

Article

Investigation of Model I Fracture in Tunnel Blasting Sections with Holes

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Abstract

In rock blasting for engineering applications—such as quarrying and tunnel construction—blasting is often detonated in carefully timed sequences to optimize rock fragmentation. This study examines Model I crack propagation in tunnel blasting sections with empty holes using circular PMMA (Polymethyl Methacrylate) samples containing pre-made initial cracks and empty holes. The distance between holes was varied from 10 mm to 30 mm. Using AUTODYN V18.0 numerical simulation software, how these holes affect crack initiation, propagation, and the surrounding stress field were analyzed. Key findings include the following: (a) Blasting stress waves diffract and reflect off empty hole edges, creating overlapping pressure zones between adjacent empty holes. Within a critical range of the empty hole distance, wider hole distance leads to slower stress wave propagation due to increased dispersion. (b) The empty holes weaken the stress concentration at crack tips, with greater distance further reducing peak strength. Proximal crack tips experience more pronounced stress field alterations than distal ones. (c) Holes hinder crack initiation, with the required stress intensity factor rising in near-linear proportion to hole separation distance.

Keywords: crack; empty holes; blasting experiment; crack propagation; stress intensity factor



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1. Introduction

Despite the emergence of modern techniques, controlled blasting remains a highly efficient approach in mining, quarry operations, and tunnel construction. Naturally occurring rock formations typically contain structural weaknesses—including cracks, fractures, and holes—that develop during geological processes. When subjected to blasting loads, these pre-existing flaws cause stress redistribution within the rock matrix. The dynamic loading often triggers fracture initiation and propagation along these natural discontinuities, ultimately resulting in rock fragmentation [1,2]. Researchers have extensively studied how uncharged boreholes affect fracture network development, yielding valuable insights into blast-induced crack behavior.

Mohanty [3] introduced a novel method for controlling fracture planes, suggesting that the concentration of stress caused by neighboring pressurized circles influences how cracks continue to spread. This technique works well with materials like plexiglass, gypsum cement, and robust inorganic polymers. Using a dynamic caustics experimental system, Yue [4] examined the stress field around holes subjected to blast stress waves. They

found that the direction of maximum tensile stress near the hole tends to shift roughly perpendicular to the line connecting the two holes. Wang's studies have shown that the presence of holes causes a rapid initial drop in dynamic fracture toughness at the crack tip from its peak, followed by oscillations up to a secondary peak before decreasing again until crack arrest [5]. Sankar [6], through dynamic experimental research using a Split Hopkinson Pressure Bar (SHPB), demonstrated that the diameter, distance, and arrangement of holes significantly affect the peak load and deformation patterns transmitted by stress waves in a cylinder. His findings indicated that a greater number of smaller-diameter holes leads to a more substantial reduction in peak load. Blasting tests on pre-drilled plates [7,8] have revealed that these holes induce varied effects on the plate's damage level, dynamic stress concentration factor, and overall stress state compared to plates without perforations. While the aforementioned research primarily investigates the effect of single holes on crack propagation, the influence of double or even multiple holes introduces a wider range of effects. Recent studies have begun to explore these more complex interactions [9,10].

Research by Li [11] demonstrated that the distance between adjacent empty holes significantly impacts crack propagation in PMMA blasting tests. Specifically, cracks are more likely to arrest when the distance between holes is reduced. Further experiments on PMMA diamond hole samples with model I cracks revealed that under compressive loading, larger angles and dimensions lead to a lower crack initiation force but an extended arrest length [12]. Studies on rock specimens indicate that hole geometry and lateral stress ratio play a crucial role in determining stress distribution and initiation conditions during blasting [13,14]. Bridwell's work [15] highlighted that the presence of holes increases the crack tip radius, reducing stress intensity and promoting crack arrest. The large-scale drop weight test, a common method for assessing material dynamic response, shows that stress waves reflect between holes, creating a compressive zone that inhibits crack growth perpendicular to their alignment [16]. Additionally, under dynamic loading, the surface effect of holes on crack propagation diminishes as hole size increases [17]. Yi's research [18] found that holes alter free crack propagation and stress fields, with normal stress on hole surfaces influencing stress intensity factors (K_I and K_{II}), while hole radius and distance have minimal impact. The crack path is also influenced by the angle between the hole and crack. Wang's drop hammer impact tests [19] revealed that at angles below 10° , cracks propagate directly toward the hole. At 20° and 30° , the path curves toward the hole without reaching it, with pure mode I fracture near the hole and a notable increase in propagation speed.

Although some research has been done on the effect of empty holes on crack propagation [20–22], there is still little research on the effect of empty holes on crack propagation and stress variation under blasting loads which have a higher loading rate and fast response [23–26]. In this paper, blasting experiments were conducted to obtain the influence of empty holes on the initiation, propagation, and surrounding stress field of cracks, and dynamic simulation software was used to study the crack initiation time, propagation path, and stress field when the blasting stress waves act on the holes. The results were mutually verified through blasting experiment and numerical simulations.

2. Blasting Experiment

This investigation aims to delve into the impact of empty holes (such as stemming holes, buffer holes, or cushion holes in blasting engineering) on the propagation of cracks caused by blasting loads. Consequently, circular plate samples featuring focused blast perforations, radial pre-existing cracks, and a double-holed configuration will be employed in subsequent blasting trials and numerical analyses.

2.1. Experimental Preparation

To investigate how empty holes impact crack growth during blasting, a radial pre-made initial crack and two empty hole samples are developed. The pre-made initial crack was finely honed with a razor-thin blade, featuring three such cracks in each sample, each spaced 120° apart, as depicted in Figure 1. The thickness of the blasting experiment sample is 15 mm, and the specimen and all holes are processed by laser equipment, ensuring effective accuracy and size. Due to the symmetrical nature of the stress wave generated by the central explosive hole, the three pre-made initial cracks remain dependent of one another. The explosive hole is situated at the center of the sample and measures 500 mm in diameter. The moment when the reflected tensile wave arrives at the distal pre-made initial crack tip is marked as t_r , while the crack initiation time at the same location is denoted as t_i (shown in Table 1). When t_i occurs before t_r , the reflected wave has no influence on crack initiation or growth—meaning the specimen dimension, 500 mm in diameter, is appropriately sized. A 7 mm wide explosive hole is bored and detonators are inserted. The main charge was Hexogen ($\text{C}_3\text{H}_6\text{N}_6\text{O}_6$), a 16 mm long explosive with a density of 1.8 g/cm^3 . The detonator's base charge was positioned within the explosive hole, and no couplings or blockages were employed during the blasting test. During the experiment, we secured the detonator with a circular rubber ring. The initial crack length was 30 mm, with the tip of the crack 10 mm from the center of the empty hole. The distance between the center of the two empty holes a ranged from 10 to 35 mm—specifically, 10, 15, 20, 25, 30, and 35 mm. Additionally, the horizontal distance from the center of the empty hole to the explosive hole was 55 mm.

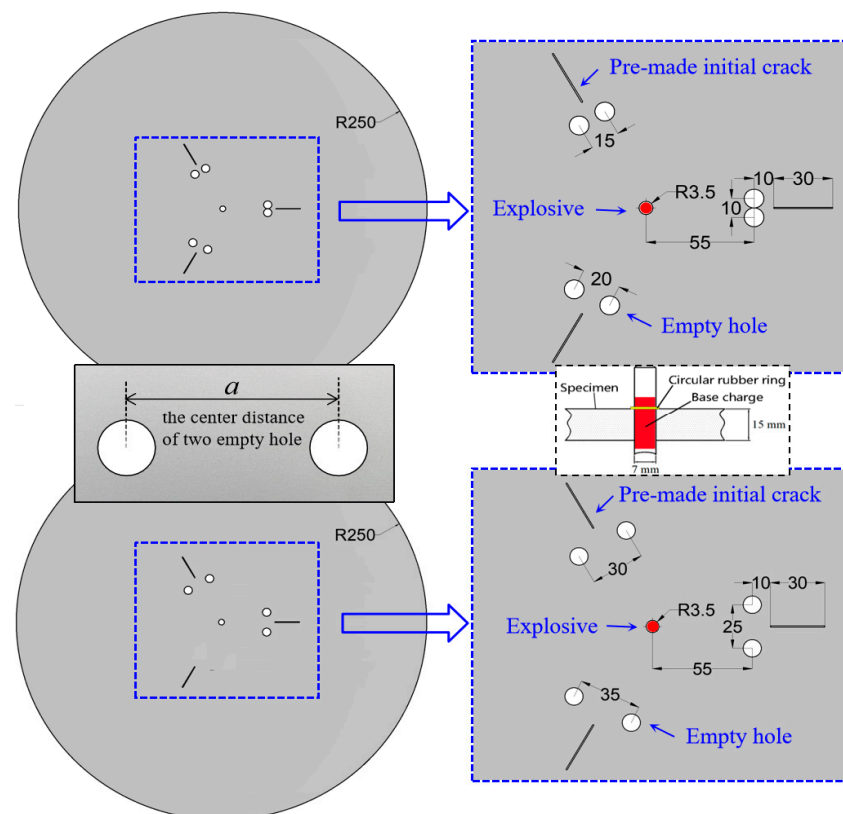


Figure 1. The specimen applied in blasting experiment.

Table 1. Dynamic propagation time of the specimens.

Time	Distance	No Holes	$a = 10 \text{ mm}$	$a = 15 \text{ mm}$	$a = 20 \text{ mm}$	$a = 25 \text{ mm}$	$a = 30 \text{ mm}$
t_i		58.10 μs	57.07 μs	53.12 μs	55.11 μs	58.02 μs	58.83 μs
t_r		187.5 μs	187.5 μs	187.5 μs	187.5 μs	187.5 μs	187.5 μs

Polymethyl Methacrylate (PMMA), behaving under fracture mechanics principles akin to rock, offers a clear window into experimental outcomes, making it ideal for this study. We assessed the dynamic mechanical properties of PMMA using a Sonic Viewer-SX, the results of which are summarized in Table 2. From these findings, we then computed the dynamic Poisson’s ratio utilizing Equation (1) [27].

$$\mu_d = \frac{C_p^2 - 2C_s^2}{2C_p^2 - 2C_s^2} \quad (1)$$

Table 2. Dynamic parameters of PMMA.

Parameters	P-Wave Speed $C_p/(\text{m/s})$	S-Wave Speed $C_s/(\text{m/s})$	Elastic Modulus $E_d/(\text{GPa})$	Poisson’s Ratio μ_d	Density $\rho/(\text{kg/m}^3)$
PMMA	2160	1450	6.1	0.31	1180

2.2. Blasting Experiment Loads

In this research, we have found that the fracture behavior of PMMA tracks closely with that of rocks, and this is a phenomenon that does not require much scrutiny to notice. In Figure 2, when the exploder in the center of the specimen gets to work, a trio of regions starts to form near the explosive hole’s rim due to the impact of the explosion’s gas and stress waves: a compression-shear fracturing zone, a radial tensile fracture zone, and a stress wave-induced elastic vibration zone. Beyond the blast’s epicenter, the shock wave fizzles out into mere stress waves, which then course through the specimen in the form of P-waves and S-waves, affecting the empty holes and any pre-made initial cracks, initiating and extending those fractures. When we set up for the simulations and computations in the future, it will be essential to take the experimental loads and use them as the foundation for all subsequent calculations. In addition, it is also necessary to trigger the strain. After it is activated, the radial and circumferential strain gauges begin to collect data immediately. The voltage signal of gauges can be converted into strains by Equation (2).

$$\varepsilon = \frac{4\Delta U}{nU_b K} \quad (2)$$

where ε is strain, ΔU is the measured voltage, n is amplification factor of dynamic strain gauge ($n = 1000$), U_b is the bridge box voltage ($U_b = 2 \text{ V}$), and K is sensitivity coefficient of strain gauge ($K = 2.1$).

To track the stresses around the explosive hole, which is encircled by a fractured region about 25 mm in diameter, we placed radial and circumferential strain gauges around 30 mm away from the explosive hole’s center to record radial strain ε_r and circumferential strain ε_c . As shown in Figure 3a.

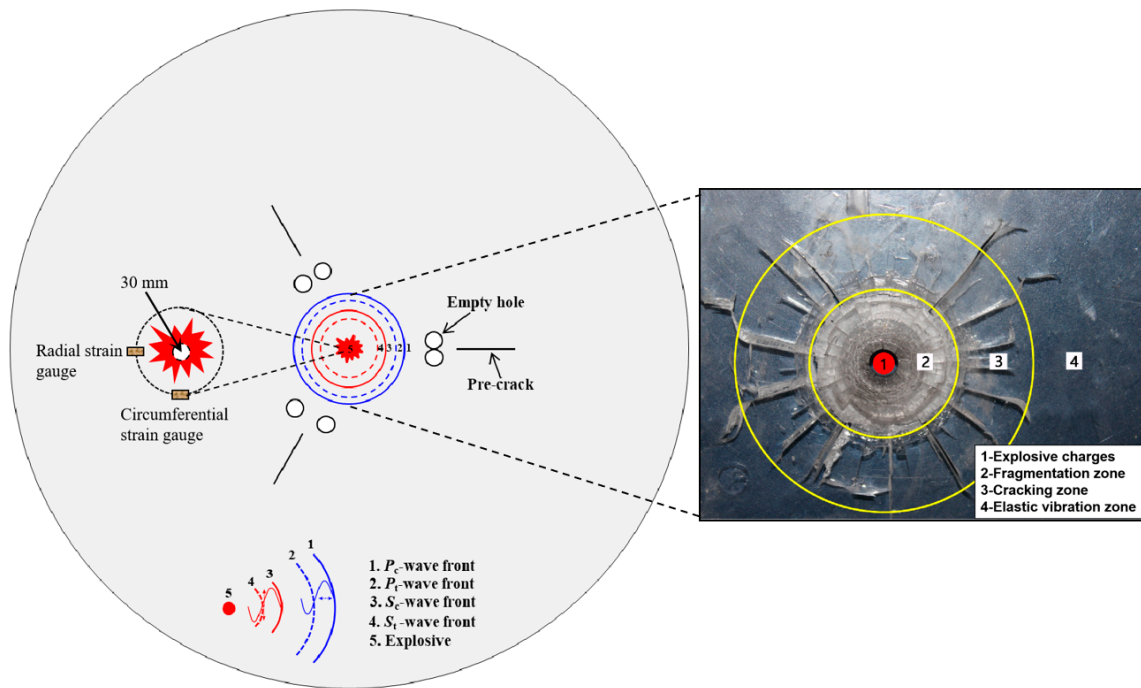


Figure 2. Propagation of blasting stress waves in specimens.

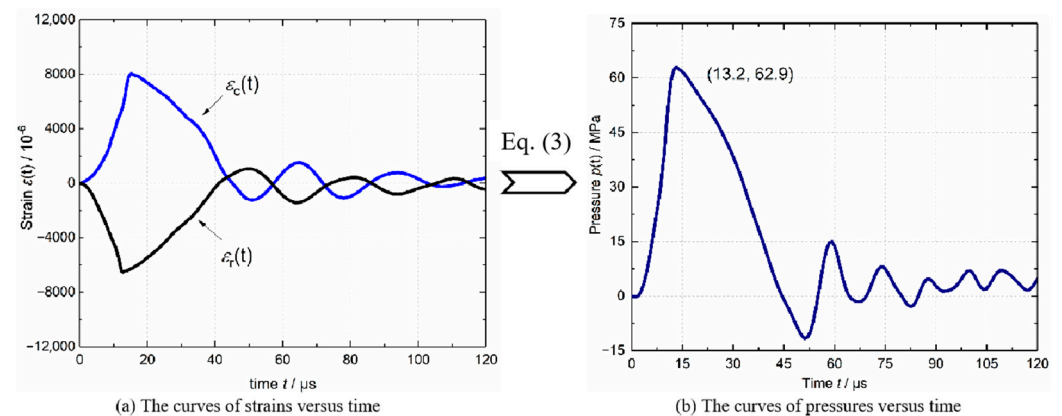


Figure 3. The curves of strains and blast-induced pressures versus time measured by the two strain gauges stuck in the place 30 mm away from the borehole center.

For plane stress problems, the blasting loads can be obtained by Equation (3) [24].

$$p(t) = \frac{E_d}{1 - \mu_d^2} (\varepsilon_r(t) + \mu_d \cdot \varepsilon_c(t)) \quad (3)$$

where $p(t)$ is the compressive stress, as shown in Figure 3b, E_d is the dynamic elastic modulus, μ_d is dynamic Poisson's ratio, as shown in Table 1.

2.3. Blasting Experiment Results

Following the detonation, the initial shock wave impacts the explosive hole, severely damaging the surrounding material and creating a fracture zone with a radius ranging from approximately 22.6 to 23.7 mm. In Figure 4a, the crack propagation pattern observed in a localized sample post-detonation. Notably, when the distance between two empty holes is set at 10 mm, the distal crack tip exhibits significantly shorter propagation compared to other intervals. This is because there is no space between the two empty holes for stress waves to propagate to the proximal side of the pre-made initial crack, while only a portion

of the diffracted stress waves are present at the distal end, resulting in a shorter crack propagation length. Meanwhile, the proximal crack tip shows minimal advancement, likely because the stress wave fails to travel effectively between the empty holes, hindering crack initiation—a finding supported by subsequent stress intensity factor analysis.

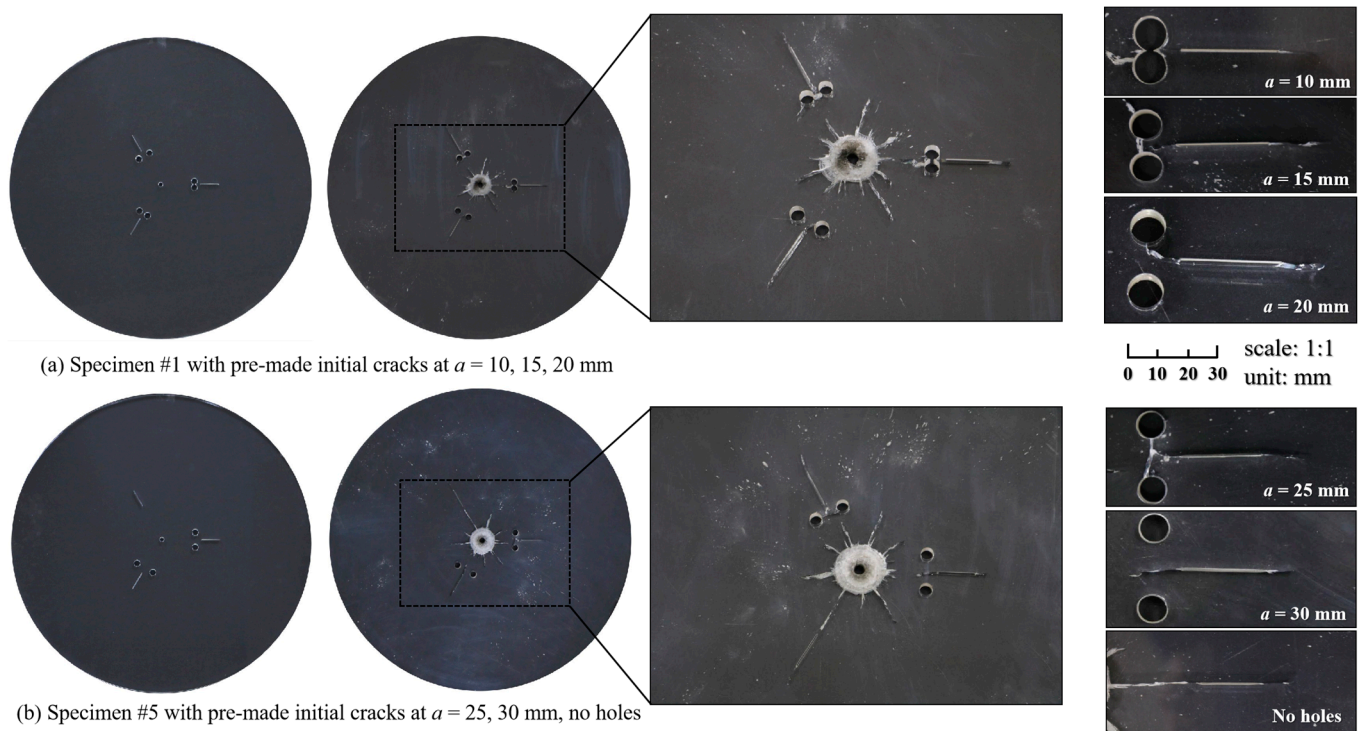


Figure 4. The experimental results under blasting loads.

As the empty hole separation distance increases, the propagation length of the distal crack tip is shortened compared to $a = 15$ mm and 20 mm, because the superposition effect of stress waves is not as obvious after the space between the two holes increases. In Figure 4b, at a 25 mm distance, the distal crack's propagation length unexpectedly decreases indicates this. This trend stabilizes at 30 mm, where the crack's growth closely resembles that observed in scenarios without empty holes. In contrast, the proximal crack tip's propagation length correlates directly with hole distance: it is shortest at 10 mm and longest at 30 mm. However, even at the maximum distance, the crack does not reach the empty hole, differing markedly from fracture behavior in unimpeded conditions.

3. Numerical Simulation Research

3.1. Model Mesh Division and Calculation Principle

To accurately replicate the outcomes of the blasting experiment, the numerical simulation employed a one-to-one specimen-to-experiment ratio. Using AUTODYN finite difference software, a 3D numerical model was constructed. The grid size of the numerical model has a significant impact on the simulation calculation time, data accuracy, etc. In order to determine the optimal grid size for this numerical simulation, convergence tests were conducted using grid size layouts of 5 mm, 2 mm, 1 mm, and 0.5 mm. Through calculations, it was found that when the grid size was below 1 mm, the calculation time and data of the numerical model tended to stabilize. Finally, it was determined that the main body should use 1 mm grid size, key stress-concentration zones near cracks and holes were refined with higher mesh density by using 0.5 mm grid size. The numerical model is meshed into 825,685 tetrahedral elements, as illustrated in Figure 5.

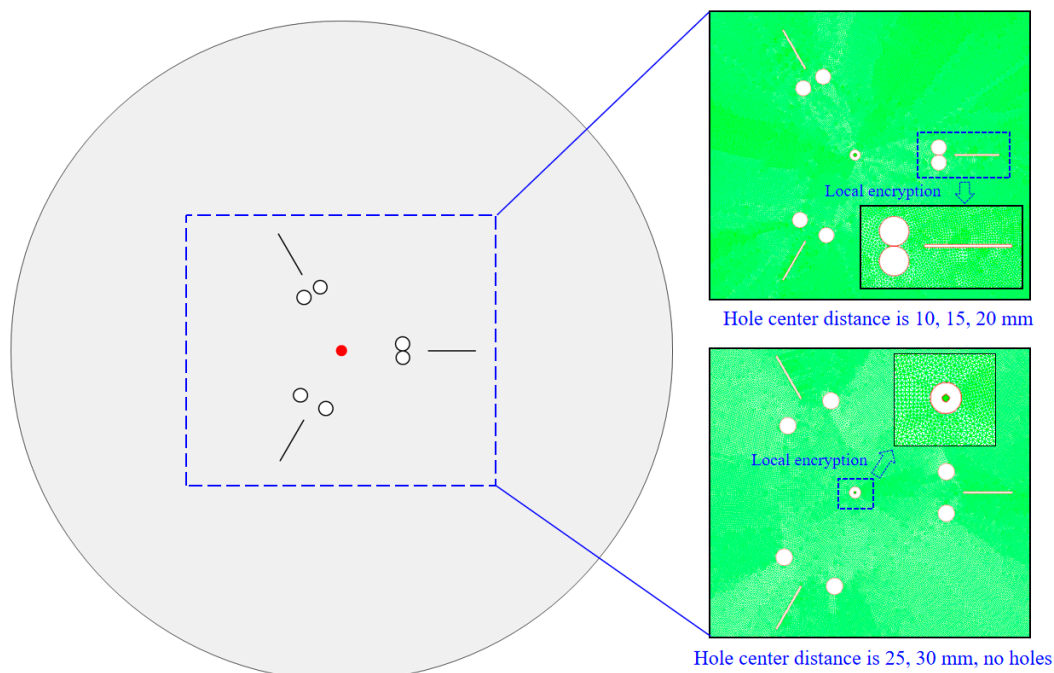


Figure 5. Mesh of the numerical model.

Before conducting numerical simulations in this study, the mesh size, constitutive parameters of the specimen and explosives were finally determined through element mesh convergence calculations. The state equations of the specimen and the explosive were determined using the Linear and JWL, respectively. Under dynamic loads, rectangular grid elements experience identical pressure, density, and strain rates. Each node navigates its path at its own pace, leading to corresponding mesh cell deformations. The material's behavior is characterized by the first principal stress and the maximum shear stress failure threshold. Specifically, if an element's first principal stress, σ_1 , equals the material's dynamic tensile strength, σ_T , or if the maximum shear stress, $\tau_{\max}$, equals the material's dynamic shear strength, τ_C , the element fails. This failure is represented in Equation (4).

$$\sigma_1 \leq \sigma_T \text{ or } \tau_{\max} \leq \tau_C \quad (4)$$

3.2. The Results of Numerical Simulation

The material constitutive parameters used in numerical simulation should be consistent with the actual blasting experiment to ensure the authenticity and reliability of the data. Therefore, the material parameters of the numerical model are from Table 1.

In this paper, PMMA used for numerical simulation exhibits brittle fracture upon failure. The stress distribution at the tip of pre-made initial cracks and around empty holes, as well as the failure mode, are demonstrated using the numerical simulation code AUTODYN, as shown in Figure 6. The stress contour of the numerical model is displayed on the left, and the failure mode is displayed on the right.

From the numerical contour in Figure 6a, it can be seen that the blasting stress wave propagated to the empty holes at about 25 μs after the detonation of the explosive, as well as the diffraction occurred at the empty holes. A region of stress wave superposition formed between the two empty holes, and the closer the distance between the holes, the greater the stress intensity in this region of stress wave superposition. This superposition affected the initiation and propagation of the pre-made initial cracks. After passing through the two empty holes, the stress wave continued to propagate towards the proximal crack tip of the pre-made initial cracks. At about 44 μs , the stress wave reached the distal crack

tip, forming stress concentration area at both the proximal and distal crack tips, which led to the initiation of the pre-made initial cracks. From the model failure diagram in Figure 6b, it can be seen that the proximal and distal crack tips were affected by the blasting stress wave. Between 52 μ s and 60 μ s, the initiation and propagation of the cracks occurred at both tips, and then the crack continued to propagate until it stopped. This is basically consistent with the results of the blasting experiment.

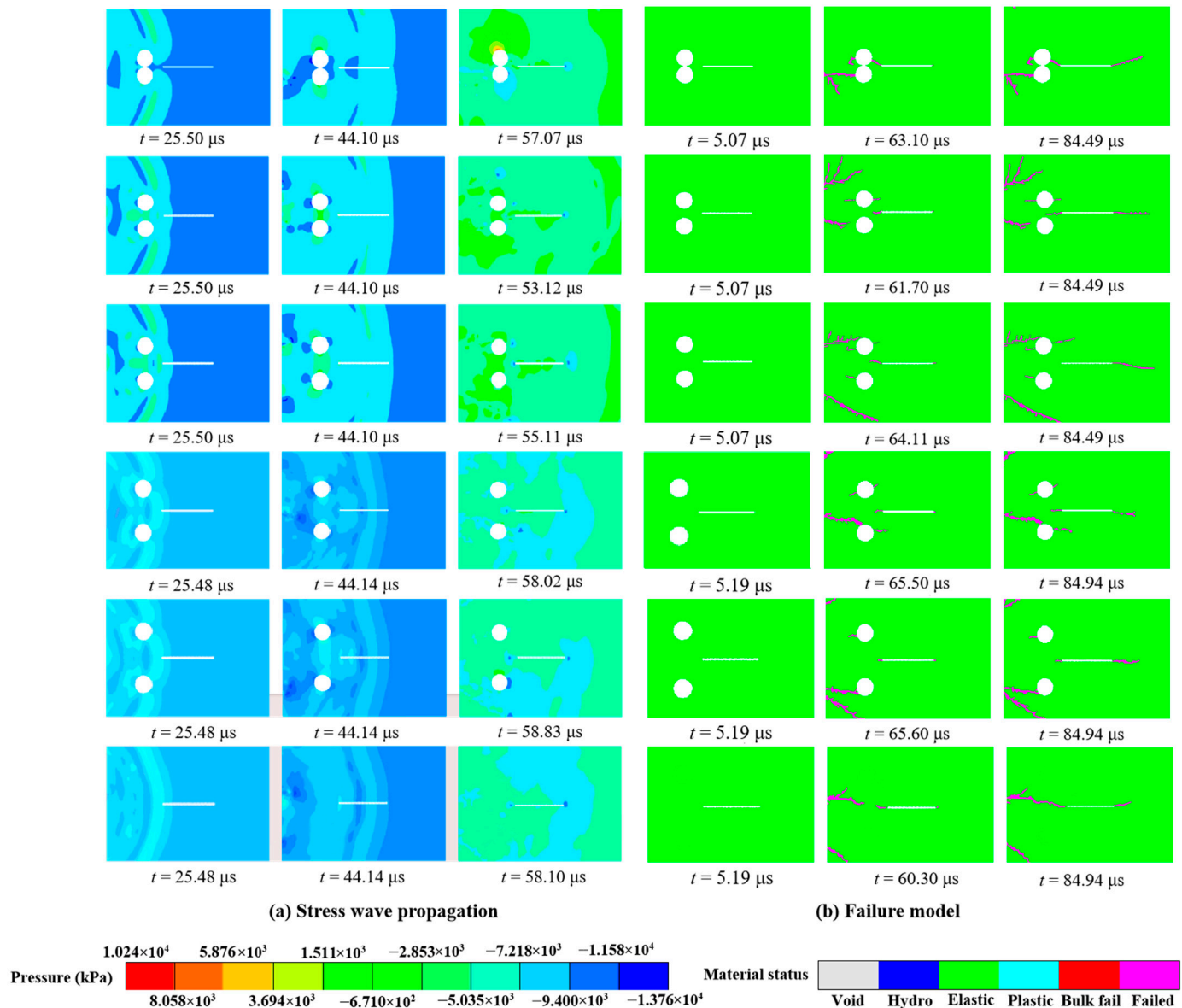


Figure 6. The stress wave and failure model by AUTODYN codes.

In order to monitor the stress field data around the empty holes, six monitoring points were arranged, numbered #1 to #6, in the direction of the line connecting the centers of the two empty holes as shown in Figure 7. Points #1, #2, #5, and #6 are, respectively, placed at the edge of the empty holes, while points #3 and #4 are, respectively, located between the two empty holes. When the stress wave propagated to the position of the empty holes, the data was recorded. From Figure 7a, it can be seen that when the hole distance is 10 mm, there is no gap between the two holes, and at this point, the stress wave cannot propagate through the two holes. Only some of the stress waves diffract past the holes, so the intensity of the stress wave is the smallest at this time. As the distance between the two holes increases, the stress wave begins to propagate between them. When the hole distance is

15 mm, the stress wave reflects and diffracts at the hole walls when diffracting past the empty holes, forming an intensity superposition between the two holes. It can be seen that the intensity values at the monitoring points #3 and #4 in the middle of the two holes are larger than those at the monitoring points #1, #2, #5, and #6 at the hole walls. This indicates that the empty holes have affected the propagation of the stress wave to some extent, causing a redistribution of the stress intensity in the stress field around the empty holes. This redistribution is mainly due to the different degrees of reflection and diffraction caused by the empty holes to the stress wave. From the intensity distribution in Figure 7a, it can be seen that the stress intensity at the hole walls is close to the intensity when there are no holes, which means that the empty holes have a smaller effect on the intensity of the stress wave diffraction; however, the stress intensity at the position where the stress waves reflect and superimpose between the two holes is larger. A smaller hole distance is more conducive to the superposition of stress wave intensity. As the hole distance increases, when it exceeds 25 mm, this superposition effect gradually weakens and can even be ignored. From Figure 7b, it can be seen that the empty holes have affected the propagation speed of the stress wave to some extent. The change in stress intensity under the condition with holes is later than that without holes. When the hole distance is 10 mm, the stress wave cannot propagate between the two holes, so the time for the intensity change should be the longest. From the data in Figure 7b, it can be seen that as the hole distance increases, the propagation speed of the stress wave becomes slower, and the time for the intensity change becomes later: the time for monitoring points #1, #2, #5, and #6 is earlier than that for points #3 and #4. This indicates that the time for the intensity change at the hole walls is earlier than that between the two holes. This is because the stress wave at the hole walls only undergoes diffraction, while at the position between the two holes, it is due to the superposition of the stress wave after reflection. The occurrence of this process is more complex than diffraction, so the data in the figure conforms to the propagation law of the stress wave.

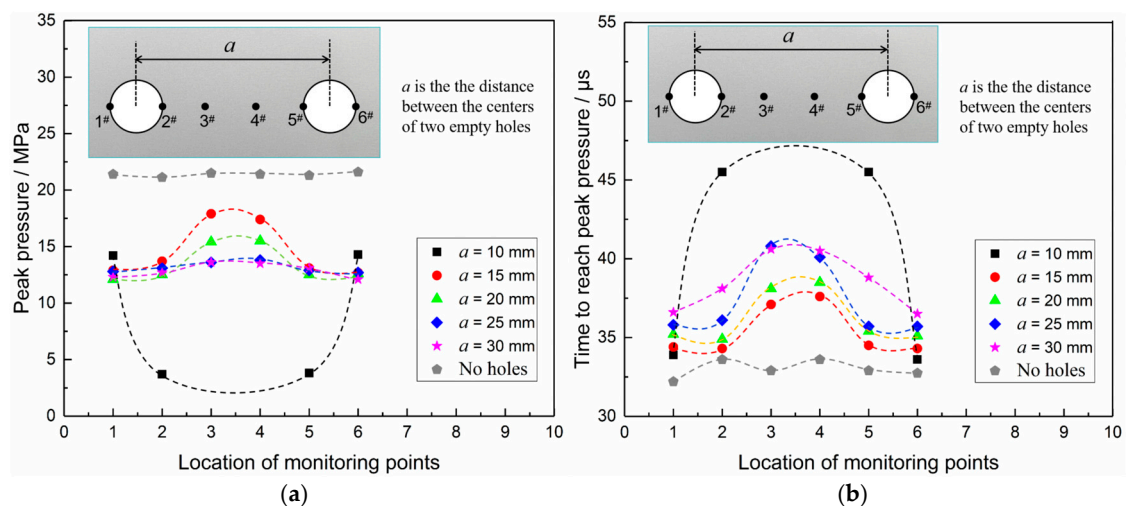


Figure 7. Stress distribution around and in the middle area of the empty holes. (a) Peak pressure. (b) Time to reach peak pressure.

In order to monitor the stress field data around the pre-made initial crack tips, four monitoring points were placed, numbered #1 and #4, at the proximal crack tip, numbered #2 and #3, at the crack tip on the side far from the empty holes. As shown in Figure 8a, the peak compressive stress at the proximal crack tip is significantly higher than that at the distal crack tip, indicating that the intensity of the stress wave attenuates as the propagation distance increases. From the data at the distal crack tips, it can be seen that the

presence of the empty holes reduces the intensity value at the crack tip, making it more difficult for the crack to initiate. This corresponds to the subsequent analysis of the stress intensity factor. The intensity at the distal crack tip gradually decreases with the increase in empty hole distance, indicating that the more dispersed the hole distribution, the lower the intensity at the distal crack tip, although this effect is not significant. From the data at the proximal crack tips, it can be seen that the presence of the holes reduces the intensity value at the crack tip, and the intensity decreases with the increase in hole distance. When the hole distance is less than or equal to 20 mm, the change in intensity is more pronounced, indicating that the influence of the holes on the stress field at the proximal crack tip is more significant compared to the distal crack. Stress diffraction and superposition occurred at the hole. When the hole distance reaches 25 mm, the holes have almost no effect on the intensity at the crack tip. As shown in Figure 8a, due to the superposition of stress waves at the empty holes, the time for the proximal crack tip to reach maximum intensity with holes is longer than without holes, and the time for the intensity change at the proximal crack tip basically increases with the increase in hole distance. The presence of the holes has an insignificant effect on the time for the distal crack tip to reach maximum intensity, and the hole distance does not significantly affect this time either.

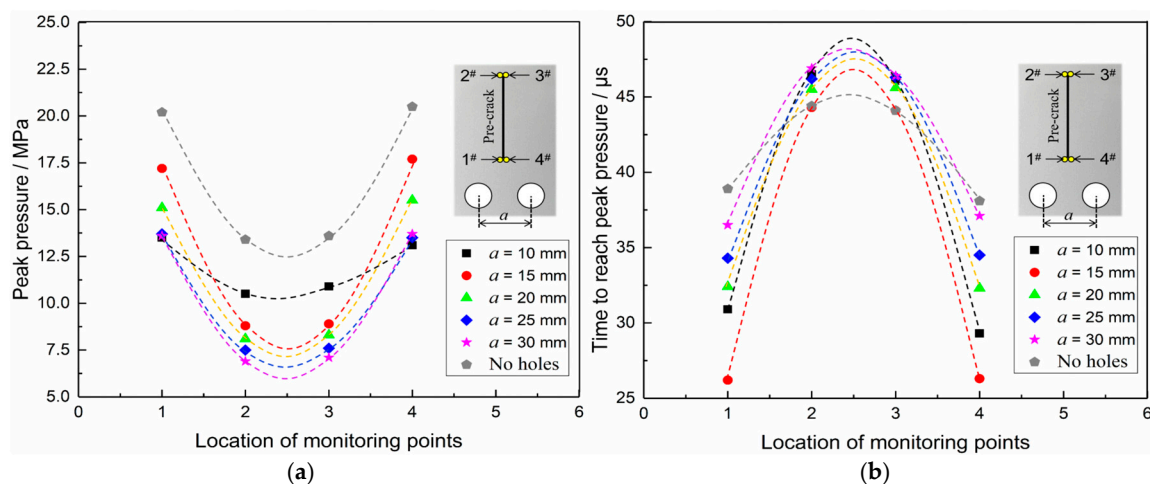


Figure 8. Stress distribution at the distal and proximal ends of the pre-made initial crack tips. (a) Peak pressure. (b) Time to reach peak pressure.

4. Dynamic Stress Intensity Factors

The dynamic stress intensity factor (SIF), often considered a critical measure in the realm of material fracture analysis, plays a pivotal role in understanding how materials behave under dynamic stress. When it comes to experiments, the Hopkinson pressure bar and the mighty drop hammer have been the go-to tools for researchers to gather insights into these factors [28–34]. Nonetheless, there is a notable lack of study specifically focusing on calculating these factors under blast conditions, particularly when empty holes are involved.

4.1. The Calculation Process of SIFs

ABAQUS is capable of handling a wide range of nonlinear simulations, from basic linear analyses to more complex dynamic stress intensity factor (SIF) computations, with particular strength in the latter. For this research, experimentally measured blasting loads were integrated with real-world mechanical properties to construct the numerical model, illustrated in Figure 9. The crack tip region employs a quarter-point triangular mesh (CPS6 elements), whereas the surrounding areas utilize quadrilateral elements (CPS8). Drawing

on fracture mechanics principles, the dynamic stress intensity factor $K_I(t)$ can be derived using Equation (5), based on the displacements observed at points A and B [35,36].

$$K_I(t) = \frac{E}{24(1-\mu^2)} \sqrt{\frac{2\pi}{r_{OA}}} [8v_A(t) - v_B(t)] \quad (5)$$

where $r_{OB} = 4r_{OA}$, and $v_A(t)$ and $v_B(t)$ are the displacements in y direction at point A and B, respectively, E is elastic modulus, μ is Poisson's rate, and r_{OA} is the distance from point O to A.

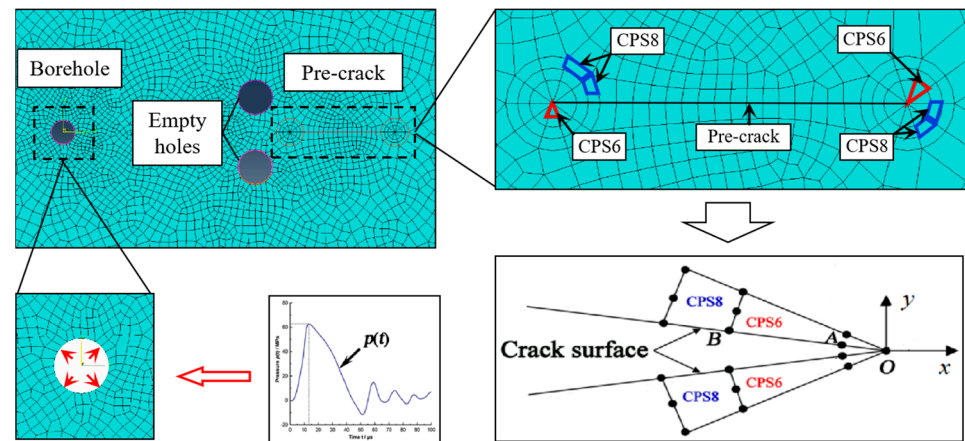


Figure 9. The numerical calculation model in SIF.

4.2. Stress Intensity Factors at Initiation

The data of dynamic stress intensity factors vary with time was recorded by ABAQUS codes as shown in Figure 10. According to the crack initiation time measured by gauge points, the SIF at initiation time can be found. As an example, the proximal crack tip of pre-made initial crack with a distance of 15 mm between the centers of two empty holes ($a = 15$ mm) is used to illustrate. In Figure 10, the crack initiation time was 56.9 μ s, then the value in the vertical axis is 2.59 $\text{MPa} \cdot \text{m}^{1/2}$, i.e., the SIF of the proximal crack tip at initiation. The crack is in a quasi-static state at initiation.

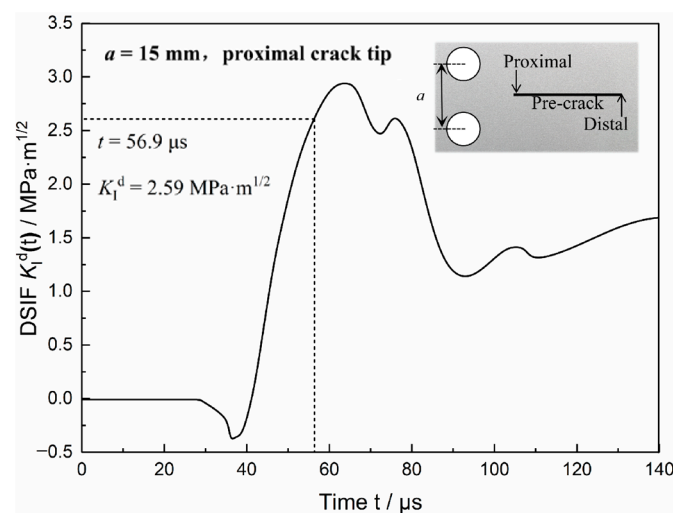


Figure 10. Pre-made initial crack SIF versus time ($a = 15$ mm).

The crack SIF at initiation of the proximal and distal crack tips under different empty hole distance conditions is shown in Figure 11. In Figure 11a, it can be seen from the crack initiation toughness data for the distal crack that, firstly, the crack initiation toughness

without empty holes is less than that with holes, indicating that the presence of empty holes increases the difficulty of crack initiation at the distal crack tips, which is consistent with the pattern that holes reduce the strength at the distal crack tips. Secondly, the crack initiation toughness at the distal crack tips is basically proportional to the hole distance, suggesting that dispersed holes reduce the intensity of stress wave propagation to some extent, which is also consistent with the pattern that a more dispersed distribution of holes reduces the strength. From the crack initiation toughness data for the proximal crack tips, it can be seen that the crack initiation toughness without holes is less than that with holes. When the hole distance is 10 mm, 15 mm, and 20 mm, the crack initiation toughness at the proximal crack tips is much greater than that without holes. When the hole distance is greater than or equal to 25 mm, the crack initiation toughness is very close to that without holes, indicating that when the hole distance is less than or equal to 20 mm, the holes have a significant impact on the crack initiation toughness, due to the stress wave superposition between holes changing the stress field at the crack tip. When the hole distance is greater than or equal to 25 mm, this impact becomes very small. In Figure 11b, the crack initiation time at the distal crack tips is basically proportional to the hole distance, and the initiation time without holes is earlier than with holes. The proximal crack tip initiates first at a hole distance of 15 mm, and as the hole distance increases, the initiation time gradually increases. When the hole distance is 25 mm and 30 mm, the initiation time for the proximal crack tip is very close to that without holes, indicating that a larger hole distance has little impact on the initiation time for the proximal crack tips.

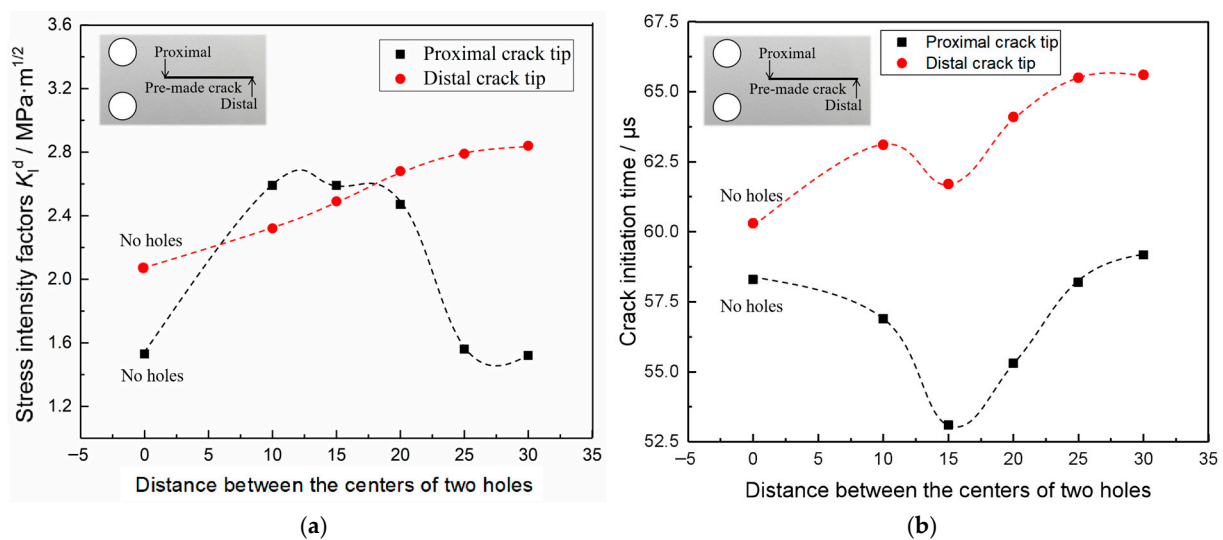


Figure 11. Initiation toughness and initiation time versus distance between the centers of two empty holes. (a) Initiation toughness versus distance. (b) Initiation time versus distance.

5. Application and Discussion

In large-scale rock blasting operations such as tunnel excavation and mining, multiple empty holes such as excavation holes, auxiliary holes, and peripheral holes are usually used simultaneously for rock breaking in tunnel blasting, as shown in Figure 12, and the detonation of these empty holes will be carried out in a certain order. Therefore, in blasting construction, when the middle explosive hole detonates, cracks near the auxiliary or peripheral holes will begin to initiate and propagate, thereby affecting the fragmentation effect of the explosion. In large-scale blasting operations, the detonation of explosives from adjacent empty holes can also affect the propagation of surrounding cracks. The research in this paper can be applied to smooth blasting of tunnel, and has certain guiding significance for the design of empty hole distance and other factors during rock breaking in shafts

and tunnels. The amount of explosives is an important parameter that affects the rock breaking effect of the section. The next step of this study is to balance parameters such as explosive charge and empty hole distance design to achieve a more economical section breaking effect.

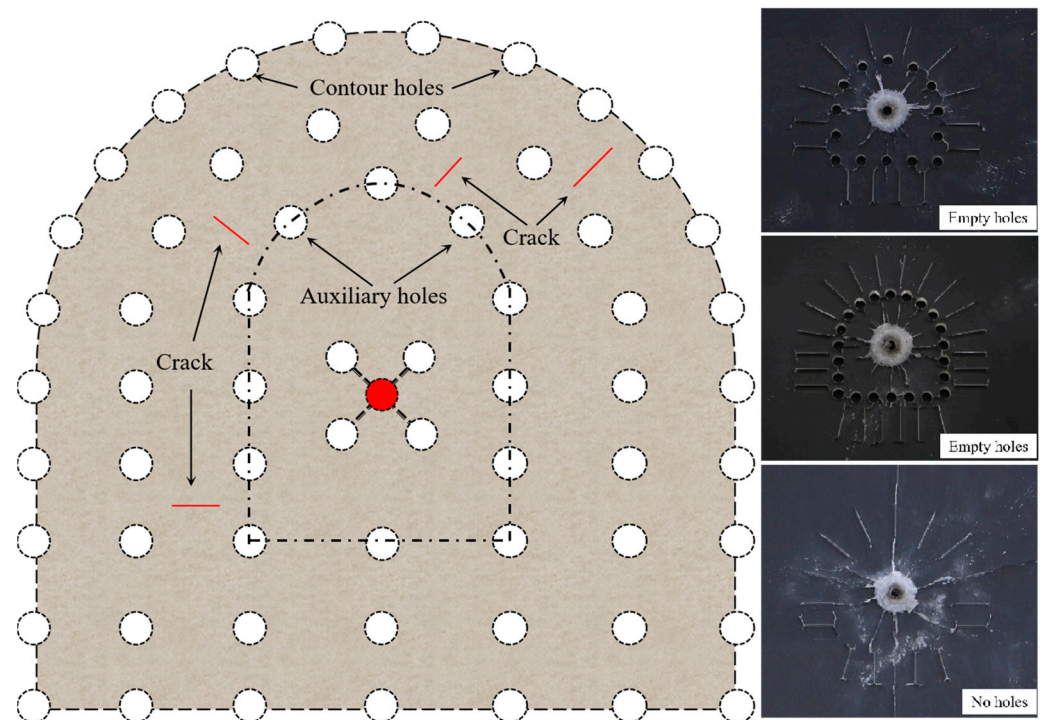


Figure 12. The coupled occurrence of holes and cracks in blasting engineering.

6. Conclusions

This study reveals that empty holes have a significant impact on the propagation of stress waves, stress distribution in local areas, and stress intensity at crack tips, which can provide laboratory data support for related engineering applications. This study was conducted under specific and idealized conditions, and the next step of research should also consider factors such as in situ rock stress, material heterogeneity, and complex geological structures. The research conclusions of this article are as follows:

- (1) Diffraction and reflection of the blast stress wave occur at the edges of the empty holes. As the empty hole center distance increases, the propagation speed of the stress waves slows down, and the time for intensity changes is delayed. Stress waves superimpose in the area between adjacent voids, forming a pressure zone, which causes the stress field behind the voids to redistribute. When the hole distance reaches 25 mm, this pressure zone gradually disappears.
- (2) The presence of empty holes reduces the compressive strength of stress waves at the proximal and distal crack tips, and the strength decreases with the center distance of the two empty hole distances increasing. When the distance is less than or equal to 20 mm, the change in strength is more pronounced, indicating that the influence of empty holes on the stress field near the crack tip is more significant than on the far crack tip; the time to reach maximum strength at the near crack tip generally increases with the increase in two empty hole distances, while the holes have little effect on the time to reach maximum strength at the far crack tip.
- (3) The presence of empty holes increases the difficulty of crack initiation at the proximal and distal crack tip, and the initiation toughness is basically proportional to the two empty hole center distances. When the distance is less than or equal to 20 mm, the

holes have a significant effect on the crack initiation toughness. When the distance is greater than or equal to 25 mm, the initiation toughness is very close to the no-hole condition; the crack initiation time at the distal crack tip is basically proportional to the distance. When the distance is 15 mm, the initiation time of the proximal crack tip is directly proportional to the hole distance. When the distance is 25 mm and 30 mm, the initiation time of the proximal crack tip is very close to the no-hole condition, indicating that a larger two empty hole center distance has little effect on the initiation time of the proximal crack tip.

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