Shahrood University of Technology

Journal of Mining and Environment (JME)

Journal homepage: www.jme.shahroodut.ac.ir

Iranian Society of Mining Engineering (IRSME)

Pre-existing Crack Effect on Damage of Inner Concrete Lining under an Internal Explosion: A Numerical Study

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Article Info

Received 6 February 2023
Received in Revised form 11 March 2023
Accepted 15 March 2023
Published online 15 March 2023

DOI:10.22044/jme.2023.12682.2304

Keywords

Concrete Damage Plasticity
Concrete, Coupled Eulerian-Lagrangian
Explosion, ABAQUS

Abstract

Engineers use various methods to evaluate the performance of concrete structures under dynamic loads, including numerical simulations, laboratory experiments, and field tests. By combining the results of these methods, the engineers can develop a comprehensive understanding of the behavior of concrete structures under dynamic loads and use this information to design more resilient structures capable of withstanding these loads. In this work, four models of the concrete lining of the circular tunnel are simulated to investigate the effect of the pre-cracked in the tunnel's concrete lining under an internal explosion loading. A crack in three different locations at angles of 0, 45, and 90 on the horizontal axis of the tunnel is investigated and analyzed. The coupled Eulerian-Lagrangian method and the constitutive behavior, such as concrete damage plasticity for concrete and Drucker-Prager for soil, allows a more accurate simulation of the internal explosion loading scenario. The selection of Trinitrotoluene and the Jones-Wilkins-Lee equation of state for the explosive provides a realistic representation of the behavior of the explosive material. The modeling results show that in an internal explosion, by examining three different locations of a crack in the concrete, the occurrence of a crack in the crown of the tunnel is more critical than two crack locations. Hence, the existence of a crack with a length of 100 cm and a depth of 15 cm in the crown of the tunnel increases the tensile damage zone by 16.59% compared to the case where there is no crack.

1. Introduction

With the advancement of technology, the construction of underground structures has become more and more straightforward. Underground structures such as gas and fuel storage caves, traffic tunnels, water transfer tunnels, industrial wastewater, and other civil structures must be designed to have the necessary stability to withstand static and dynamic loadings. Various phenomena, such as the impact of a projectile on a structure (impact loading), earthquakes, rapid movement of floods around the structure, and explosions, are among the loadings considered dynamic [1]. Although the occurrence of these phenomena cannot be predicted, a structure must always have a relative and initial stability in the face of these types of loading. Increasing the importance of a structure according to its application and sensitivity, more attention to stability against dynamic loading becomes more necessary. Investigating and paying attention to the stability of a tunnel against explosion is very important. Traffic tunnels are considered communication routes between different areas because of their multiple uses [1-3].

It is essential to consider the response of the support system to dynamic loading when designing underground structures. The stability of the structure depends not only on the concrete lining but also on the support system used. The selection of an appropriate support system is critical to ensure the stability and safety of the structure against dynamic loads such as earthquakes, impacts, and explosions. Different support systems, such as steel frames, concrete lining, wooden support systems, or rock bolts, can stabilize underground structures. The

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response of each support system to dynamic loading must be analyzed in order to determine its suitability for a particular project. By evaluating the performance of different support systems under dynamic loads, the engineers can make informed decisions about which system is best suited for a particular project and ensure the stability and safety of the underground structure. In conclusion, analyzing the response of the support system to dynamic loading is a crucial step in ensuring the stability of underground structures against dynamic loads. The results of these studies can inform the design and selection of appropriate support systems, contributing significantly to the safety and reliability of underground structures. [3]. For example, in a study, Thai *et al*. [4] investigated the local damage of reinforced concrete tunnels exposed to ballistic missile attacks using finite element analysis. FE (Finite Element) LS-DYNA software has been used to simulate the impact of a ballistic missile on tunnels. Their numerical study based on the four types of tunnel concrete lining modeled in this study are Korea's most common concrete support systems. This numerical study only pays attention to the impact aspect of the missile and emphasizes that the ballistic missile does not carry explosives. The results of the modeling by Tahi *et al.* showed that flaking, penetration, and cracking in the underground structure depend on the thickness of the concrete lining.

Daraei *et al.* [5] in a numerical study on the response of masonry tunnels as consequential and ancient structures in Iran to intense earthquakes, showed that a support system should be used to strengthen these structures. Per the results of their numerical study, it was shown that using a shotcrete maintenance system containing steel fibers shotcrete or internal concrete coating increases the structure's life against seismic loads, and the inner concrete lining performs better than steel fibers shotcrete against seismic loads

In the dynamic loading conditions of the earthquake type, various studies have been conducted which show that the thickness of the concrete lining, the amount of weathering of the rocks covering the tunnel, the weathering effect on rocks, and the concrete lining of the tunnel as a support system, different shapes of tunnels, discontinuities effect, and the presence of complications in the maintenance system are effective in the stability of tunnels in seismic loadings of earthquakes. For example, we can mention the study of Tsinidis *et al*. [6], Tsinidis *et al*. [7], Wang *et al.* [8]., Zaid *et al*. [9], Najm and Daraei [10].

Explosion is a dynamic loading and can be considered a random or spontaneous phenomenon. For example, the explosion of a car carrying fuel (such as gasoline or gas) in a tunnel as an internal explosion causes the tunnel to collapse, blocking the communication path between two areas. In addition to the internal mode, the explosion can occur on the surface [11]. For example, we can refer to construction activities on the earth's surface to harvest the zone's soil or random explosions on the earth's surface, which is deep under a tunnel. Two main factors of the explosion, which are the vibration of the ground, or the movement of the blast wave, and the pressure caused by the expansion of the gases resulting from the burning of the explosive and its expansion in the structure, play a fundamental and essential role in the stability of an underground structure [11, 12].

A dangerous circumstance such as an explosion is essential for underground structures for five reasons:

1) Underground structures are not like surface structures that are safe from escaping smoke and gases from explosions and cannot be controlled more easily [13].

2) Underground structures bear a slag weight by default, and their maintenance systems are designed so that any damage to this system will cause disturbances in stress balancing and the destructive effect of other loads on the structure [14].

3) Cracks and water leakage into the tunnel may occur due to the explosion. These phenomena may not show themselves at the beginning of the explosion. With the passage of time and the influence of other factors, they can be seen over an extended period. For example, an explosion at a longer distance in a tunnel can cause micro-cracks sprouting caused by the blast wave, and these micro-cracks expand due to weathering, earthquakes, fault movement, or gravity force [15].

4) The construction of an underground structure such as a tunnel or a power storage cave is based on many studies, such as geological surveys to avoid active faults and have suitable conditions to create economic savings. In addition to financial losses, the explosion that destroys a concrete structure causes much time to be spent to build a similar structure [16].

5) Occasionally, surface or internal explosions inside an underground structure may not be severe, but the repetition of this type of loading causes severe

> damage to the structure. Suppose an explosive pattern is repeated periodically on the earth's surface in which a tunnel passes to remove a specific tonnage of soil and rock. Removing a part of the soil and rock layer will reduce the distance between the explosion point and the tunnel. Although, at first, the loading of the surface explosion may not affect the performance of the underground structure, its repetition can cause more severe damage to the tunnel in the continuation of the surface blasting process [16].

Various studies have been carried out on tunnel stability under the surface or internal explosion loading as small-scale laboratory, large-scale field tests, numerical, and analythical studies such as other dynamic loads. For example, in blast wave propagation, Lak *et al*. [17] analythically showed that the general Green's function could correctly interpret and persuade the manners of the blast wave. The convergence of the results of this analytical research in the values of particle velocity of maximum stress and strain with numerical study in FLAC software makes this analytical method correct.

Zaid *et al*. [18], by numerical analysis using the finite element method on quartzite rocks in North India, showed that the thickness of the tunnel concrete lining significantly affects the stability of large-diameter tunnels. However, in the stability of tunnels with a small diameter, the thickness of the concrete lining does not have much effect on the stability of the tunnel. Also, the shape change due to expansion is highly dependent on the depth of the tunnel placement, and the shape changes of the tunnel change exponentially with the increase in depth.

The study by Mussa *et al*. highlights the importance of considering the impact of surface explosions on underground structures. Using numerical modeling, the authors found that using a concrete cover as a maintenance system could help reduce the tunnel deformation caused by an explosion. Additionally, increasing the thickness of the concrete cover and changing the depth can further reduce changes in the shape of the tunnel. The study also emphasizes the impact of the surface explosion wave, which passes over the solid part of the soil and affects the underground structure, and highlights the importance of considering this wave when designing underground structures against explosive loads [19].

In a numerical study, Zhang and Yang [20] dealt with the interaction of soil and concrete lining of the tunnel under an internal explosion in FE LS-DYNA. During the numerical modeling, they also investigated the effect of pore pressure, and showed that the liquefaction phenomenon is possible in the soil with 50 to 200 kilograms of explosives. Furthermore, in the area close to the explosive material, tensile failure occurs in the tunnel lining, and with distance from the explosion area, the failures are of the compression type.

In their study, Li and Li used elastodynamics and numerical simulations in PFC2D (Particle Flow Code in 2 Dimensions) to examine the impact of the wavelength (λ) to tunnel diameter (D) ratio (λ/D) on the dynamic response of underground tunnels under explosion load. They found that for λ/D ratios greater than 2, dynamic failures mainly occur in the roof and floor of the tunnel. They also discovered that an enormous blasting load with a higher amplitude leads to a more extensive damage zone surrounding the rock in the tunnel. As the tunnel's lateral pressure coefficient and buried depth increased, the spalling crack on the incident side of the tunnel shortened while the damage zone in the roof and floor enlarged [21].

Sadique *et al*. [22], in a numerical study on three types of rocks such as basalt, granite, and quartzite, showed that the strength and stability of the tunnel under an internal explosion depended on the rock texture and modulus of elasticity of the rock in which the tunnel is dug. Moreover, quartzite rock's tunnel stability is higher than in basalt and granite.

In the science of fracture mechanics, it was found that complications and discontinuities in the rock cause the structure to fail before reaching the theoretical strength determined based on analytical or experimental relationships in the laboratory. This event is regardless of the static or dynamic loading type. In the dynamic conditions of the wave movement and the structure's response in rocks and steel materials, what is discussed in the dynamics of a surface structure such as steel is different. A discontinuity in the rocks causes the wave to be damped earlier. Many studies have examined rock discontinuities and the interaction between blast waves and discontinuity for example, Hajibagharpour et al [23], in a numerical study using the two-dimensional discrete element method, showed that the rock fracture mechanism around the hole was due to the effect of the blast wave on the crack density. The surrounding area of a blast hole depends. The results of this numerical study were in close agreement with various experimental relationships in the field of explosion and the existence of discontinuity around the blast hole.

In summary, a tunnel's stability and damage ratio under an explosion is influenced by various factors such as the tunnel and concrete linings' geometrical parameters, the surrounding soil and rock's parameters, and the explosive's related parameters. Pre-existing cracks in the rocks and concrete can also reduce their strength. Fracture mechanics studies have shown that increasing the length and depth of cracks can decrease the fracture toughness of the structure. The study by Zhang *et al*. [24] investigated the effect of crack length on the fracture toughness of limestone under tensile loading. The pressure caused by the expansion of gases is also considered an influential factor in this study.

Examining the dynamic force of the explosion on substantial damage, concrete containing cracks gives the engineers the conception to boost and involve a complete support system in that area as soon as possible if cracks occur. Engineers can also use concrete containing additives before implementing a design, which improves the resistance parameters of concrete compared to ordinary concrete. Various studies have been done in this regard. For example, Golewski and Sadowski [25], showed that concrete containing 20% fly ash increases the fracture toughness of concrete compared to normal concrete against tensile loading.

Furthermore, Golewski and Sadowski [26], in another study showed that the resistance against crack growth of concrete under mode I, mode II, and mode III loading increases with the addition of 20% fly ash. If this percentage increases, the resistance parameters of concrete decrease. This study shows that it is always necessary to determine the optimal percentage of materials in the design of concrete for better performance in various conditions. This work can play an essential role in the internal coating of concrete.

Modifying the binder composition with three pozzolanic active materials increased the analyzed mechanical parameters for each of the combinations compared to the results obtained for the control concrete. In addition, as the content of fly ash rises throughout each quaternary concrete series, the material becomes more ductile and shows a less brittle failure. Therefore, with high fracture toughness and lower brittleness, this boosted concrete can be used in reinforced concrete structures subjected to dynamic or cyclic loads [27].

This applicable study will investigate the effect of pre-existing crack location on the severity and type of damage caused to the inner concrete lining under internal explosion. The stability of the tunnel crown under tension is essential, as inner concrete lining performs poorly under tensile loading. These findings can inform the design of more resilient concrete structures, and help improve their safety against internal explosion loads. The paper is structured in three sections, each addressing different aspects of the study on the impact of pre-existing cracks in inner concrete lining on the damage caused by an internal explosion in a tunnel. The first section, methodology of crack effect on concrete lining under an internal explosion, outlines the method used to investigate the effect of cracks on the concrete. The second section, simulation, and discussion of the numerical study presents the results of the numerical simulations and discusses their implications. Finally, the third section, the conclusion, summarizes the essential findings and provides insights into the significance of the study.

2. Methodology of Crack Effect on Concrete Lining under an Internal Explosion

There are three primary experimental, analytical, and numerical methods for crack analysis in a structure regardless of the type of loading, both static and dynamic. In the problem of the effect of cracks in a structure under an internal explosion loading, analytical analyzes are very straightforward, and many effective parameters in these relations are ignored. This is while the experimental methods of load explosion relationships are only around small-scale laboratory studies. However, these results can be generalized to larger-scale conditions, but these relationships are only occasionally authentic. In order to investigate the effect of cracks in a structure under explosion loading, it is suggested to use numerical methods. Numerical methods, such as FEA (finite element analysis), are commonly used to simulate and analyze the effects of cracks in structures under internal explosion loading. FEA allows for considering all relevant parameters and provides more accurate results than analytical methods. However, FEA requires detailed input data and computational resources, which can make it more time-consuming and expensive than analytical methods. In conclusion, numerical methods are more comprehensive and accurate but analytical methods are simpler and faster, while experimental methods provide real-world data but are limited in scope [20, 22].

The step of the proposed methodology for modeling a structure with a crack under an internal explosion loading is presented in Figure 1. The goal is to provide insights into the behavior of such structures under explosion loads and to identify the factors that influence their performance.

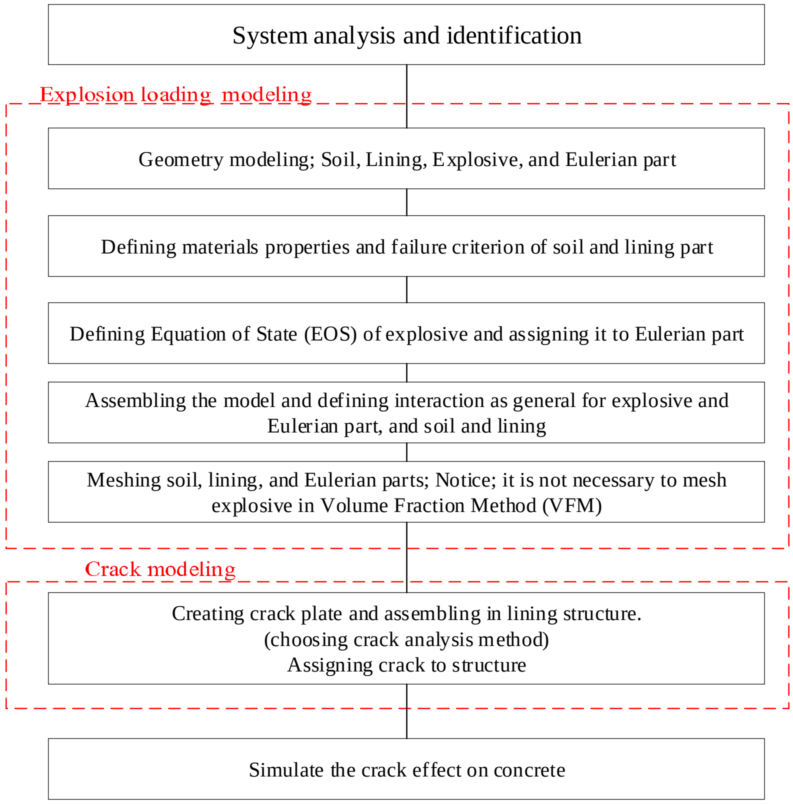


Figure 1. The methodology of numerical investigation of the crack effect in the concrete lining of the tunnel under an internal explosion loading

The methodology involves numerical simulations, experimental testing, or a combination of both. The analysis results may be used to develop design guidelines and to enhance the understanding of the mechanics of structures under internal explosion loading. This analysis is done in two general parts:

- Explosion loading modeling: This refers to modeling the physical processes and effects of an explosion on structures and materials. It involves simulating the high-pressure and high-temperature shock waves generated by the explosion and the subsequent dynamic response of the structure.
- Crack modeling: This involves simulating the formation, propagation, and evolution of cracks in structures under various loading conditions, including thermal, mechanical, and environmental effects. Crack modeling aims to predict the structural behavior and failure modes and determine the factors that influence crack growth and stability.

Also, the ABAQUS software was used for the analysis in this article. ABAQUS is a software program used for FEM (finite element methods) and simulation of various engineering problems, including structural, mechanical, and thermal systems. It is widely used in various industries, such as aerospace, automotive, energy, and others. The software allows users to model and analyze complex systems and make predictions about their behavior under different conditions. More details are provided in the following sections.

2.1. Explosion loading modeling

This section can be summarized as follows:

- Step 1: Geometry Modeling: The first step in explosion loading modeling is to create the analyzed system's geometry. This involves defining the shape and size of the tunnel and its components, including the concrete lining, soil, Eulerian part and explosives. The goal is to accurately represent the physical layout of the system in the computational model.
- Step 2: Constitutive behavior: A behavioral model is assigned to each geometry part. The behavioral model defines the material properties and the physical behavior of the material under the influence of an explosion. For example, the concrete lining may be modeled as a brittle material, while the soil may be modeled as a more deformable material.
- Step 3: Explosive Equation of State: for modeling explosive loading it is necessary to define explosive material, TNT. This involves defining

the properties of the explosive and its behavior when detonated, such as its energy release, shockwave propagation, and heat transfer. Defining EOS of explosive can find pressure of explosion is assigned as loading force to the model.

- Step 4: Volume Fraction: after making geometry, assembling, assigning properties, meshing, boundary conditions and interaction, it is necessary to assign explosive to Eulerian part. [28, 29]

2.2. Crack modeling

This section can be summarized as follows:

- Step 1: Crack Creation: In this step plate of crack is created as a plate and is assigned to structure. In order to investigate crack growth and analyze the response of pre-existing cracks in the structure to dynamic loading such as an internal explosion type, the extended finite element method has been used. With the help of this method, the impact of cracks in the structure on the damage caused by the explosion can be entirely determined.

More details of each step are given during numerical study as below.

2.3. Numerical study

The geometry model represents the physical layout of the system being analyzed in the finite element (FE) model. It defines the shape and size of each component in the model, such as the concrete lining, soil, and explosives. By defining the geometry, the model becomes a visual representation of the physical system and provides the basis for the subsequent numerical analysis. The assembly model describes the relative position relationships among all the geometry parts. The overall dimensions of the model are $45 \times 45 \times 45$ m. The tunnel drilled in this block has an internal diameter of 6.8 m. The distance from the top of the tunnel to the ground is 18 m. A concrete lining of the tunnel with a thickness of 35 cm is considered for the tunnel (Figure The explosion has been selected in the center of the tunnel (Figure 3).

Furthermore, the CEL (Coupled Eulerian-Lagrangian) method is used because large deformations occur under explosion. The CEL method is commonly used to model large deformations that occur under explosion loading. The CEL method couples an Eulerian representation of the surrounding medium with a Lagrangian representation of the deformable structure. The Eulerian part of the model tracks the motion of the surrounding medium, such as the soil, while the Lagrangian part of the model tracks the deformation of the structure, such as the concrete lining. The CEL method is particularly useful for modeling complex and highly nonlinear problems, such as the response of structures to an explosion. It allows for a more accurate representation of the physical behavior of the system, including the propagation of shock waves, material failure, and large deformations. By using the CEL method, the engineers can better predict the behavior of structures under explosion loading and identify critical failure modes. In this method, the deformation of the body is not accompanied by the meshing change (Figure 4). This method is used to solve the dynamic problems of blast loading or impact loading. The CEL method can use for geotechnical modelings, such as pile jacking in the soft ground and slope stability analysis [30].

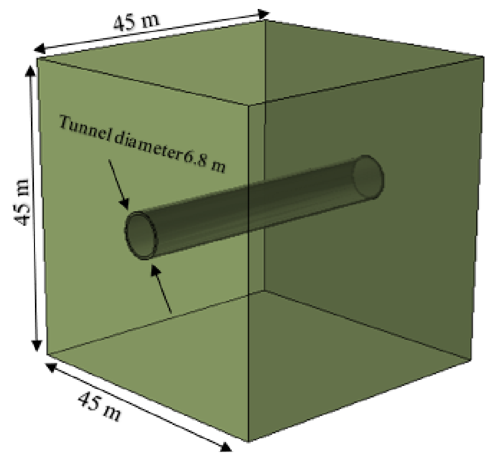


Figure 2. Schematic representation of the 3D model of the tunnel and soil block

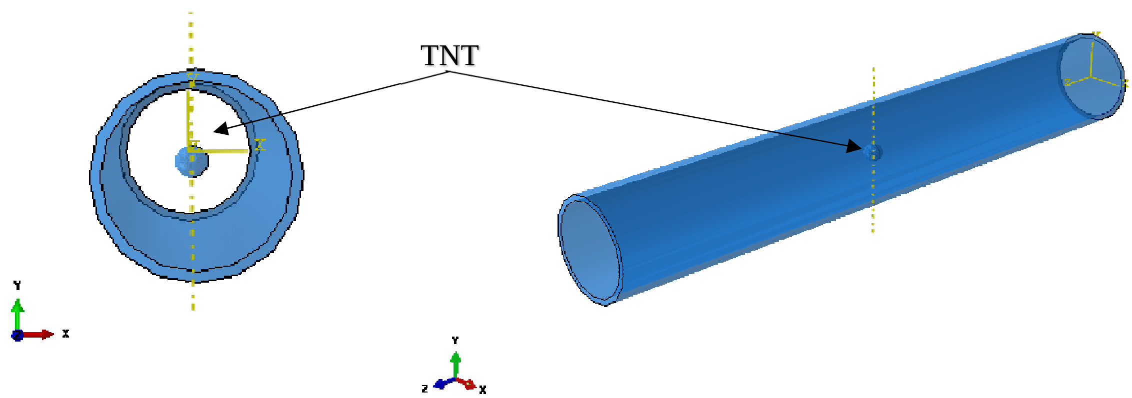


Figure 3. Schematic representation of 3D location of explosion in the tunnel

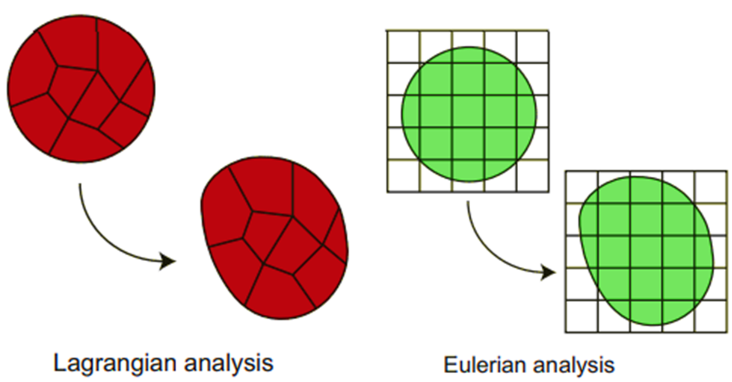


Figure 4. Deformation of a continuum in Lagrangian and Eulerian methods [30].

2.3.1. Trinitrotoluene (TNT)

The explosion of a small delivery truck in the tunnel is simulated. According to (Table 1), the charge of TNT equivalent to this vehicle (small delivery truck) is estimated [31]. In this article, TNT is simulated with a sphere shape with a radius of 0.64 cm. the radius of TNT was calculated effortlessly by mass and density of TNT. The EOS (equation of state) used for the explosive is JWL (Jones-Wilkins-Lee) method. According to (Equation 1), this method can obtain the pressure from the explosion with chemical reaction from the explosion of TNT. TNT properties and JWL parameters for TNT are in (Table 2) [17, 28]. No delay time in the explosion has been considered in the modeling accomplished (Figure 5.-a).

$$P = A\left(1 - \frac{\omega}{R_1 V}\right)e^{-R_1 V} + B\left(1 - \frac{\omega}{R_2 V}\right)e^{-R_2 V} + \frac{\omega E}{V} \quad (1)$$

Where:

P: Pressure caused by the explosion

E: Internal energy of the explosive per volume (V)

R_1, R_2, A, B, and ω: Explosive constants.

Table 1. TNT equivalent filling a vehicle [31].

Vehicle description	TNT equivalent (Kg.)
Sedan	227
SUV or Van	454
Small delivery truck	1814
Container or water truck	4536
Semi-trailer	27216

Table 2. TNT properties and JWL parameters for TNT [22].

Parameter	Measure
Mass density (kg/m^3)	1630
A (MPa)	373800
B (MPa)	374700
Ω	0.35
R_1	4.15
R_2	0.9
Detonation energy density (kJ/kg)	3680
Detonation wave speed (m/s)	6930

2.3.2. Soil around the inner concrete lining

In this study, sandy loam soil has been selected for modeling soil around the tunnel to interact gravity of top layer on lining structure and make numerical study more realistic, and the behavior model assigned to the soil is Drucker -Prager. The Drucker–Prager model is a pressure-dependent three-dimensional failure criterion for frictional materials such as rocks and soil. The Drucker–Prager criterion is a generalized Mohr-Columb failure criterion, an extension of the Von Mises criterion, and Nadai's failure criterion for soil in dynamic loadings, such as explosion loading [32, 33]. The parameters of the sandy soil in this model are according to (Table 3). (Figure 5.-b)

Table 3. Drucker–Prager parameters of sandy loam soil [33].

Parameter	Measure
Mass density (kg/m^3)	1920
Young's modulus (MPa)	182
Poisson's ratio (-)	0.3
Cohesive strength (kPa)	0.75
Friction angle (°)	46°
Dilation angle (°)	4°
Flow stress ratio (-)	1

2.3.3. Inner concrete lining

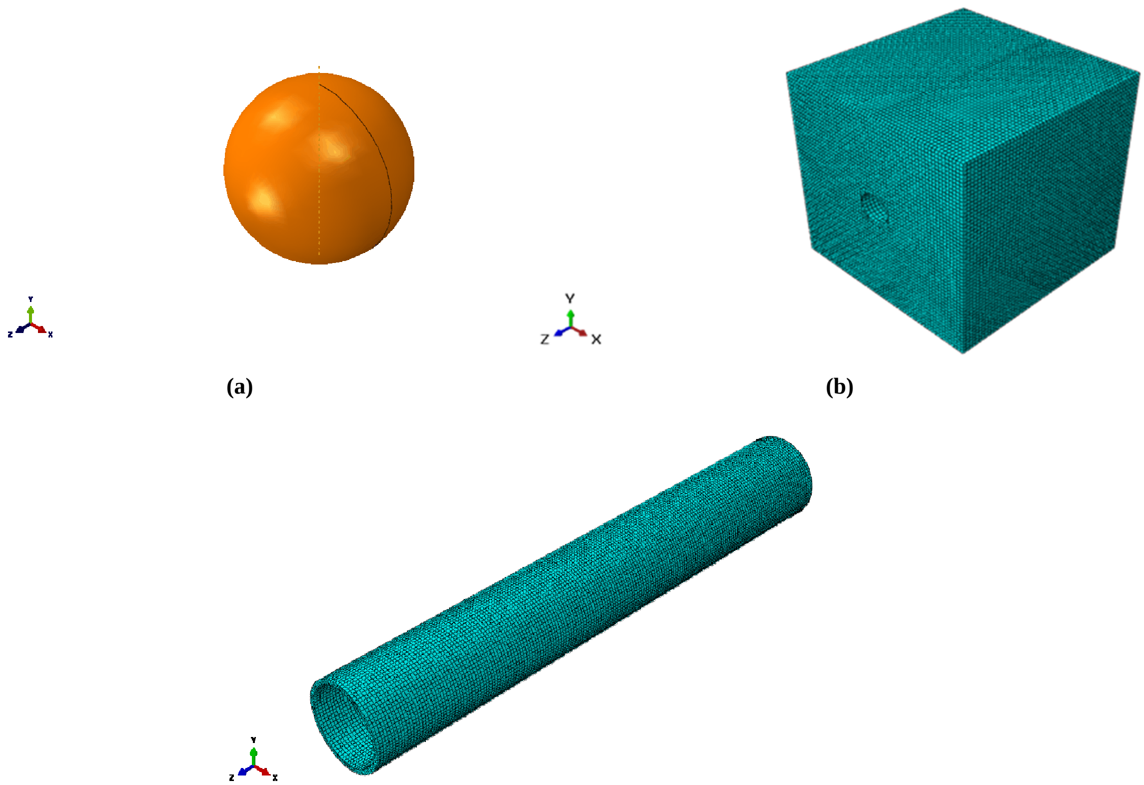
The stability of the concrete support system of the tunnel is essential due to various factors such as the PH of groundwater, earthquakes, concrete mixing designs, and explosive pressure [34]. The behavior of concrete is not perfectly elastic, and the presence of cracks causes the behavior of this material to be more plastic. Thus, it is necessary to use a failure criterion based on the plastic behavior of materials in numerical modeling. CDP (Concrete Damage Plasticity) is one of concrete's most efficient failure criteria. The CDP failure criterion, by examining the primary damage parameter, which depends on the plastic strain ratio of concrete, comprehends substantial damage when the elements' strain overextends the ultimate concrete strain during the numerical analysis. In this case, the failure occurs in the structure [35]. The CDP parameters of concrete in this article are in (Table 4, and 5). (Figure 5.-c)

Table 4. CDP parameters of concrete [35].

Parameter	Measure
Mass density (kg/m^3)	2500
Young's modulus (MPa)	21.2
Poisson's ratio (-)	0.2
fb0/fc0	1.16
K	0.67
Dilation angle (°)	31°
Eccentricity	0.1
Viscosity parameter (-)	0

Table 5. Tensile behavior and tension damage of concrete [35].

Tensile behavior		Tension damage	
Yield stress (MPa)	Cracking strain	Damage parameter	Cracking strain
2	0	0	0
0.02	0.000943396	0.99	0.000943396



(a) (b)

(c)

Figure 5. 3D-modeling of a) TNT, b) Soil with its meshing, and c) Concrete lining with its meshing

2.3.4. Simulate crack and its analysis way

The XFEM (extended finite element method) is one of the most potent and widely used numerical methods defined based on the FEM (finite element method). The difference between XFEM and the FEM is that this method solves problems with very high convergence regardless of the relative position of the mesh and discontinuities. By increasing the degrees of freedom of the nodes, this method can provide the governing relationships of the studied environment with the help of modeling without the need to match the mesh with discontinuity geometry. This numerical method can investigate crack growth quickly. In investigating crack growth, the FEM requires meshing to be adapted to the crack expansion at each growth stage [36].

For analyzing crack growth, XFEM is used. On the other hand, the stress intensity at the crack's tip is exceptionally heightened, so the matching of the mesh and the use of fine mesh in the finite element method cause this numerical method's lack of optimal efficiency. Furthermore, using a single element manually in the conventional FEM at each crack growth stage is challenging. Thus, the use of the XFEM is preferred [36]. In this study, the crack was made as the plate corresponding to the tunnel's lining.

The tunnel's concrete lining has a crack complication with a depth and length of 15 cm and 100 cm in three locations in the middle length of the tunnel’s length (Figure 6).

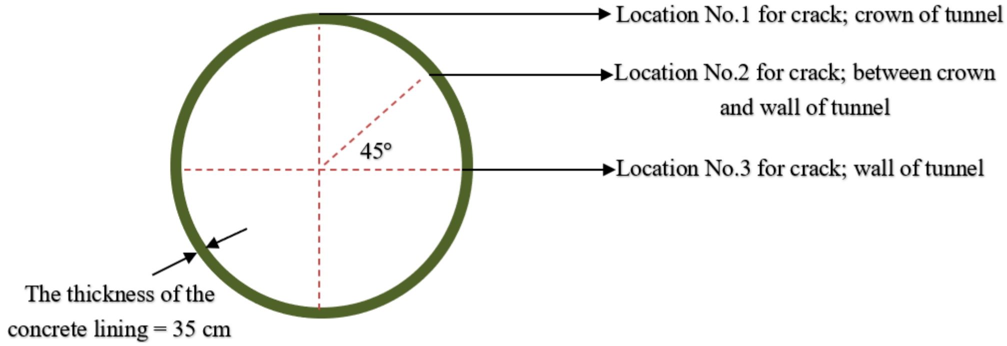


Figure 6. Schematic of concrete lining and crack location

3. Results and Discussions of Numerical Study

The numerical modeling results indicate that the presence of cracks significantly impacts the stability and damage to the tunnel's concrete lining. By comparing the results of a model without cracks to models with cracks, the engineers can gain insights into the effects of cracks on the structural behavior of the tunnel under internal explosion loading. The amount of deformability (displacement) in the tunnel crown, wall, and the position between the wall and the crown can be visualized through displacement plots or graphs. Figure 7 shows the distribution of deformations in the structure and the magnitude of the deformations. By analyzing the displacement plots, the engineers can determine the critical locations in the structure where the deformations are the largest and where failure is most likely to occur.

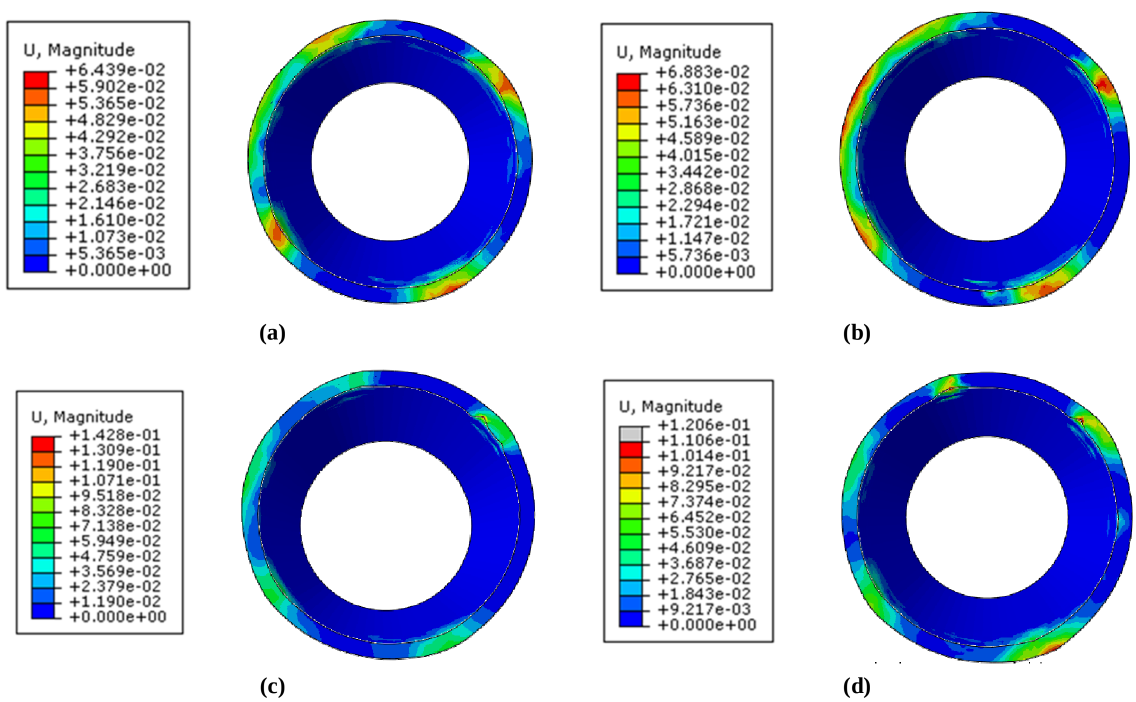


Figure 7. Deformation of the lining of the tunnel under explosion loading a) without crack-b) with a crack at the crown of the tunnel-c) with a crack between the crown and middle of wall-d) with a crack in the middle of the wall of the tunnel

This information can be used to design more robust and secure structures and implement effective mitigation strategies to protect against internal explosions.

The results show that if there is a crack in the tunnel crown, the tunnel deformation change in the tunnel crown under explosion loading has increased by 63.54 % compared to the case where there is no crack. If there is a crack between the wall and the crown of the tunnel, the change in the deformation of the tunnel at the same point the tunnel under explosion loading is increased by 68.84 % compared to the case where there is no crack. Furthermore, if there is a crack in the tunnel wall, the change in the deformation of the tunnel at the same point of the tunnel under explosion loading is increased by 60.37 % compared to the case where there is no crack Figure 8.

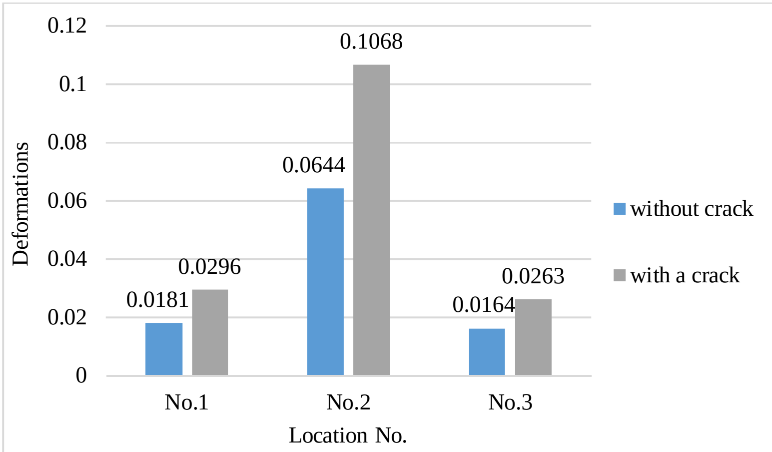


Figure 8. Deformations of three different points of the tunnel's concrete lining without cracks and with a crack.

According to Figure 9, it is clear that in the conditions where there is a crack in the concrete lining of the tunnel, by default, due to the weight of the upper layer, there is a possibility of tensile crack propagation. However, under the conditions of the internal explosion, the tensile damage in the crown of the concrete lining is more than in two others cases where the crack is in the wall or between the crown and the wall. According to Figure 10, it is evident that the compressive damage caused by the internal explosion is more in the concrete wall. Hence, the total damage (tensile and compressive damage) in the area between the crown and the wall of the concrete lining of the tunnel is more because, in this case, the weight of the upper layer and the pressure of the explosion cause the failure and destruction of the structure to be of a mixed-mode fracture [37, 38]. For this reason, the deformation changes in Figure 8 are more significant for a point between the wall and the crown of the tunnel. This increase in value indicates the accuracy and verification of the numerical modeling.

Furthermore, the zone of tensile damage along the length of the tunnel in the case that there is no crack in the tunnel's concrete lining is 4.16 m, 3.84 m, and 4.04 m, respectively, for the crown, wall, and between the wall and the crown of the tunnel's concrete lining. The presence of cracks in the crown of the tunnel in the zone of tensile damage in these three points is 4.85 m, 3.5 m, and 4.18 m, respectively. The zone of compressive damage along the length of the tunnel in the case that there are no cracks in the tunnel's concrete lining is 2.96 m, 4.60 m, and 3.99 m, respectively, for the crown, wall, and between the wall and the crown of the tunnel concrete lining, and if there is the crack in the crown of the tunnel is the compressive damage area at these three points, 2.96 m, 5.11 m, and 4.88 m, respectively.

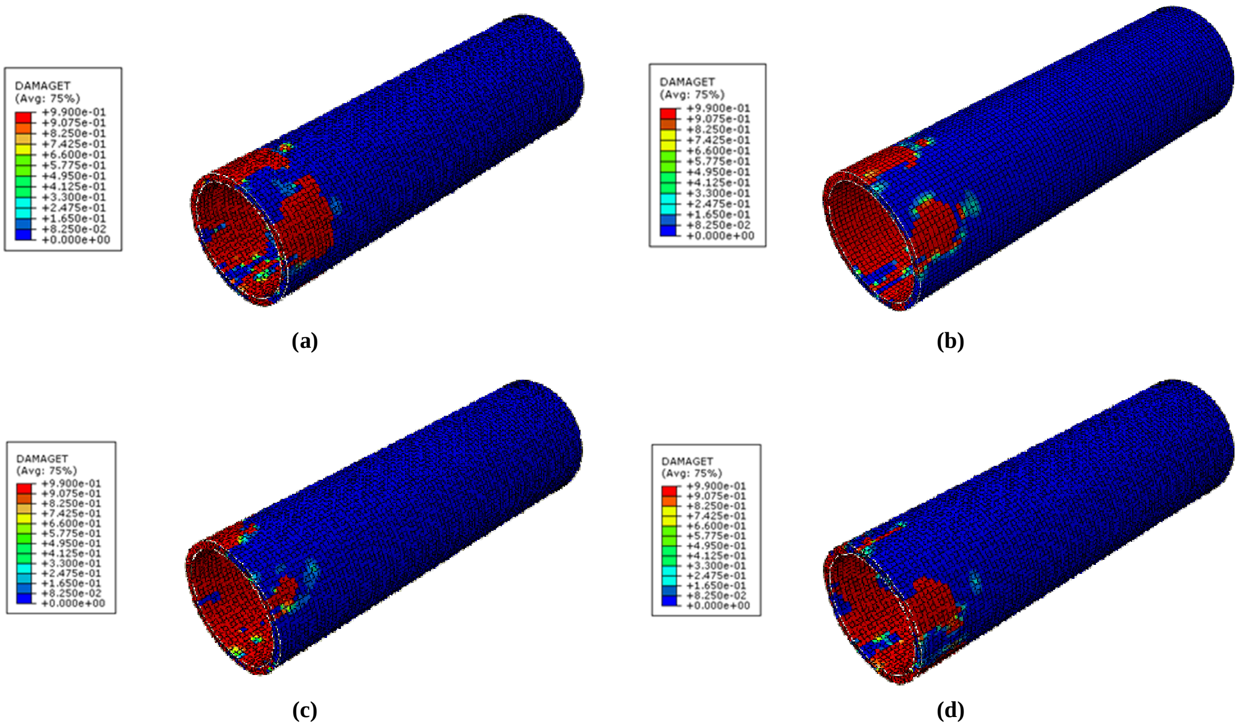


Figure 9. Tensile damage of the lining of the tunnel under explosion loading a) without crack-b) with a crack at the crown of the tunnel-c) with a crack between the crown and middle of wall-d) with a crack in the middle of the wall of the tunnel

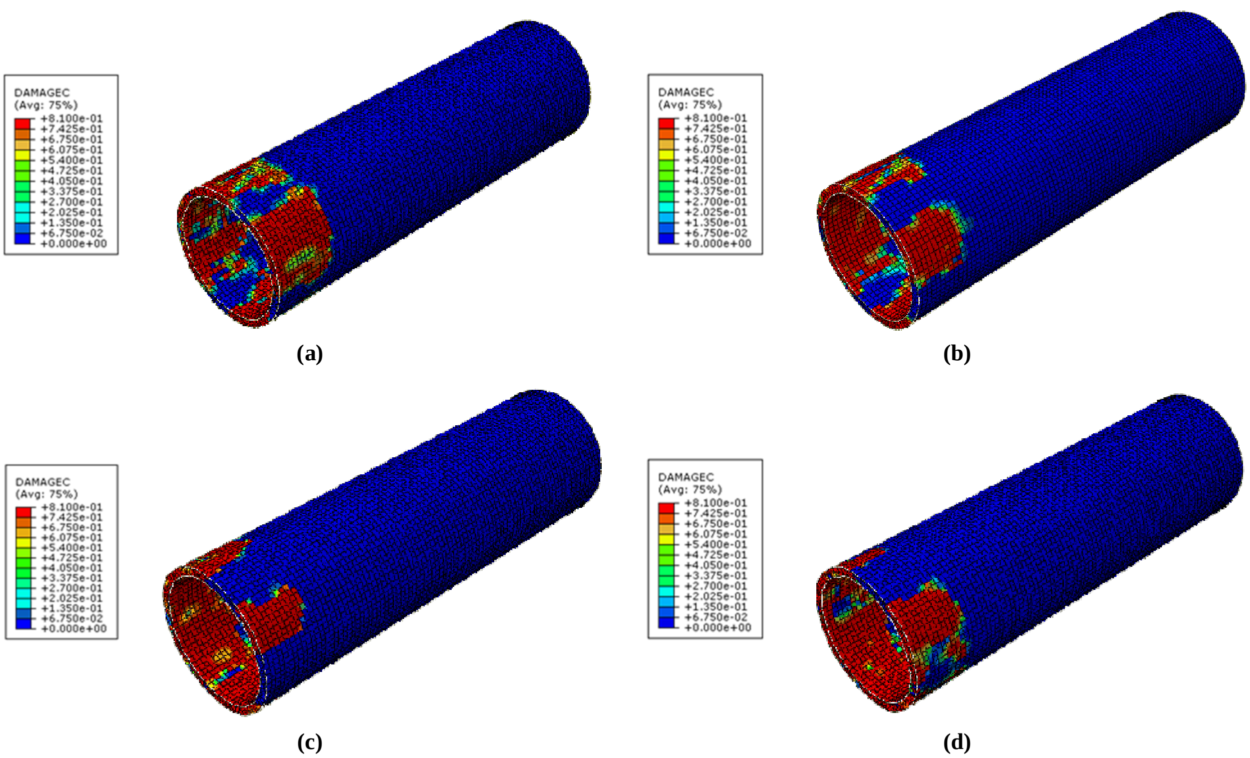


Figure 10: Compressive damage of the lining of the tunnel under explosion loading-a) without crack-b) with a crack at the crown of the tunnel-c) with a crack between the crown and middle of wall-d) with a crack in the middle of the wall of the tunnel

4. Conclusions

This numerical study shows that the presence of pre-existing crack and its location in the inner concrete lining is significant. When the tunnel is affected by an internal explosion, these cracks play an essential role in the severity of the destruction of the underground structure. Four different modeling modes were performed; these four modes included the absence of cracks, the presence of cracks in the tunnel crown, wall, and between the tunnel wall and crown. If there is a crack in the crown of the tunnel's concrete lining, the tensile damage in the tunnel's concrete lining under explosion is more than in the case where there is no crack. The study highlights the importance of addressing cracks in the concrete lining of a tunnel, as concrete is weak under tensile loading. It is necessary to take necessary and intelligent measures to improve the tunnel maintenance system to prevent damage caused by internal explosions. By moving from the crown of the tunnel's concrete lining towards the wall of the concrete lining, the severity of the damage caused by the compressive loading of the explosion increases and due to the effect of the weight of the upper layer in the area between the two points of the crown and the wall of the concrete lining of the tunnel, mixed-mode failing occurred. Also, results show that;

- The existence of a crack with a length of 100 cm and a depth of 15 cm in the middle of the tunnel length and the crown part of the concrete lining under an internal explosion causes the length of the tensile damage zone in the concrete lining to increase by 16.59%. Increasing the damage zone's length increases the probability of tunnel collapse and complete blocking.
- The presence of a crack with a length of 100 cm and a depth of 15 cm in the middle of the tunnel length and the section of the concrete lining wall of the tunnel under internal explosion causes the length of the compressive damage zone in the concrete lining wall to increase by 11.09%.
- The presence of a crack with a length of 100 cm and a depth of 15 cm in the middle of the tunnel length and the section between the crown and the wall of the concrete lining of the tunnel under an internal explosion causes the length of the compressive and tensile damage zone in this area of the concrete lining to be 31.22% and 3.46% respectively.
- The ratio of the total number of destroyed elements for the three-location number one, two and three in the case where there is a crack with a length of 100 cm and a depth of 15 cm in the inner and concrete cover to the case where there is no crack is equal to 15.9, 13.2 and 9 respectively. It shows that a pre-existing crack in the crown of concrete lining causes more damage and is more critical than other situations.
- Conducting a numerical study along with the review of technical literature indicates that although the existence of cracks in the structure of the concrete inner lining of a tunnel is a susceptible and essential structure, with the sudden occurrence of a dynamic phenomenon, the damages resulting from aerodynamics such as an explosion increase.
- Engineers should consistently deal with essential cases before implementing a inner concrete lining, including its failure mechanism and stable and unstable crack growth in the structure under static and dynamic conditions, such as checking the concrete mixing designs and using concrete reinforcement materials. Behind the structure is enforced; if there are cracks in the concrete, crucial provisions must be made to strengthen the stability of the structure.

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اثر ترک از پیش موجود بر آسیب پوشش بتنی داخلی تحت انفجار داخلی: یک مطالعه عددی

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ارسال 2023/02/06، پذیرش 2023/03/15

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چکیده:

مهندسین از روش‌های مختلفی برای ارزیابی عملکرد سازه‌های بتنی تحت بارهای دینامیکی از جمله شبیه سازی عددی، روش‌های آزمایشگاهی و آزمایش‌های میدانی استفاده می‌کنند. با ترکیب نتایج این روش‌ها، مهندسان می‌توانند به درک جامعی از رفتار سازه‌های بتنی تحت بارهای دینامیکی دست یابند و از این اطلاعات برای طراحی سازه های انعطاف پذیرتری با قابلیت تحمل این بارها استفاده کنند. در این تحقیق، چهار مدل از پوشش بتنی تونل دایره‌ای برای بررسی اثر ترک‌های از پیش موجود در پوشش بتنی تونل تحت یک بار انفجار داخلی شبیه‌سازی شد. یک ترک در سه مکان مختلف در زوایای صفر، 45 و 90 درجه نسبت به محور افقی تونل بررسی و تحلیل شده است. روش توأمان اویلر-لاگرانژی و مدل‌های رفتاری مختلف، مانند آسیب پلاستیک بتن برای پوشش بتنی و دراکر-پراگر برای خاک، امکان شبیه‌سازی دقیق‌تری از سناریوی بارگذاری انفجار داخلی را فراهم کرد. انتخاب TNT و معادله جونز-ویلکینز-لی برای ماده منفجره نمایشی واقعی از رفتار مواد منفجره ارائه می دهد. نتایج مدل‌سازی نشان می‌دهد که در انفجار داخلی، با بررسی سه محل مختلف ترک در بتن، وقوع ترک در تاج تونل بحرانی‌تر از دو محل دیگر ترک است. به نحوی، وجود ترک به طول 100 سانتیمتر و عمق 15 سانتیمتر در تاج تونل، ناحیه آسیب کششی را در مقایسه با حالتی که ترک وجود ندارد، 16/59 درصد افزایش می‌دهد.

کلمات کلیدی: آسیب پلاستیک بتن، بتن، اویلری-لاگرانژی توأمان، انفجار، ABAQUS.