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ANALYSIS OF CRACK RESPONSE ON STRUCTURES DUE TO BLASTING AND NON-BLASTING FACTORS

I. Vojinović[1#], S. Stojadinović[2], I. Svrkota[1], M. Stojanović[1], D. Šabaz[1]

[1]Mining and Metallurgy Institute Bor, Bor, Serbia
[2]University of Belgrade, Technical Faculty in Bor, Bor, Serbia

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Abstract

Seismic waves caused by blasting activities can be a source of damage to structures. The most common damage is the appearance of cracks or the widening of existing cracks. Structures are also affected by environmental factors. Depending on the conditions, temperature and humidity can cause a stronger reaction in the cracks than blasting. However, the effects of non-blasting factors last much longer than those of blasting, so the load gradually increases, allowing for an even and timely distribution of stress around the crack tip. On the other hand, blasting factors act over a short period of time, resulting in a rapid increase in the stress intensity factor at the crack tip and a faster release of stress energy. The FEM (finite element method) analysis of these impacts was conducted on a model in the ABAQUS CAE software. The results of the analysis show that the influence of blasting factors is significantly higher compared to the influence of non-blasting (environmental) factors. The strain energy and the stress intensity factor per unit time are much higher under the influence of blasting factors. The strain energy is 9.58 × 1010 times higher, and the stress intensity factor at the crack tip is 309583 times higher due to the dynamic load, observed over a period of 0.033 seconds.

Key words: *seismic waves, blasting, FEM method, ABAQUS CAE, crack, environmental factors.*

1. Introduction

Primary blasting is one of the several fundamental technological phases in the process of surface and underground excavation of solid rock masses, mineral raw materials, or overburden. It is conducted with the largest diameters of boreholes, the greatest quantity of explosives per blast, and the largest volume of material prepared by a single blast for further technological processing [1].

This technological operation is accompanied by undesirable and unavoidable effects, such as seismic waves that people perceive as tremors or ground vibrations. Ground vibrations can have significant intensity and may cause damage to nearby structures. As the seismic wave passes through the foundation soil of a structure, it causes oscillation of the structure itself, which can lead to the occurrence of damage in the form of new structural cracks (deep cracks in walls, supporting columns, etc.), facade cracks, or the widening of existing cracks [2].

Damage to structures may also exist prior to the passage of seismic waves generated by blasting. Pre-existing structural damage can result from a variety of factors, such as natural seismic waves (earthquakes), soil subsidence or uplift, landslides, the impact of wind, water, sun, frost, etc. [3, 13, 14].

Numerous studies highlight the significant impact of daily temperature changes, humidity variations, soil settlement, and everyday human activities on structural damage. They indicate that, in some cases, the impact of blasting is considerably smaller than the aforementioned influences. However, regardless of how small the impact of blasting may be, it should not be ignored [3].

The impact of each factor on structural cracks is generally observed through the reactions of the cracks themselves, particularly their widening. However, when comparing the duration of blasting and non-blasting factors, a significant difference can be noted. The duration of blasting factors is on the order of milliseconds (ms), whereas the duration of non-blasting

#Corresponding author: ivica.vojinovic@irmbor.co.rs

factors can span several hours or even days.

The impact of blasting, as a transient dynamic load, although it affects structures for a short period of time (ms), induces complex stresses within them that are significantly greater than those from loads acting over longer periods [4]. Previous studies have focused on monitoring crack responses to environmental influences over durations of 37 hours and to the passage of seismic waves [4]. Therefore, this study aimed to confirm, based on longer durations (72 hours) and more extensive measurements across multiple cracks, that dynamic stress resulting from ground vibrations indeed causes higher stresses at the crack tip.

According to references [3, 4-10], the crack response in terms of its widening due to blasting can be much smaller compared to the influence of other factors. However, the stress intensity at the crack tip is significantly higher with blasting-induced vibrations because these are dynamic stresses. Specifically, research results from [4] indicate that due to dynamic loading, the equivalent crack response is 126 times greater compared to the influence of other (static) stresses.

Results from the literature provide the basis and motivation to continue further detailed research on this topic. Flowchart of the research methodology is shown in the Figure 1.

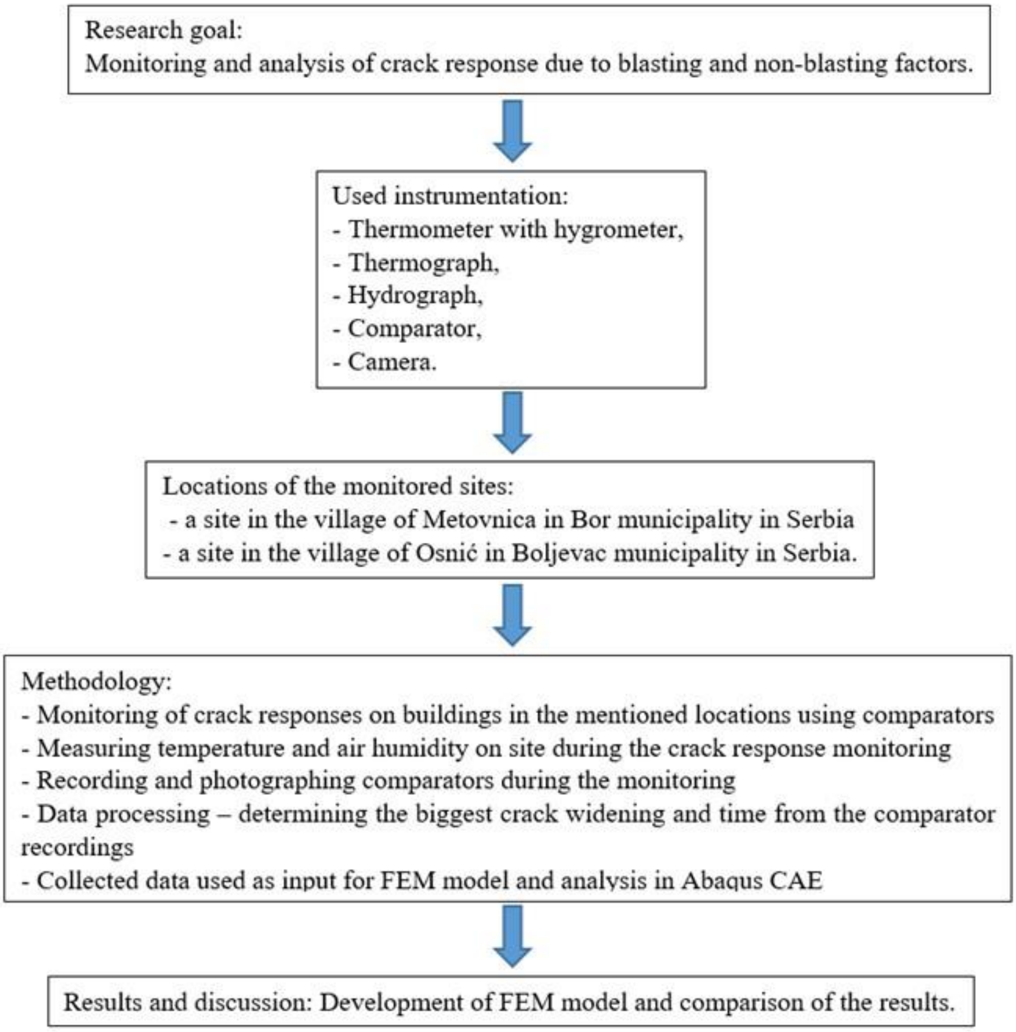


Figure 1 Methodology flowchart

2. Materials and Methods

To monitor the responses of structural cracks on residential buildings exposed to environmental influences and seismic waves resulting from blasting, the following equipment was used:

HACCURY DYWSJ thermometer with hygrometer capable of measuring temperature and relative humidity of the air (temp. range -30 to +50 °C, RH range 0-100 %, temp. tolerance +/-1 °C, moisture tolerance ±5%), Veb. Feingeratebau thermograph and hydrograph (temp. range -35 °C to +45 °C, RH range 0-100 % and tolerance ±3%), comparator manufactured by Soil Test Inc., Evanston, IL, USA. This comparator has a measurement range up to 25 mm, with the scale graduated in 0.01 mm increments. The monitored influential parameters include temperature (°C), relative humidity (%), and crack reaction (mm).

For the purposes of this study, research was conducted at two locations. The first measurements were carried out at a site in the village of Metovnica in Bor region in Serbia, where the crack response during blasting was monitored during the construction phase of two parallel declines for exploratory work in the copper and gold deposit "Čukaru Peki" (Figure 2).

Figure 2 Locations of the monitored sites

The second set of measurements was conducted at an old family house in the village of Osnić in Boljevac municipality in Serbia (Figure 2), where the responses of three cracks to environmental influences were monitored.

The monitoring of crack responses to seismic waves caused by blasting was conducted on an older building near the current mining operations. For measurement purposes, a comparator was used, placed on a structural crack between stone blocks of the building (Figure 3). The cause of the crack formation was not determined; it is possible that the crack occurred due to the age of the building and prolonged exposure to natural factors, primarily soil settlement.


Figure 3 Comparator on the object at Metovnica site

Photographs and video recordings were used to capture the crack response in terms of the movement of the comparator's pointer. Monitoring of the crack response on this building was conducted in two series of blasts, resulting in two recordings that were further analyzed. Since seismic waves caused by blasting induce short-term movements, recording the comparator itself provided the best method for tracking the crack response.

At the building in the village of Osnić, the monitoring of crack response to environmental influences was conducted. Due to the age of the building and the variety of materials used in its construction, the structure has experienced multiple damages manifested as structural cracks.

The cracks are most likely a result of land sliding (the house is located on a slope), soil settlement, and uplift due to inadequate rainwater drainage systems. However, the exact causes of these damages have not been precisely determined. Cracks are present on each side of the building, so measurements were conducted on three cracks: one on the shaded side, one on the sunny side, and one on the partially sunny side of the house.

Before the measurements began, a thermograph and hydrograph were placed near the crack to record temperature and relative humidity readings (Figure 4). Additionally, a thermometer with a hygrometer was placed next to the wall of the building.

Figure 4 Thermograph and hydrograph positioned near the cracked wall

The first measurement was conducted on the shaded side of the house, where the crack runs from bottom to top, possibly caused by ground uplift or sliding (Figure 5a). A comparator was mounted directly on the crack, and before measurements commenced, the comparator was zeroed and photographed (Figure 5b).

Measurements were taken every 2 hours over a period of three days (72 hours for one crack). Preparation for measurement, reading values, as well as the assembly and disassembly of the comparator, were identical for each reading series.

The first reading was conducted on the shaded side. After completing the readings, the position of the comparator pointer was photographed, followed by disassembly and relocation of the comparator to the next crack.

The next series of readings were conducted on the sunny side of the house (Figure 6).

a) b)

Figure 5 Crack on the shaded side (a) with the thermometer and comparator at the start of monitoring (b)

a) b)

Figure 6 Crack on the sunny side, outside (a) and inside (b)

The last reading was taken on the partially sunny side of the house (Figure 7).

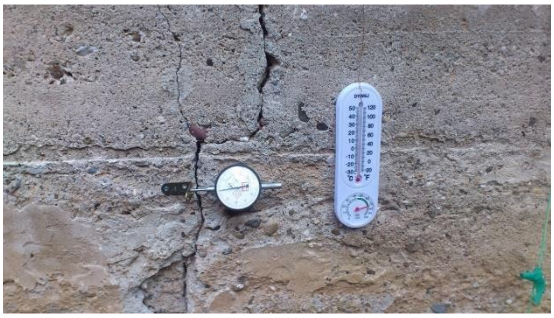


Figure 7 Crack on the partially sunny side with thermometer and comparator

3. Results of the research and discussion

Two recordings were analyzed showing the crack response to the seismic waves caused by blasting, as recorded by the comparator. The recordings were divided into frames using media player software, specifically "KMPlayer." The frame rate (fps - frames per second) of the recordings was 30 fps, meaning there were 30 frames per second. With this in mind, the duration of one frame can be determined using the formula (1):

$$30\,fps \rightarrow \frac{1}{30} = \frac{second}{frame} = 0.0333\ \left[{}^{s}/_{frame}\right] \quad (1)$$

Out of the total number of frames (considering both recordings), 160 frames were selected for analysis (60 frames for the first recording and 100 frames for the second recording), from which the displacement values of the comparator pointer were read. This method determined the displacement value of the comparator pointer per frame. The obtained data were further processed in Microsoft Excel 2010 (Figure 7).

The decreasing values of the comparator displacement represent crack widening, while increasing values indicate crack closure or contraction. It was found that for Recording 1, the largest crack widening reaction was 0.042 mm (ranging between -0.002 mm and 0.04 mm) over a time period of 0.033 s (from 0.693 s to 0.726 s), whereas for Recording 2, the largest crack widening reaction was 0.012 mm (ranging between -0.01 mm and 0.002 mm) over a time period of 0.033 s (from 1.551 s to 1.584 s).

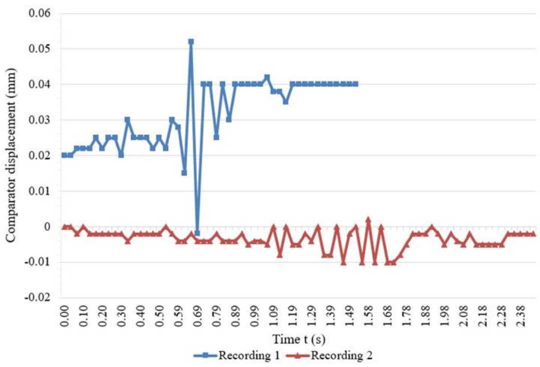


Figure 8 Crack response due to blast vibrations

After recording all parameters and crack responses on the building in the village of Osnić, the obtained data were further processed similarly to the previous case. Through data processing, it was determined that the largest crack reaction occurred on the sunny side (Crack 2), with a widening of 0.210 mm (ranging between -0.1 mm and 0.11 mm) over a period of 14 hours (from 16:00 on Day 2 to 06:00 on Day 3). On the partially sunny side (Crack 3), the widening was 0.048 mm (ranging between -0.002 mm and 0.046 mm) over 16 hours (from 16:00 on Day 1 to 08:00 on Day 2), and on the shaded side (Crack 1), it was 0.010 mm (ranging between -0.028 mm and -0.018 mm) over 36 hours (from 16:00 on Day 1 to 18:00 on Day 3) (Figures 9 – 11).

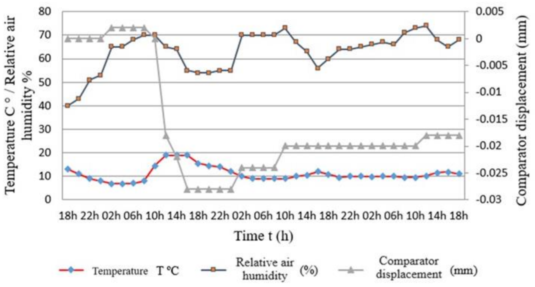


Figure 9 Graphical representation of changes in temperature, relative humidity, and crack 1 response

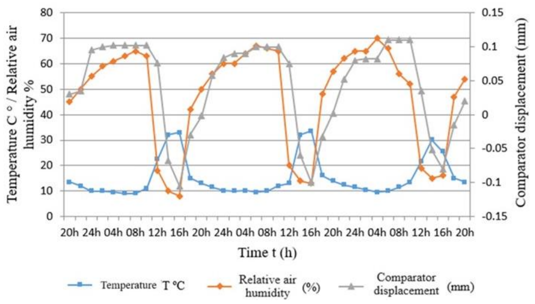


Figure 10 Graphical representation of changes in temperature, relative humidity, and crack 2 response

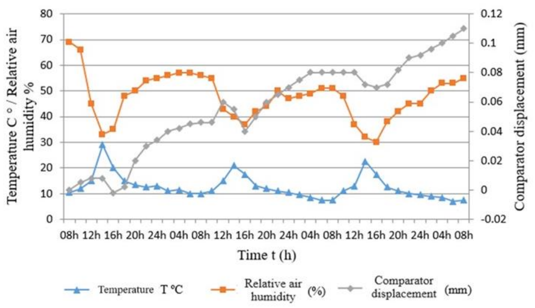
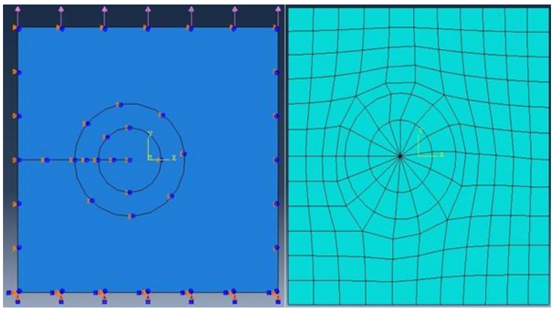


Figure 11 Graphical representation of changes in temperature, relative humidity, and crack 3 response

Obtained data from comparator displacement and duration of crack response was used as input data for FEM model and further analysis. FEM is a numerical method used for solving engineering and mathematical physics problems. Analytical solutions to these problems require solving boundary value partial differential equations. FEM utilizes variation methods to obtain exact or approximate solutions. The study or analysis conducted using FEM is often referred to as Finite Element Analysis (FEA). The finite element method (FEM) is commonly used in evaluating blast-induced ground vibrations, either individually or coupled with other methods. The numerical approach by FEM allows monitoring, in time and space, the seismic waves. This facilitates the evaluation of the rock mass response to the induced dynamic efforts. [11, 12].

Abaqus CAE (Complete Abaqus Environment – Computer Aided Engineering) is equipped for FEM analysis and is used for modeling and analyzing mechanical components and assemblies, as well as for displaying the results of FEM analysis. For this study, the academic version of the software, SIMULIA Abaqus Student Edition 2018, was used. However, the academic version has certain limitations in modeling and performing more advanced analyses, but it meets the requirements of this research [11].

According to recommendations and instructions from relevant documentation on fracture mechanics in Abaqus software, a Finite Element Method (FEM) model was created for analysis [11]. The analysis was conducted on a 2D model with dimensions of 1 mm x 1 mm (Figure 12a).



a) Geometry of the model with applied load
b) Model divided into a finite number of elements

Figure 12 FEM model in Abaqus CAE

The applied element type in the model is CPS 8 ("8 node biquadratic plane stress quadrilateral element"), while the region around the crack tip is modeled with CPS 6 ("6 node quadratic plane stress triangle element"). The material assigned to the model is elastic and isotropic, with properties corresponding to concrete: Young's modulus E = 30 GPa, Poisson's ratio v = 0.2, and density γ = 2.4 t/m³.

Due to the limitations in Abaqus software regarding unit selection for specific input quantities, all dimensions were standardized to the same unit. In our case, all units were expressed in millimeters.

The entire model is meshed into a finite number of elements (Figure 12-b). Each finite element is of the same type as the overall model. The mesh density applied is 0.09 mm x 0.09 mm.

Considering the computational constraints, it is nearly impossible to account for all factors influencing crack propagation. Therefore, the loading applied to this model is simplified to pressure along the upper edge of the model, acting in the direction of the Y-axis.

For the analysis of both blasting and non-blasting factors, the same model was used, but with different analysis parameters applied in each case.

Regarding the constraints, they are the same for all cases. The entire model is restricted in movement along the X and Z axes, while movement along the Y axis is allowed. The model is constrained along its lower edge in all axes using the "ENCASTRE" option (U1=U2=U3=UR1=UR2=UR3=0), while loads are applied along the upper edge of the model.

To determine the amount of pressure required for the appropriate crack response, a separate analysis was conducted. Based on the results of this analysis, it was determined that for a crack response to blasting factors, in the form of a 12 μm expansion, a pressure of σ = 260 MPa needs to be applied, and for a 42 μm expansion, a pressure of σ = 900 MPa is required.

Regarding the crack's response to non-blasting factors, a pressure of σ = 4440 MPa is needed for a crack expansion of 210 μm, for a 48 μm expansion, a pressure of σ = 1015 MPa is required, and for a 10 μm expansion, a pressure of σ = 220 MPa is necessary. The load value for each analysis gradually increases with the number of increments, from 0 to the maximum load value.

The duration of the crack response analysis to blasting factors, for both cases, is 0.033 seconds. The total analysis time is divided into 100 increments, with the duration of each increment being 0.00033 seconds.

The duration of the crack response analysis to non-blasting factors is, for the shaded side, 129600 seconds or 36 hours, for the partially sunny side, 57600 seconds or 16 hours, and for the sunny side, 50400 seconds or 14 hours. The total analysis time is divided into 1000 increments, with the duration of each increment being 129.6 seconds for the shaded side, 57.6 seconds for the partially sunny side, and 50.4 seconds for the sunny side.

The analysis focused on two parameters: the Stress Intensity Factor (SIF) at the crack tip (KI) and the strain energy in the entire model (Figure 13).

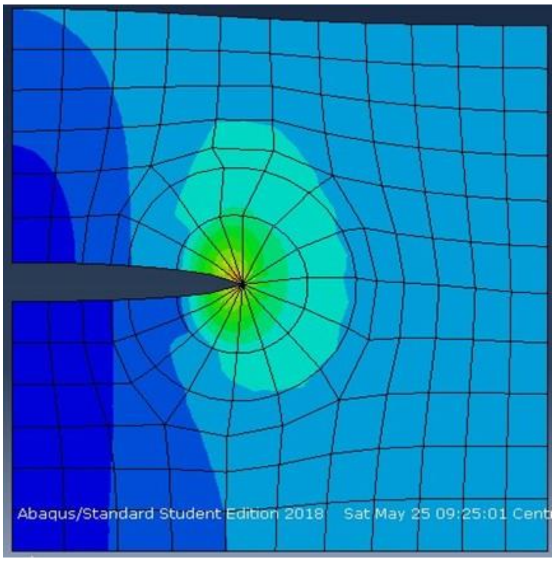


Figure 13 Model of the crack after FEM analysis

The obtained results are presented in the form of graphs "SIF-Time" and "Energy-Time," which can be seen in the following figures (Figure 14 and Figure 15).

From the monitoring results of non-blasting factors, it can be seen that the largest comparator displacement was on the sunny side. Hence, these results were taken into comparison with the blasting factors for further analysis.

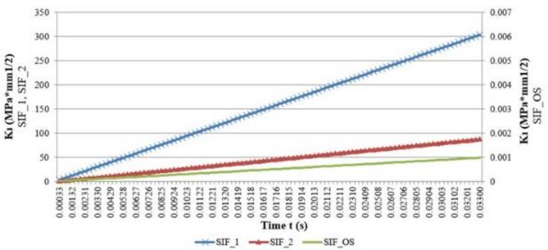


Figure 14 SIF versus Time, all influences

It can be seen from Figure 14, that stress intensity factor (SIF) linearly increases over time, thus representing a linear function of the form y = kx. If in the expression y = kx changes are made in a way that y =SIF, x=Time => SIF = kTime, then $k = \frac{SIF}{Time}$. Following this fact, we can calculate the coefficient k for each function.

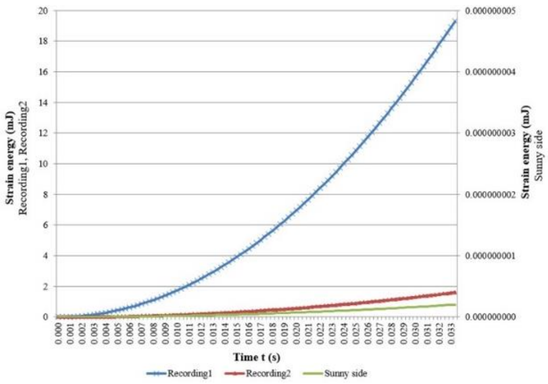


Figure 15 Strain Energy versus Time, all influences

Blasting factors:

- Recording 1: $k_1 = \frac{SIF_1}{Time_1}$ => k_1 = 9 181. 91 (2)
- Recording 2: $k_2 = \frac{SIF_2}{Time_2}$ => k_2 = 2 652. 55 (3)

Non-blasting factors:

- Sunny side: $k_{os} = \frac{SIF_{os}}{Time_{os}}$ => k_{os} = 0.029659 (4)

If we compare the slope coefficients k1, k2, and cos, we can see that (k1, k2) >> cos. It can be said that due to blasting influences (Recordings 1 and 2), the stress intensity factor (SIF) at the crack tip increases much faster over time compared to non-blasting influences (Figure 14). Assuming that the stress intensity factor (SIF) at the crack tip is equal for both blasting and non-blasting factors, we can calculate how many times faster the SIF increases during blasting influences at the crack tip.

$$SIF_1 = SIF_{OS} \quad (5)$$

$$k_1 t_1 = k_{OS} t_{OS} \quad (6)$$

$$t_{OS} = \frac{k_1 t_1}{k_{OS}} \quad (7)$$

$$t_{OS} = 309\ 582.59 t_1$$

SIF_1 – Stress intensity factor 1(blasting influence),
SIF_{OS} - Stress intensity factor for the sunny side (non-blasting influence),
k_1 – directional coefficient for Recording 1,
k_{OS} - directional coefficient for sunny side,

t_1 – time for Recording 1,
t_{OS} – time for sunny side record.

In addition to the stress intensity factor at the crack tip, the strain energy in the entire model was also monitored. In Figure 15, we can observe the increase in strain energy over time for all influences. Strain energy follows a quadratic function of the form $y = kx^2$. Using a similar analogy as with SIF, we can express this as y = Energy, x = Time => Energy = k $Time^2$, and further calculate the coefficient k.

Blasting factors:

- Recording 1: k_1 = 17 728. 65
- Recording 2: k_2 = 1 479. 58

Non-blasting factors:

- Sunny side: $k_{os} = 1.849796863 \times 10^{-7}$

It can be observed that (k1, k2) >> kos.

It can be said that due to blasting influences (Recordings 1 and 2), the stress energy per unit time increases much faster compared to non-blasting influences.

4. Conclusion

By performing an FEM analysis of the obtained reactions in ABAQUS, it was shown that although the crack response is larger under non-blasting factors, the strain energy and stress intensity factor per unit time are much larger under blast influences. The strain energy is 9.58×10^{10} times larger, and the stress intensity factor at the crack tip is 309583 times higher due to the dynamic loading, observed over a period of 0.033 seconds.

The study of the obtained results shows that dynamic loading caused by the blasting activities prevents adequate and timely stress distribution in the structural elements of the object. As a result, there is a risk of material fatigue, further damage, or the appearance of new defects in the structure.

Based on the above, future research could focus on determining the critical values of the stress intensity factor, i.e. the point at which material fracture and crack progression could occur. In addition, the effects of blasting and non-blasting factors on the overall damage to the structure could be investigated. Among other aspects, the condition of the building, the type of soil on which the building's foundation stands, the building's location, the construction method, the duration of exposure to vibrations, the number of basions, etc. should also be considered.

It is evident that even in cases where the impact of blasting is significantly less than other factors, it should not be neglected, and its impact on nearby structures should always be monitored.

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ANALIZA REAKCIJA PUKOTINA NA OBJEKTIMA USLED MINERSKIH I NEMINERSKIH FAKTORA

I. Vojinović[1#], S. Stojadinović[2], I. Svrkota[1], M. Stojanović[1], D. Šabaz[1]

[1]Institut za rudarstvo i metalurgiju Bor, Bor, Srbija
[2]Univerzitet u Beogradu, Tehnički fakultet u Boru, Bor, Srbija

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Izvod

Seizmički talasi izazvani minerskim aktivnostima mogu biti izvor oštećenja na objektima. Najčešće oštećenje je pojava novih pukotina ili proširenje postojećih. Objekti su takođe podložni uticajima faktora životne sredine. U zavisnosti od uslova, temperatura i vlažnost mogu izazvati jaču reakciju u pukotinama nego miniranje. Međutim, efekti ne-minerskih faktora traju znatno duže od efekata miniranja, pa se opterećenje postepeno povećava, omogućavajući ravnomernu i pravovremenu raspodelu napona oko vrha pukotine. S druge strane, minerski faktori deluju tokom kratkog vremenskog perioda, što za rezultat ima brz porast faktora intenziteta napona na vrhu pukotine i brže oslobađanje energije. Analiza ovih uticaja primenom FEM metode izvedena je na modelu u softveru ABAQUS CAE. Rezultati analize pokazuju da je uticaj minerskih faktora značajno veći u poređenju sa uticajem ne-minerskih (ekoloških) faktora. Energija deformacije i faktor intenziteta napona po jedinici vremena su znatno viši pod uticajem minerskih faktora. Energija deformacije je 9,58 × 10^{10} puta veća, a faktor intenziteta napona na vrhu pukotine je 309583 puta veći usled dinamičkog opterećenja, posmatrano tokom perioda od 0,033 sekunde.

Ključne reči: *seizmički talasi, miniranje, FEM metoda, ABAQUS CAE, pukotina, faktori životne sredine.*