frontal explosions exhibit higher localized risk near the front row and reflective surfaces, necessitating attention to the design of corners and proximity to walls. Central explosions, however, result in more extensive overpressure distribution, emphasizing the importance of structural reinforcements and protective measures across the entire mosque layout. Emergency planning should prioritize evacuation routes that avoid high-risk areas like corners and central rows while considering the dynamics of each blast scenario to optimize protective strategies.

In conclusion, this comparison highlights that while frontal explosions are more predictable in terms of injury localization, central explosions demand broader mitigation efforts due to their extensive impact range. Future architectural designs and safety measures should account for these distinctions to effectively reduce blast-related casualties in confined spaces.

5. conclusion

The paper emphasizes the critical need for measures to protect individuals from the harmful effects of blast waves, especially in high-risk environments like mosques. The findings of the study are useful for those interested in assessing and mitigating risks associated with explosions, as well as clinicians who need to determine safe limits for injuries caused by blast loads. The research utilized computational fluid dynamics to investigate explosions that occurred inside a confined mosque. The explosions are caused by the detonation of 1.5, 2.5, and 5.0kg TNT bombs, and they took place in the front and center of the mosque.

The interaction between the blast and the structure of the mosque significantly complicated the evolution of the blast wave. The history of overpressures is recorded at various locations around the mosque. In fact, the shock focusing on the interaction of two or more waves creates regions of very high pressure and temperature which can lead to various issues. As such, it is crucial to be aware of this phenomenon and take appropriate measures to mitigate its effects. The probe placed close to the sidewall is undoubtedly exposed to the high-pressure region of the moving Mach stem, which significantly impacts the primary blast injuries (PBIs). The location closest to the explosion centers poses the highest risk of injury or death, even with a TNT package weighing as little as 1.5 kg. Near the sidewalls record high overpressure with long wave duration due to reflection. However, the corners of the mosque (probes D and F) have the second-highest peak overpressure. Based on the research findings, it can be concluded that those who pray adjacent to the solid walls, especially near the corners of the mosque, are at the highest risk of PBIs.

For the frontal explosion, although the peak overpressure is the highest at probe A, the short duration of its positive phase makes it uncertain whether prayers located there will survive or not.

Raising awareness among the public, engineers, and healthcare professionals about the potential health impacts of explosions is vital for preventing tragic events and enhancing preparedness. Numerical simulations play a critical role in identifying high-risk buildings and informing safer architectural designs. The study's findings underscore the importance of minimizing reflective surfaces and sharp corners in mosque designs to reduce pressure amplification and associated risks. Strategic placement and proper sizing of emergency exits are essential to facilitate efficient evacuations in high-occupancy spaces. Furthermore, public education initiatives should focus on raising awareness about blast-related risks and protective measures, while emergency response agencies can leverage these insights to improve disaster planning and preparedness. By integrating these recommendations, communities can enhance the safety of gathering places like mosques and better protect individuals from the devastating effects of confined explosions. Another important consideration in architectural planning is human behavior during emergency evacuations. To ensure an effective evacuation plan for large groups, it is important to carefully design the location and size of emergency exits [34, 35]. Emergency response agencies should use this data to improve disaster education and response plans to minimize morbidity and mortality in the event of a terrorist attack.

Future research should explore confined explosions in diverse environments, such as schools, transportation hubs, and public gathering spaces, to generalize findings and refine safety measures. Incorporating human response modeling would provide valuable insights into the dynamic behaviors of individuals during emergency scenarios, enabling the development of more effective evacuation plans and injury mitigation strategies. Additional studies could also investigate the effects of varied structural designs and materials on blast-wave propagation to propose safer architectural practices.

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Table 1: Peak overpressure (P) and positive-phase duration (D) at probes for the frontal and central explosions.

Explosion	Probe	Distance (m)	1.5 kg		2.5 kg		5.0 kg	
			P (kPa)	D (ms)	P (kPa)	D (ms)	P (kPa)	D (ms)
Frontal	A	1.25	365	2.9	423	2.4	447	2.6
Frontal	B	8.75	112	7.3	143	12.5	149	12.7
Frontal	C	18.75	114	19.2	127	24	132	17.5
Frontal	D	15.05	326	10.3	383	12.2	399	10.9
Frontal	E	17.37	199	13.2	234	13.4	249	13.5
Frontal	F	24.01	295	18.6	323	20	333	20
Central	A	10.0	94	10	106	20.7	112	21.6
Central	B	0.0	5407	0.6	6837	0.6	5891	0.6
Central	C	10.0	255	20.1	300	13	325	11.6
Central	D	18.3	458	13.5	563	13	602	13.9
Central	E	15.0	176	11.4	210	11.5	236	10.7
Central	F	18.3	459	13.5	563	13	604	13.9

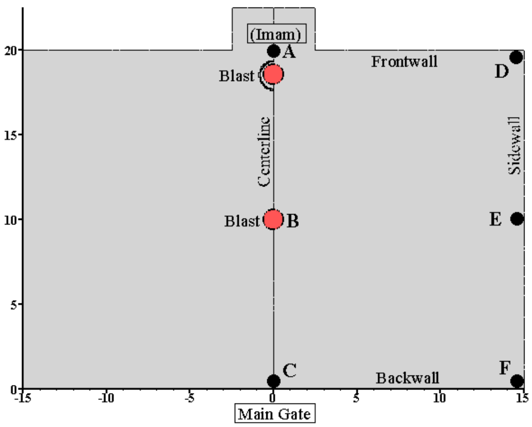

Fig. 1: Layout of the mosque showing the boundary conditions and assigned probe locations.

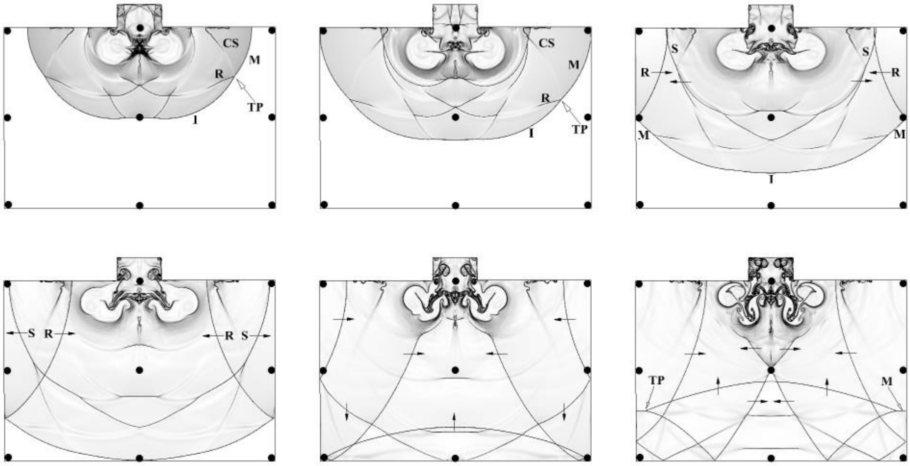

Fig. 2: Schlieren patterns for the propagation of the frontal-mosque explosion; black dots indicate probes. Incident wave, I; reflected wave, R; contact surface, CS; Mach stem, M; triple point, TP; secondary wave, S.

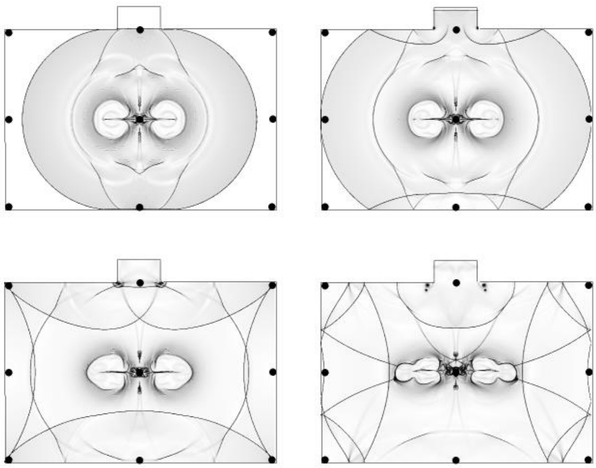

Fig. 3: Schlieren patterns for the propagation of central-mosque explosion; black dots indicate probes.

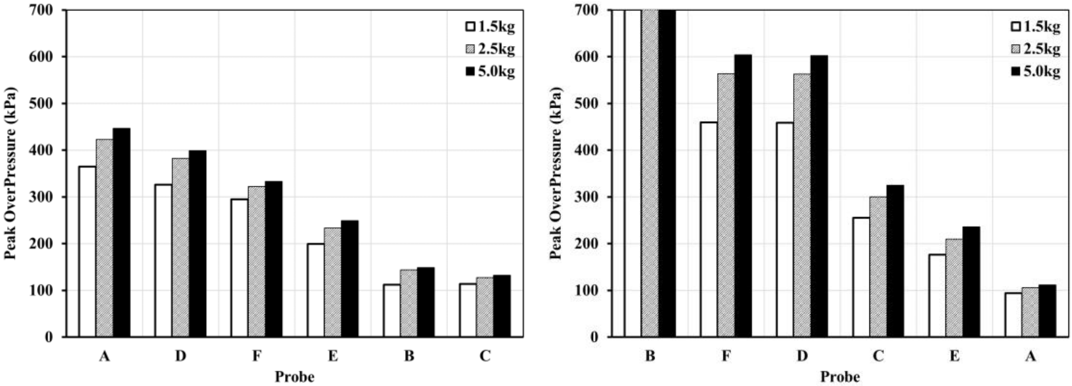

Fig. 4: Peak overpressure (arranged highest to lowest) at the probes for the frontal (left) and central (right) explosions.

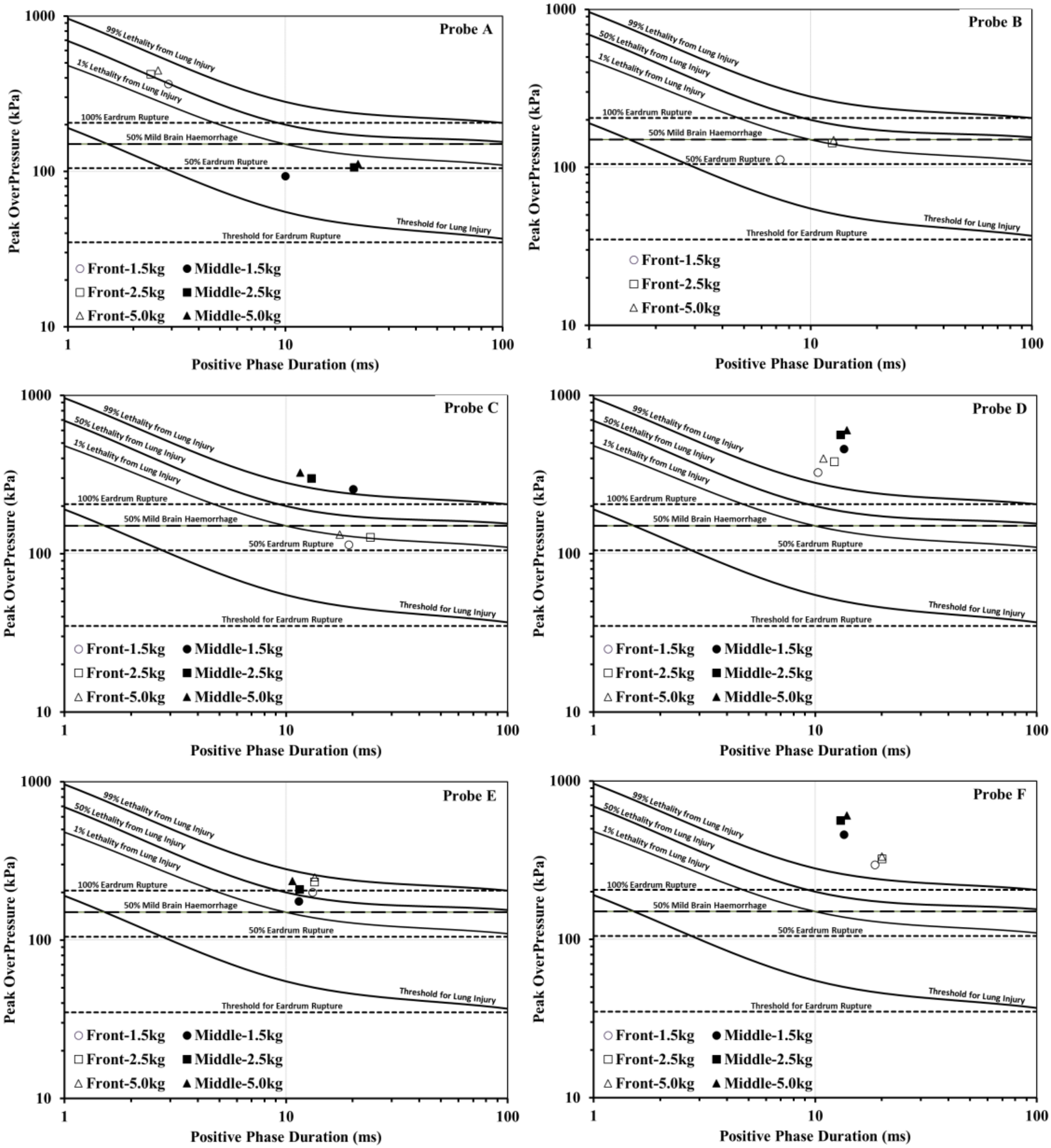

Fig. 5: Primary blast injury (PBI) risk at probes (denoted by markers) for different blast intensity plotted against the PBI criteria represented by Denny *et al*. [11] (denoted by lines).