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BLAST DAMAGE IN ROCK: FROM DETONATION TO CRACK PROPAGATION

SPRÄNGSKADOR I BERG; FRÅN DETONATION TILL SPRICKBILDNING

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ABSTRACT: Vid tunnel- och ortdrivning, så är borrning och sprängning den mest använda tekniken för berguttag i hårt berg. Höga krav ställs för minimalt överberg och reducerade skador i kvarvarande berg. Vår forskning fokuserar på en djupare förståelse av de sprängningsinducerade sprickor som uppkommer vid sprängning. Denna artikel sammanfattar sprängförsök gjorts i labskala med höghastighetskamera, där fokus var att förstå interaktionerna mellan sprängmedel och omgivande berg med avseende på sprickinitiering, sprickutveckling och sprickinteraktioner. Viktiga parametrar som frikoppling, specifik laddning och guidehål har visat sig ha betydande inverkan på resultaten. Resultaten förbättrar förståelsen för hur dessa designparametrar styr sprickornas fortplantning, vilket möjliggör nya möjligheter att designa sprängningar där oönskade eller skadliga sprickor minimeras.

ABSTRACT: Drilling and blasting remain central to tunneling in Sweden, where high standards for minimal overbreak and damage drive the research towards a deeper understanding of blast-induced cracks. Recent research rethinks the approach of examining the effects of explosive detonation and its interaction with the surrounding rock. This paper synthesizes advances from small-scale studies on crack initiation, development, and coalescence during blasting. Key parameters, such as decoupling ratio, specific charge, and the strategic use of empty guideholes significantly influence the extent and direction of blast-induced cracks. High-speed imaging offers valuable information about crack propagation behavior. The results enhance the understanding of how these blast design parameters govern crack propagation, enabling the tailoring of the blast designs that promote desired cutting cracks while minimizing the unwanted or damaging ones. The emphasis of this work refers to tunnel contour stability and efficient rock cutting, contributing to crack propagation control. The findings provide a foundation for evaluating blast damage, supporting a more precise, sustainable, and safer tunneling while identifying gaps for future research.

Keywords: Experiments, Ultra-High-Speed Photography, Digital Image Correlation, Tunnelling, Blast Design Optimization.

1. INTRODUCTION

Blasting has a long tradition as a hard rock excavation method for tunnels and other infrastructures across Scandinavia. Furthermore, the strict requirements on contour quality, meeting the designed cross-section and minimal blast-induced damage guide both, industry and scientific research. Achieving smooth and stable tunnel perimeters while limiting the overbreak and blast-induced cracks remaining in the rock mass is

essential for safety and cost-efficiency and affect positively to sustainable use of resources (Barker, et al., 1978; Pomasoncco- Najarro, et al., 2022). Despite of decades of operational experience, the fundamental behaviour of crack initiation, propagation and interaction around the blastholes are not yet fully understood.

Recent research has increasingly focused on understanding the crack propagation behavior and sequence by using the high-resolution and time evolution techniques, moving away from post-blast observations. (Chi, et al., 2019). In particular, ultra-high-speed (UHS) photography combined with Digital Image Correlation (DIC) opens new possibilities to observe the crack initiation and propagation (Zhang, et al., 2021; Chi, et al., 2022). Additionally, it is useful to track the displacement and strain fields that permit quantifying the crack length and velocities between others (Sutton, et al., 2009; McCormick & Lord, 2010; R. San Miguel, et al., 2024; R. San Miguel, et al., 2026a). These advancements offer an important opportunity to enhance our understanding of the breakage of rock-like materials during blasting.

Within this context, Sweden has emphasized the need for improved control of blast-induced cracks, especially in the holes that define the final excavation boundary, or contour/perimeter holes. The design of these holes includes variables such as decoupling ratio – the gap between the explosive charge and the blasthole, initiation time and the use of guideholes (empty holes). They have shown to impact the role of the cracks to propagate in a controlled and beneficial direction or result in unwanted overbreak and damage (Ouchterlony, et al., 2002; Zhang, 2016; Yang, et al., 2019; Ittner, 2018). While numerical modelling and field observations provide valuable insights (Raina, et al., 2000; Pu, et al., 2021; Mitchell, et al., 2023; Xu, et al., 2023), having experimental data from a controlled and well-instrumented environment that isolate the influence of individual design parameters remains a challenge.

To address this gap, the latest research studies performed in Sweden experimentally investigate blast-induced crack propagation in rock-like material as magnetite mortar (Stiftelsen Bergteknisk Forskning, 2020). The study focused on single- and double-blasthole configurations and included other designs with empty guideholes arrangements to enhance the cutting cracks. Across the experimental campaign, blast-design variables were systematically varied: (a) decoupling ratio, (ii) initiation time between blastholes, and (iii) blasthole-guidehole configuration. By combining controlled small-scale blasting with UHS photography and DIC, it was possible to directly visualise how crack initiate, propagate and interact under different design conditions (Rodriguez San Miguel, 2024).

This paper synthetises the results from a series of fundamental level tests, and shows how specific decoupling ratios, initiation times and hole layouts can promote desired crack paths. The novelty also lies in the use of fully non-contact methods adapted from other research disciplines to the fascinating field of crack propagation by blasting. These contributions lay the groundwork for implications in the contour blasting, as they offer a foundation for designing more predictable blasting operations in rock environments.

2. MATERIAL AND METHODS

The blasting experiments were conducted using magnetite mortar, which is material that mimics the rock in Northern Sweden. It was chosen as it can be reliably mixed in the laboratory and its physico-mechanical properties have been extensively characterized (Johansson & Ouchterlony, 2011). The samples were designed as cylinders (150 mm x 300 mm) and were cast and cured under controlled conditions to ensure uniformity across the experimental campaign. Each sample was prepared with a predefined number of

blastholes and drilled if needed to achieve decoupling conditions. Blasthole diameter, spacing and alignment were kept as constant as possible within the experimental preparation. Guideholes were drilled as well and left uncharged to serve as intended crack attractors. To enable DIC analysis of surface deformation, the samples were prepared with a speckle pattern consisting of white dots.

PETN cord was selected as an explosive due to its handling properties. The strength of the explosive cords was 3.6 g/m, 5 g/m and 12 g/m and their velocity of detonation (VoD) measured 6994 m/s, 7248 m/s and 7486 m/s respectively. Measurements regarding explosive core diameter ($Ø_e$) were taken. Decoupling ratio (f) was calculated by dividing the diameter of the explosive by the diameter of the blasthole ($Ø_{bh}$). Initiation was performed using detonators and the delay was achieved by varying the PETN cord lengths ($L_{bh/e}$). The mass of explosives used in the volume of magnetite mortar or specific charge (q) and the mass of explosive per unit length in the blasthole or linear charge concentrations (q_l) were calculated. The primary variables such as decoupling ratio, initiation time and hole configuration were systematically varied. Table 1 summarizes the test variables configuration.

Table 1. Experimental campaign: parameters and variables

Sample	Study type	No. Blastholes	No. Guideholes	$Ø_{bh}$ [mm]	$L_{bh/e}$ [mm]	PETN cord strength [g/m]	$Ø_e$ [mm]	q [kg/m^3]	q_l [kg/m]	f	Delay [µs]	Reference
B01	*	1	-	6	275	5	2.40	0.28	0.005	2.5	-	
B02	*	1	-	6	278	5	2.40	0.28	0.005	2.5	-	
B03	*	1	-	6	265	5	2.40	0.28	0.005	2.5	-	
B04	*	1	-	10	273	5	2.40	0.28	0.005	4.2	-	[5]
B05	*	1	-	10	270	5	2.40	0.28	0.005	4.2	-	
B06	*	1	-	10	283	5	2.40	0.28	0.005	4.2	-	
B07	*	1	-	12	274	5	2.40	0.28	0.005	5.0	-	
B08	*	1	-	16	268	12	4.13	0.68	0.005	3.9	-	[2]
B09	**	2	-	6	280	3.6	2.42	0.41	0.007	2.5	0.0	[6]
B10	**	2	-	6	283	3.6	2.42	0.41	0.007	2.5	0.0	[2, 6]
B11	**	2	-	6	277	3.6	2.42	0.41	0.007	2.5	0.0	
B12	**	2	-	6	280	3.6	2.42	0.41	0.007	2.5	57.2	[6]
B13	**	2	-	10	271	3.6	2.42	0.41	0.007	4.1	0.0	
B14	**	2	-	10	272	3.6	2.42	0.41	0.007	4.1	0.0	[2, 6]
B15	**	2	-	10	274	3.6	2.42	0.41	0.007	4.1	0.0	[6]
B16	**	2	-	10	255	3.6	2.42	0.41	0.007	4.1	57.2	
B17	***	1	2	6	250	5	2.40	0.28	0.005	2.5	-	[3]
B18	***	1	4	6	274	5	2.40	0.28	0.005	2.5	-	
B19	***	2	1	6	276	3.6	2.42	0.41	0.004	2.5	0.0	
B20	***	1	2	6	280	5	2.40	0.28	0.005	2.5	-	[4]
B21	***	1	4	6	283	5	2.40	0.28	0.005	2.5	-	
B22	***	4	1	6	280	3.6	2.42	0.81	0.004	2.5	0.0	

* Fundamental study of decoupling effect

** Cutting plane along the Inter-blasthole zone study under different decoupling ratio and initiation time

*** Crack directionality under different blasthole and guidehole configurations

[1] (R. San Miguel, et al., 2024); [2] (R. San Miguel, et al., 2025a); [3] (R. San Miguel, et al., 2025b); [4] (R. San Miguel, et al., 2025c); [5] (R. San Miguel, et al., 2026a); [6] (R. San Miguel, et al., 2026b)

Crack initiation and propagation were recorded on the sample surface perpendicular to the blasthole with an ultra-high-speed camera (UHSC) synchronized with the data acquisition system. A high-intensity LED-light system provided uniform lightning and minimized blur. Further details of the setup can be found in previous work done by the same authors (Rodriguez San Miguel, 2024). Time resolution between 20000 and 38000 frames per second (FPS) were used depending on the tests series but always ensuring to capture crack propagation. The initiation system was synchronized with the UHSC and the acquisition system to collect the data of each blast event (R. San Miguel, et al., 2023).

The methodology workflow is illustrated in Figure 1. The collected data consisted in UHSC image sequences, which were preprocessed to enhance the clarity between the speckles and the background for DIC analysis. DIC was performed using Digital Image Correlation engine and ZEISS CORRELATE software. The DIC resulting displacement and strain fields were used to determine crack initiation points and strain localization zones between others. Additional information on sample preparation, setup and analysis

procedures can be found in previous work done by the authors (Rodriguez San Miguel, 2024; R. San Miguel, et al., 2026a).

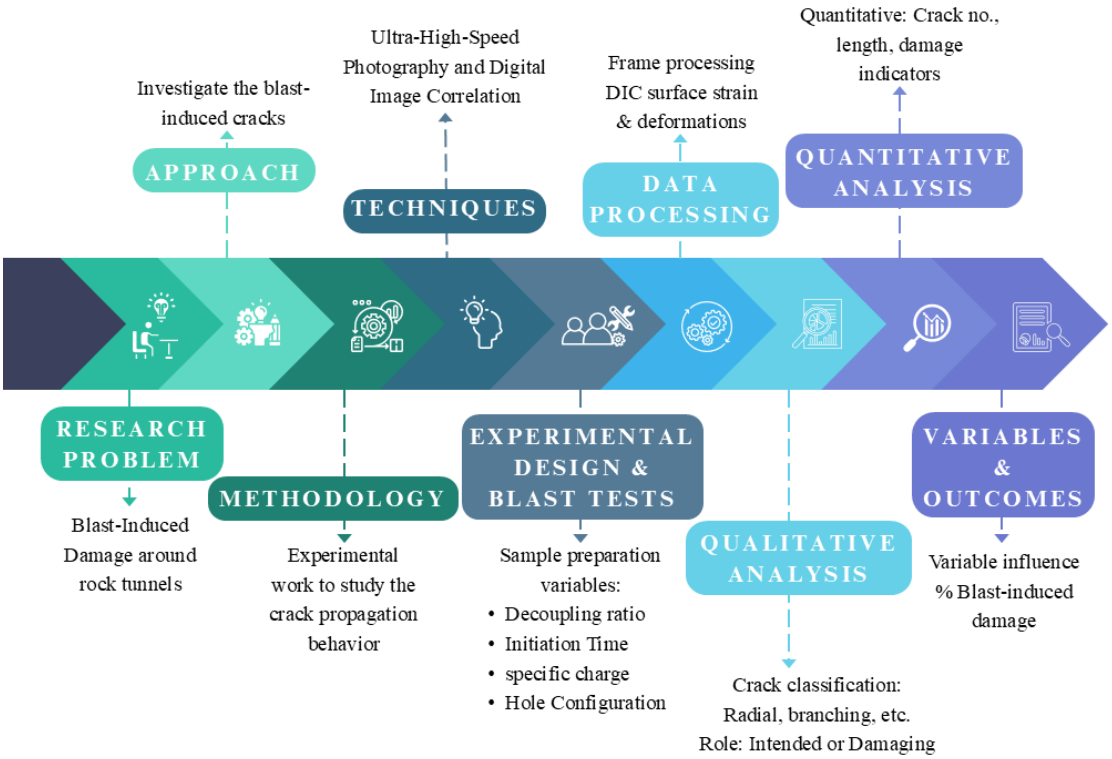


Figure 1. Blast-Induced Damage estimation through small-scale experiments workflow

Combining UHS photography with DIC results, the post-blast characterization of each test included the differences in the crack development from detonation to gas ejection. Crack classification and trajectories were visually evaluated and lengths were measured. Both qualitative and quantitative comparisons across the tests were conducted using the above-mentioned metrics.

3. RESULTS AND ANALYSIS

The results from the UHS photography shows that across the tests , the damage process followed a consistent sequence: (i) detonation and initial stress wave-induced sample deformation, (ii) crack initiation at the blastholes or edges of the sample, (iii) rapid crack propagation and formation of a system of cracks (iv) first gas ejection from the cracks and crack opening, (v) in some cases secondary crack propagation (branching, blastcone, etc.). Despite these general similarities during the process, notable differences in crack propagation paths, and final fracture patterns were observed as a function of decoupling ratio, initiation sequence and hole/guidehole configurations.

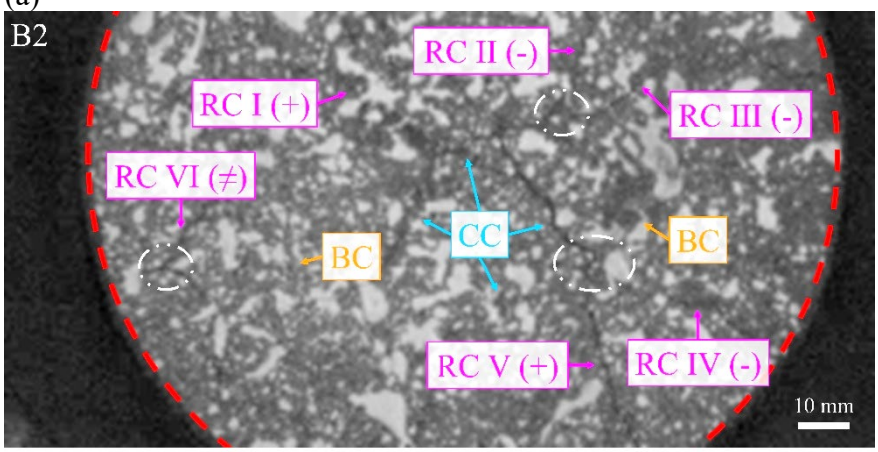
The qualitative analysis to track the crack development from detonation until the first gas ejection from any crack, as identified from the UHSC recordings. Figure 2 shows characteristics examples from experimental results. Single-blasthole experiments produced a characteristic radial crack pattern, with cracks initiating at the blastholes and propagating outwards in a star-shaped pattern. In several cases, radial cracks propagated

from the edges of the sample inward towards the blasthole due to the free boundary. Occasionally, crack branching occurred during propagation, leading to more complex fracture network (Figure 2 a). Tests conducted with lower decoupling ratio or higher specific charge exhibited denser crack patterns with higher number of cracks and less straight trajectories. The single-blasthole tests provided a baseline reference for interpreting crack interaction and coalescence behavior in the multi-blasthole configurations.

Two-blasthole experiments included both different decoupling ratios combined with simultaneous detonation and delayed initiation, where the detonation of the first blasthole pre-conditioned the surrounding material prior to the detonation of the neighboring blasthole. The results revealed clear crack interaction effects regardless of the initiation timing of the blastholes. In all the tested configurations, cracks initiated in each blasthole and propagated towards the inter-blasthole region, eventually coalescing to form a cutting plane between the holes. Similarly to the single-blasthole results, some cracks propagated between the blasthole and the edges, considered due to the boundary conditions. Simultaneous detonation consistently promoted a highly symmetric crack propagation path and coalescence (Figure 2 b). In contrast, delayed detonation altered the stress field in the inter-blasthole region, directing the crack propagation towards the blasthole previously detonated (Figure 2 c).

Introducing empty guideholes significantly modified the crack propagation paths by acting as crack attractors. In most of the tests, when the distance between a blasthole and a guidehole was equal or smaller than the distance between two charge blastholes, cracks propagated toward the guideholes before cracks propagating towards the adjacent blasthole (Figure 2 d). In contrast, if this distance was longer, the blasthole shows stronger influence (Figure 2 e). This behavior confirms the role of the guideholes in redirecting fracture paths by altering stress and strain distribution. The effects of the guideholes were observed consistently across different hole configurations and the corresponding specific charge.

(a)



t = 395.62 µs

Propagation direction

(+): Blasthole towards the edges; (-): Edges towards the blasthole ; (≠): Non detectable

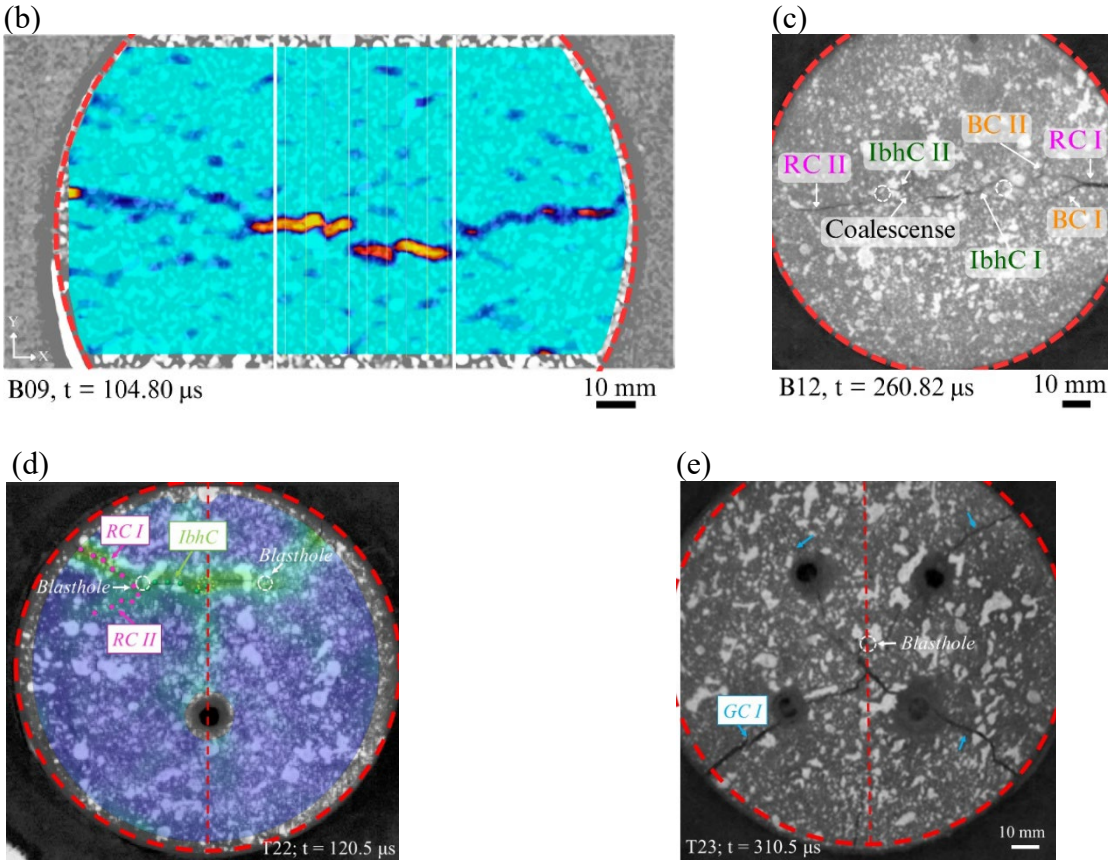


Figure 2. (a) Single-blasthole: Post-failure analysis results (R. San Miguel, et al., 2026a); (b) Two-blasthole results: DIC strain map (R. San Miguel, et al., 2026b); (c) Two-blasthole results: Post-failure analysis results (R. San Miguel, et al., 2026b); (d) 1 blasthole & 4 guideholes: Visual analysis from UHS photography (R. San Miguel, et al., 2025c); (e) DIC results of study with 2 blastholes & 1 blasthole (R. San Miguel, et al., 2025c)

A summary of the quantitative results is shown in Table 2. The cracks were classified according to their propagation origin and path as radial (RC), branching (BC), guidehole (GC), interguidehole (IghC), and circumferential (CC) also forming the blastcone. The results show that in the single-blasthole samples, increasing the decoupling ratio reduced the radial cracks. In the two-blasthole samples, the number of radial cracks is similar since they are due to the boundary conditions. The inter-guidehole cracks number corresponds to the connection between the blastholes in the samples. The majority of the inter-guidehole cracks follow the same trend as the inter-blasthole cracks but with the exception of not propagating when the distance between the guidehole and the blasthole is longer than between blastholes. In general, the circumferential cracks propagate to form the blastcone, with the difference that when there are guideholes in the design they propagate after the first gas ejection from another crack instead of being part of the crack system before the gas ejection.

In general, gas ejection timing for single-blasthole tests shows the largest median (398 µs) and the widest variability (217 µs), suggesting different breakage behaviors within the cases due to decoupling ratio effect and specific charge as the sample with decoupling ratio 5 did not break. Two-blasthole results show the most stable response in gas ejection timing, with a moderate median (272 µs) and the smallest variability (97 µs). The tests

with different hole configurations show a similar median to the two blasthole results (265 µs) but with a considerable wider variability (160 µs) due to the presence of guideholes.

Table 2. Experimental results regarding blast-induced crack type and level of blast-induced damage

Sample	First gas ejection [µs*]	Radial cracks (RC)	Branching cracks (BC)	Guidehole cracks (GC)	Interguidehole cracks (IghC)	Circumferential cracks (CC) / Blastcone
B01	390	7	2	-	-	Yes
B02	398	6	2	-	-	Yes
B03	396	6	2	-	-	Yes
B04	603	3	0	-	-	Yes
B05	610	4	0	-	-	Yes
B06	878	2	1	-	-	-
B07	0	0	0	-	-	No
B08	396	6	1	-	-	Yes
B09	270	5	1	-	2	No
B10	265	4	1	-	2	No
B11	236	4	2	-	2	No
B12	261	2	2	-	2	No
B13	275	3	2	-	2	Yes
B14	309	5	2	-	2	Yes
B15	375	4	0	-	2	Yes
B16	493	2	0	-	2	Yes
B17	580	5	2	2	0	0
B18	280	0	1	4	1	0
B19	240	5	Yes **	0	2	Yes **
B20	210	4 (2**)	No	2	No	Yes **
B21	330	0	Yes **	4	No	Yes **
B22	250	2	1	4	4	No

* After detonation

** After the first gas ejection

Figure 3 presents the cracks relative to their contribution to the blast design. On one hand, the cracks that were desired/expected to be created with the tested blast design were classified as intended cracks. On the other hand, the unintended ones were classified as damaging with an important difference in their origin, if they are due to the blast design, or the experimental constraints, and/or boundary conditions of the sample. Overall, the tests provided positive results, as the intended cracks or damaging cracks due to the boundary conditions are a substantial portion of the total crack percentage. This result indicates that controlled fracture development was generally achieved. However, the percentage of the damaging cracks due to the blast design varies significantly between configurations, reflecting the influence of the blast design parameters.

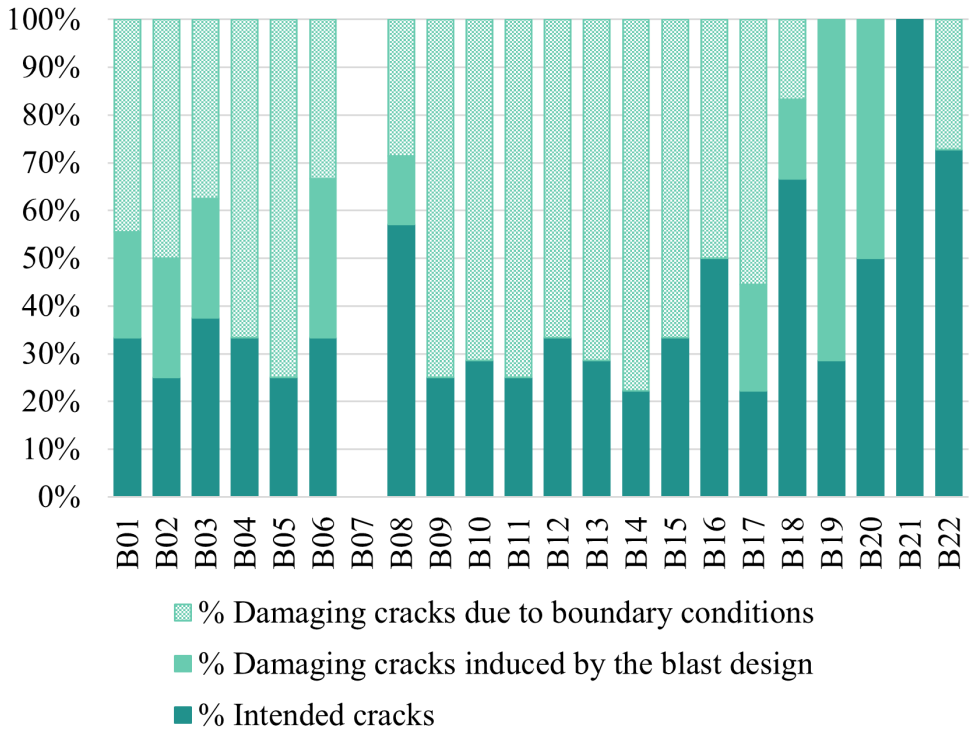


Figure 3. Results: Intended cracks & damaging cracks

4. DISCUSSION & FUTURE WORK: FIELD APPLICABILITY/ REAL-WORLD APPLICATIONS

The findings have been comprehensively supported in detail in previous studies and can be seen in more detail in the corresponding references (Table 1). Therefore, this section discusses to what extent the insights gained from the small-scale experiments could be applied/extrapolated to field blasting scenarios. The herein results confirm that decoupling ratio, initiation timing and guidehole configuration act as dominant variables governing the development and direction of the intended/cutting cracks.

These results are relevant for contour blasting practices in Swedish tunneling projects, among others. The ability to promote directional cracks while minimizing the blast-induced damage beyond the contour line is critical to achieve stable excavations and control overbreak.

Despite the advantages of the present experiments, several limitations must be acknowledged. Scaling effects inherent to small-scale blasting tests influenced crack propagation behavior, particularly outside the hole interaction zone, where the response of the rock does not resemble the rock mass that is blasted for tunnel excavations. While magnetite mortar provides well-controlled and homogeneous properties, it cannot fully represent the heterogeneities and discontinuities typically present in a natural rock mass. Additionally, small-scale test boundary conditions differ from in situ conditions, potentially affecting crack development, interactions and stress redistribution while breaking between others. These factors should be considered when extrapolating the results to field applications.

Translating small-scale findings to field-scale blasting involves significant challenges. First, the boundary conditions, the rock mass heterogeneities, natural fractures, and discontinuities at field scale cannot be replicated in small-scale specimens. Second, the explosive energy per unit volume differs significantly between the small-scale (g/m) to field charge (kg/m). Third, the blast-induced crack event is a dynamic fracture behavior problem and time dependent.

A recommendation for future work could focus on qualitative and quantitative measurement of crack propagation in field scale in tunnel environments to establish a multi-scale correlation and validation. By reproducing the selected combinations of decoupling ratio, initiation time, specific charge and hole configuration at field scale, the scalability could be evaluated. This approach will provide a basis for identifying the scale effects and extrapolating the small-scale tests results to practical tunneling applications.

5. CONCLUSIONS & TAKE AWAYS

This work summarizes the latest progress of research in Sweden regarding crack propagation by blasting in the frame of blast-induced damage. Several small-scale tests have been conducted to investigate the efficiency of using decoupling ratio, detonation delay and empty guideholes in the blast design and their impact on the resulting rock breakage with reduced damage. Some lessons or take aways from this research study are:

- Non-contact techniques such as UHS photography complemented with DIC method prove to be a successful method to capture blast-induced cracks around blastholes and track their propagation behavior.
- The post-failure and DIC analysis before gas ejection from the crack revealed stochastic crack propagation around a single blasthole, with consistent patterns in terms of crack number, type and development direction. The quantitative analysis of the crack density showed that increasing the decoupling ratio reduces the percentage of damaging cracks. Note that, when reaching a decoupling ratio of 5, the blast was not successful as no cracks developed.
- For the tests with more than one hole, the behavior inside the interaction zone of the holes is of the one of interest. An outstanding result is that the hole arrangements are the primary force driving the crack propagation and directionality, shadowing other variables such as delay time between blastholes or varying the specific charge.
- A final thought regarding scalability and practical relevance of the test consists in continuing the work by measuring cracks in tunnel blast case studies. This will contribute to establishing a correlation between small-scale and field-scale results. The following outcomes are believed to contribute to blast-damage prediction linked to blast design variables.

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