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Numerical and Rational Analysis of Shotcrete Lining for Rock Tunnels under Effect of Explosion Loads

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NUMERICAL AND RATIONAL ANALYSIS OF SHOTCRETE LINING FOR ROCK TUNNELS UNDER EFFECT OF EXPLOSION LOADS

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ABSTRACT

Tunnels in rock media are considered one of the most important types of fortified structures that can be used to resist the progressive development of military destructive weapons. The geological formation of tunnel rock mass has a great influence on the degree of protection to human and weapons. This protection degree is based mainly on both the utilized system of tunnel lining and the type and quality of rock mass which reduces the effect of wave propagation generated by explosion. Shotcrete lining is one of the most commonly used support system used in tunnel lining.

Understanding the dynamic response and damage characteristics of shotcrete lining for rock tunnels due to explosion loads is essential for safe design. The main aim of this paper is to investigate the stresses and displacements of shotcrete lining under blasting loads and the effect of different of rock mass qualities on the wave propagation associated with the explosion. In order to achieve this aim, numerical analysis technique, commercial software package, AUTODYN version 6.1 is used to perform 90 three-dimensional elasto-plastic dynamic models to analyze rock-shotcrete lining interaction. A parametric study was carried out taking into consideration the effect of Rock Mass Rating (RMR), tunnel radius, charge weight and detonation distance. The numerical simulation of explosion in rock mass is extremely demanding, requiring hydrodynamic computer codes, combined with non-linear dynamic codes based on finite elements which is a very complex approach. Therefore, regression analysis is used for statistics prediction of the behavior of shotcrete lining. A rational analysis is conducted to form non-linear equations to predict stresses and displacements of shotcrete lining at tunnel crown based on the results of the parametric study. The suggested equations were used to form design charts for different values of Rock Mass Rating. A comparison between the results of the numerical simulation and rational analysis for the different models showed a good matching.

INTRODUCTION

Blast-induced ground excitation has a great influence on the construction of fortified structures. Understanding the dynamic response and damage characteristics of shotcrete lining for rock tunnels due to explosion loads is essential for safe and economic design of underground structures.

Shotcrte is an important and often used material in tunnelling and mining. The problem with shotcrete on rock subjected to vibrations has been studied through numerical modeling based on two approaches. The first was elastic stress wave theory resulting in a model for one-dimensional analysis of shotcrete on rock through which elastic stress waves propagate towards the shotcrete. The second approach was the two-dimensional finite element model consists of beam elements that were used for modeling the flexural stiffness and mass of the shotcrete, however the fractured rock and spring elements were used to obtain elastic coupling between shotcrete and rock [1].

MODELING

Nonlinear three-dimensional numerical finite element model was carried out using AUTODYN code to simulate the dynamic response of shotcrete lining for vertical side wall rock tunnels due to explosion loads. The overall configuration of the three-dimensional finite element model used in this study is shown in Fig. (1). The mechanical properties of simulated rock mass are calculated according to the modified

Hoek-Brown failure criterion, [2] and Rock Mass Rating (RMR = 40, 60 and 80) which classify the rock mass quality according to Bianiwaski 1989 as hard, moderate and poor rock [3]. The mechanical properties of the rock for different mass rating and shotcrete lining which were used in this study is presented in Table (1) and (2), respectively. This analysis adopts RHT material model developed by Riedel, Hiermaier and Thoma is used to simulate the elasto-plastic behavior of shotcrete lining and rock mass, [4],[5]. Transmitting boundary is applied at the model boundaries to represent the infinite media of rock mass. The Lagrangian subgrid is used to simulate rock mass and shotcrete lining as a solid elements and joint to joint technique was used to simulate rock-lining interaction. Euler subgrid is used to simulate air and explosive materials. In this paper, shotcrete lining with 35 MPa compressive strength will be studied in a parametric study which includes as shotcrete thickness, (t_c = 200, 300 and 400 mm) as shown in Fig. (2), Rock Mass Rating, (RMR = 40, 60, and 80), charge weights, (W = 2500, 7500 and 10000 kg), crown-detonation distances, (D = 5 and 10 m) and tunnel radius, (R = 3, 4.5 and 6 m).

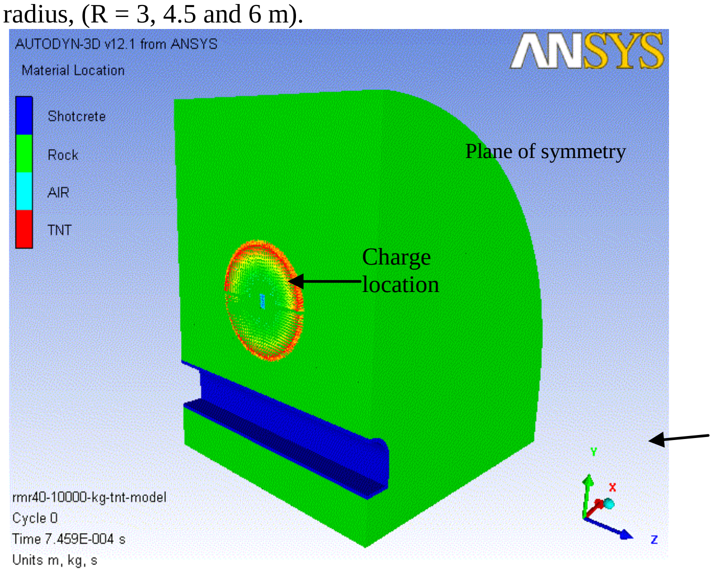

Fig. (1) Geometry of the numerical model

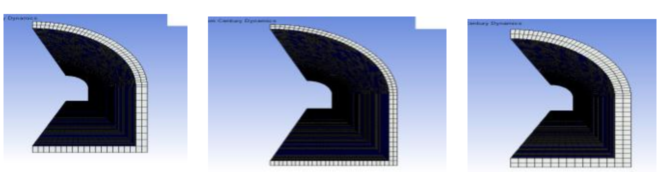

Fig.(2) Different thickness of simulated shotcrete

ANALYSIS OF SHOTCRETE LINING FOR POOR ROCK TUNNEL (RMR = 40)
(COMPRESSION AND TENSILE STRESSES)

The procedure of the analysis depends on the possibility of shotcrete lining to resist the effect of different charge weights according to the Rock Mass Rating (RMR), and shotcrete lining thickness. To study the behavior of shotcrete lining with this type of rock mass, 42 numerical model of shotcrete lining were analyzed under the effect of charge weights (W = 2500, 7500 and 10000 kg) at crown-detonation distances (D = 5 and 10 m). The failure criteria of shotcrete lining due to explosion loads depends on the nature of shotcrete as a brittle material which fails due to the excessive tensile stresses above the allowable tensile stress limit. The tunnel crown is considered as the weakest point on the tunnel perimeter due to the free surface in vertical direction, so that the tunnel crown will be studied in the following analysis according to the induced compression, tensile stresses and displacement.

Table (1) Mechanical properties of different Rock Mass Rating

Rock Mass Rating	RMR 40 Poor	RMR 60 Moderate	RMR 80 Hard
Young modulus (MPa)	14.3	50.6	129.5
Uniaxial compressive strength (MPa)	0.285	0.62	4.71
Tensile strength (kPa)	28.5	62	471
Shear strength (kPa)	51.3	111.6	847.8
Unit weight (kN/m3)	24	25	26.5
Bulk modulus (MPa)	11.9	42.1	107.9
Shear modulus (MPa)	5.5	19.5	49.8
Min. strain to failure	0.0075	0.005	0.0025

Table (2) Mechanical properties of shotcrete lining

Young modulus (MPa)	14.3
Uniaxial compressive strength (MPa)	35
Tensile strength (MPa)	3.5
Shear strength (kPa)	6.3
Unit weight (kN/m3)	27.5
Bulk modulus (MPa)	11.9
Shear modulus (MPa)	1.67e 4
Min. strain to failure	0.01

For tunnel radius R= 3 m

The effect of explosion loads on shotcrete lining is accompanied with compression and tensile stresses which cause failure in shotcrete lining depending on the utilized thickness of shotcrete lining. Fig. (3) and Fig. (4) show the relation between the shotcrete thickness expressed by the ratio (t_c/R) and the induced compression and tensile stresses in shotcrete lining, respectively, taking into consideration the effect of applied charge weights at different crown-detonation distances.

As shown in Fig.(3), the induced compression stresses of shotcrete lining with $t_c/R \geq 0.067$ was less than the allowable compressive strength of shotcrete lining (f_c = 35 MPa) under the effect of different charge weight and crown-detonation distances which indicates that no damage occurring in shotcrete lining due to compression stresses.

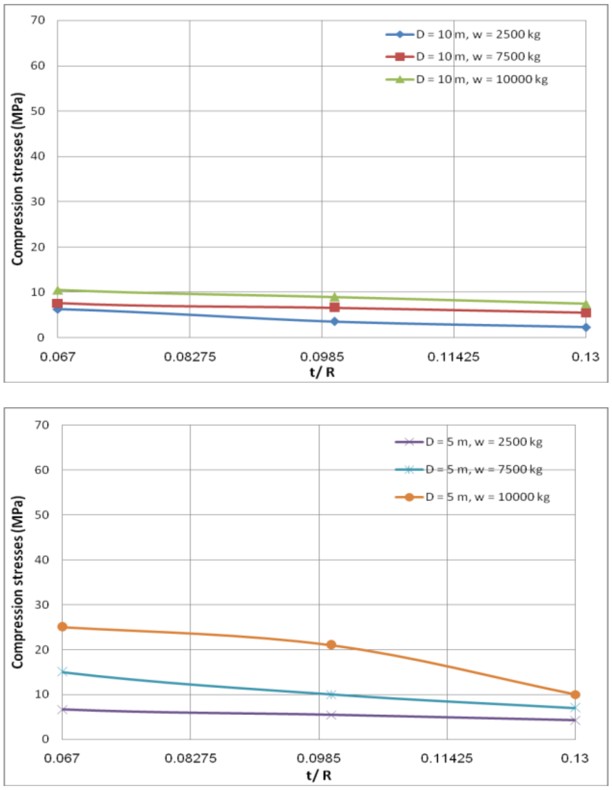

Fig.(3) Peak values of induced compression stresses in shotcrete lining at tunnel crown versus the (t_c/R) for R = 3 m and RMR = 40

Fig.(4-a) showed that, for applied charge weights (W= 2500, 7500 kg) located at D = 10 m the induced tensile stresses of shotcrete lining with $t_c/R \geq 0.067$ was less than the allowable tensile strength of shotcrete lining (f_t = 3.5 MPa) which indicates no damage occure in the lining. Whereas, for applied charge weights (W= 10000 kg) located at D = 10 m the tensile stresses of shotcrete lining with t_c /R ≤ 0.09 was greater than the allowable tensile strength. From Fig.(4-b), it is noticed that, for applied charge weights (W= 2500 kg) located at D = 5m the tensile stresses of shotcrete lining with t_c /R ≥ 0.067 was less than the allowable tensile strength. Also, for applied charge weights (W= 7500 kg and W = 10000 kg) located at D = 5m the tensile stresses of shotcrete lining with $t_c/R \leq 0.1$ and $t_c/R \leq 0.12$ respectively, was greater than the allowable tensile strength. The values of induced tensile stresses for D = 5 m were higher than the corresponding values of D = 10 m by a range between 10 % and 35 % with an average percentage 24%.

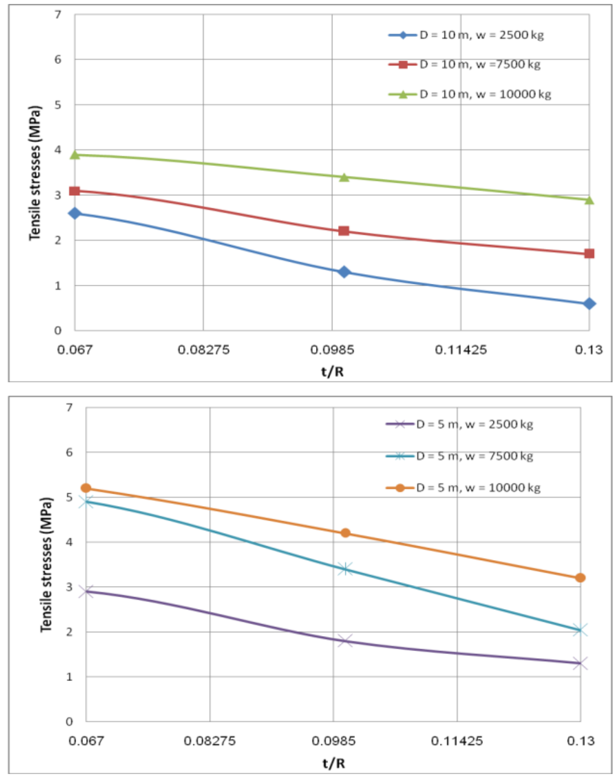

Fig.(4) Peak values of induced tensile stresses in shotcrete lining at crown versus the (t_c/R) for R = 3 m and RMR = 40

For tunnel radius R= 4.5 m

As shown in Fig.(5-a), it is noticed that, the compression stresses of shotcrete lining with $t_c/R \geq 0.044$ and crown-detonation distances (D = 10 m) was less than the allowable compressive strength. Refer to Fig.(5-b),it is cleared that, for applied charge weights (W= 2500 kg and 7500 kg) located at D = 5 m the compression stresses of shotcrete lining with tc/R ≥ 0.044 was less than the allowable compressive strength.
From Fig.(5-b),it is cleared that, for applied charge weights (W= 10000 kg) located at D = 5 m the compression stresses of shotcrete lining with $t_c/R \leq 0.05$ was greater than the allowable compressive strength.

From Fig.(6-a), it is cleared that, for applied charge weights (W= 2500 kg) located at D = 10 m the tensile stresses of shotcrete lining with tc/R ≥ 0.044 was less than the allowable tensile strength. Also, it is cleared that, for applied charge weights (W= 7500 kg and W = 10000 kg) located at D = 10 m the tensile stresses of shotcrete lining with tc/R ≤ 0.067 and tc/R ≤ 0.088 respectively, was greater than the allowable tensile strength. As shown in Fig.(6-b), it is cleared that, for applied charge weights (W= 2500 kg, W= 7500 kg and W = 10000 kg) located at D = 5 m the tensile stresses of shotcrete lining with tc /R ≤ 0.06, $t_c/R \leq 0.08$ and $t_c/R \leq 0.088$ respectively, was greater than the allowable tensile strength. The values of induced tensile stresses for D = 5 m were higher than the corresponding values of D = 10 m by a range between 5 % and 45 % with an average percentage 15.4%.

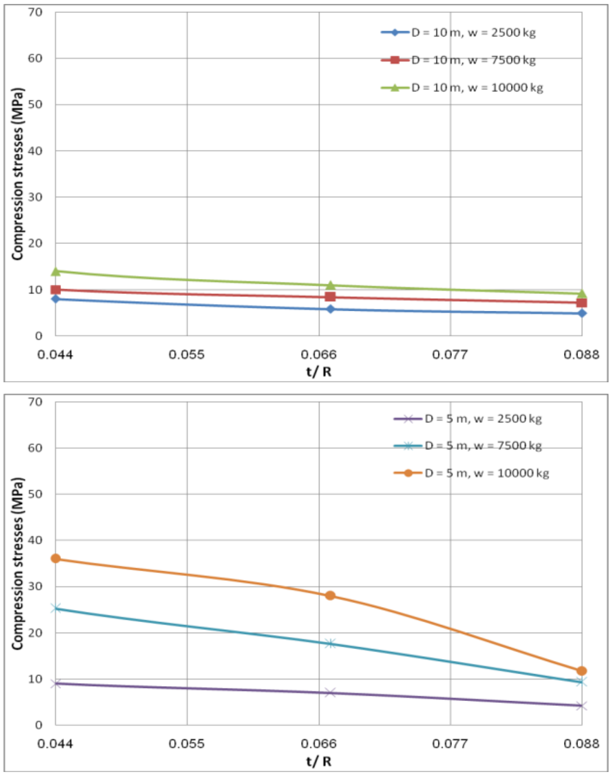

Fig.(5) Peak values of induced compression stresses in shotcrete lining at tunnel crown versus the (t_c/R) for R = 4.5 m and RMR = 40

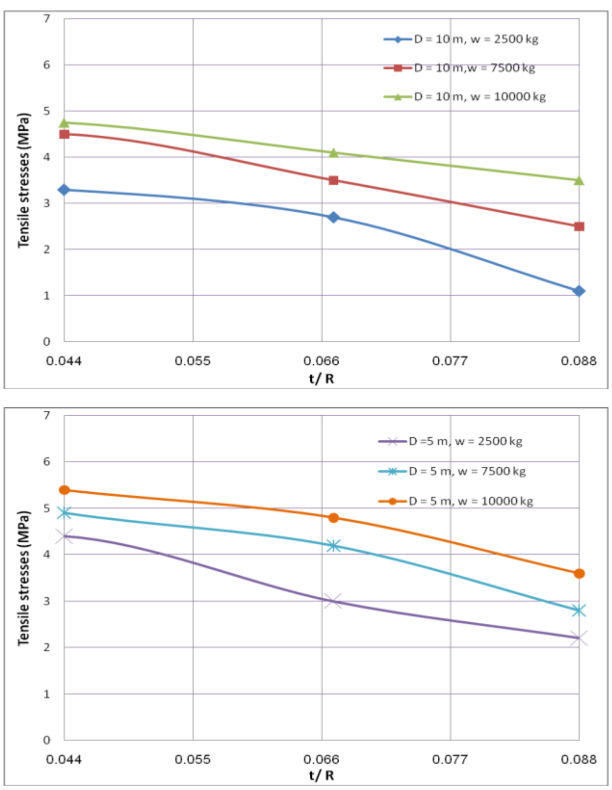

Fig.(6) Peak values of induced tensile stresses in shotcrete lining at crown versus the (t_c/R) for R = 4.5 m and RMR = 40

For tunnel radius R= 6 m

As shown in Fig.(7-a), it is cleared that, for applied charge weights (W= 2500, 7500 kg and 10000 kg) located at D = 10 m the compression stresses of shotcrete lining with $t_c/R \geq 0.033$ was less than the allowable compressive strength.
From Fig.(7-b), it is cleared that, for applied charge weights (W= 2500 kg and 7500 kg) located at D = 5 m the compression stresses of shotcrete lining with $t_c/R \geq 0.033$ was less than the allowable compressive. Also, it is noticed that, for applied charge weights (W= 10000 kg) located at D = 5 m the compression stresses of shotcrete lining with $t_c/R \leq 0.045$ was greater than the allowable compressive strength. The values of compression stresses for D = 5 m were higher than the corresponding values of D = 10 m by a range between 33 % and 62 % with an average percentage 44 %.

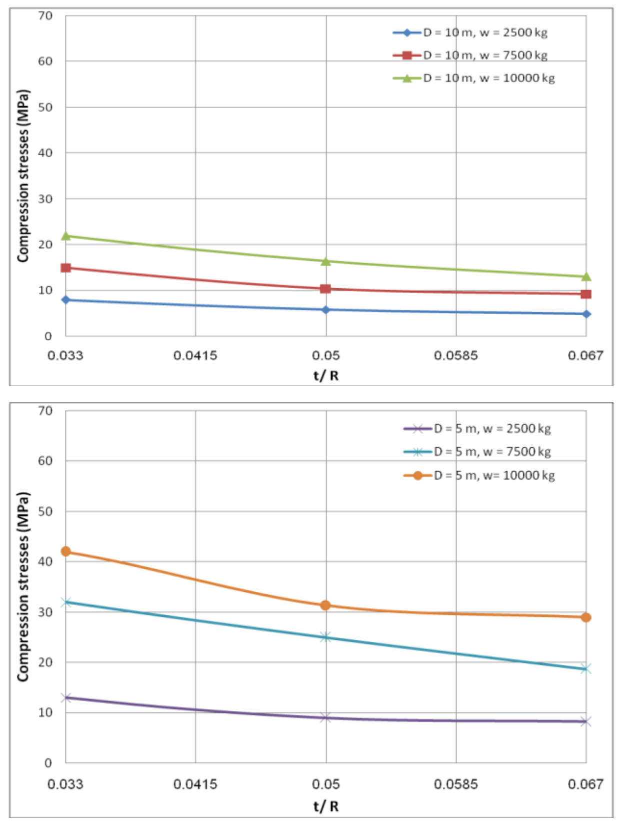

Fig.(7) Peak values of induced compression stresses in shotcrete lining at crown versus the (t_c/R) for R = 6 m and RMR = 40

From Fig.(8-a), it is cleared that, for applied charge weights (W= 2500 kg) located at D = 10 m the tensile stresses of shotcrete lining with $t_c/R \geq 0.033$ was less than the allowable tensile strength. Also, it is cleared that, for applied charge weights (W= 7500 kg and W= 10000 kg) located at D = 10 m the tensile stresses of shotcrete lining with $t_c/R \leq 0.054$ and $t_c/R \leq 0.067$ respectively, were greater than the allowable tensile strength. From Fig.(8-b), it is cleared that, for applied charge weights (W= 2500 kg and W= 7500 kg) located at D = 5 m the tensile stresses of shotcrete lining with $t_c/R \leq 0.044$

and $t_c/R \leq 0.065$ respectively, were greater than the allowable tensile strength. Also, it is cleared that, for applied charge weights (W= 10000 kg) located at D = 5m the tensile stresses of shotcrete lining $t_c/R \leq 0.067$ was greater than the allowable tensile strength. The values of induced tensile stresses for D = 5 m were higher than the corresponding values of D = 10 m by a range between 6 % and 20 % with an average percentage 11%.

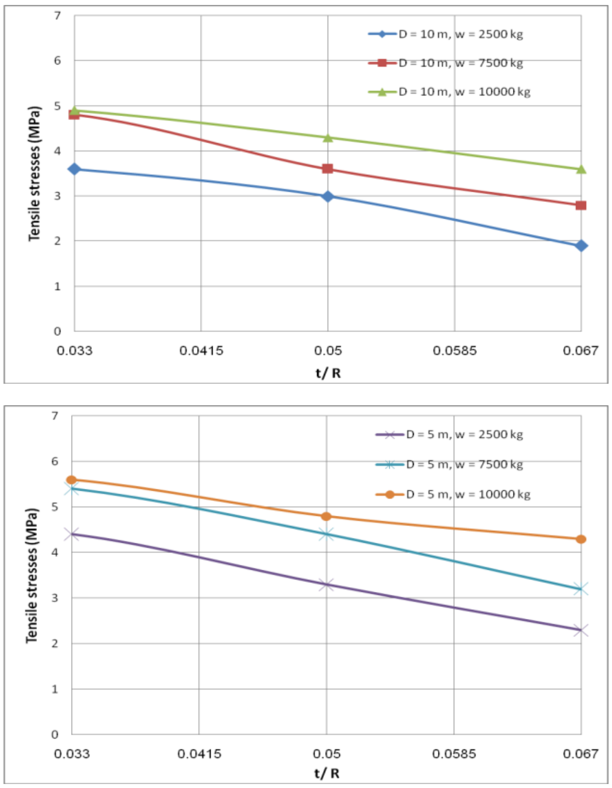

Fig.(8) Peak values of induced tensile stresses in shotcrete lining at crown versus the (t_c/R) for R = 6 m and RMR = 40

ANALYSIS OF SHOTCRETE LINING FOR MODERATE ROCK TUNNEL (RMR = 60)
(COMPRESSION AND TENSILE STRESSES)

To study the behaviour of shotcrete lining with this type of rock mass, 24 numerical model of shotcrete lining were analyzed under the effect of charge weight (W = 7500 kg and 10000 kg) for RMR= 60. These charges were located at crown-detonation distance (D = 5 m).

For tunnel radius R= 3 m

Fig. (9) shows the relation between the shotcrete thickness expressed by the ratio (t_c/R) and the induced compression and tensile stresses in shotcrete lining, respectively, under effect of applied charge weights at crown-detonation distance (D = 5 m). As shown in Fig.(9-a), for applied charge weight (W = 7500 kg) the compression stresses of shotcrete lining with $t_c/R \geq 0.067$ was less than the allowable compressive strength (f_c = 35 MPa) which indicates no damage occure in the lining. For applied charge weights (W = 10000 kg) the compression stresses of shotcrete lining with $t_c/R \geq 0.09$ was less than the allowable compressive strength. As shown in Fig.(9-b), for applied charge weight (W = 7500 kg) the tensile stresses of shotcrete lining with $t_c/R \geq 0.07$ was less than the allowable tensile strength.
For applied charge weight (W = 10000 kg) the tensile stresses of shotcrete lining with $t_c/R \leq 0.13$ was greater than the allowable tensile strength.

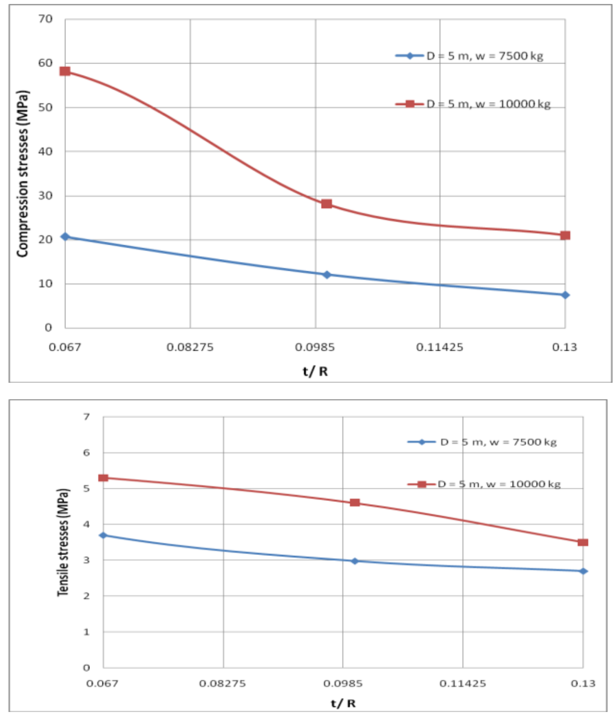

Fig.(9) Peak values of induced compression and tensile stresses in shotcrete lining at tunnel crown versus the (t_c/R) for R = 3 m and RMR = 60

For tunnel radius R= 4.5 m

As shown in Fig. (10-a), for applied charge weight (W = 7500 kg) the compression stresses of shotcrete lining with $t_c/R \geq 0.044$ was less than the allowable compressive strength. For applied charge weight (W = 10000 kg) the compression stresses of the shotcrete lining with $t_c/R \geq 0.06$ was less than the allowable compressive strength. As shown in Fig. (10-b), for applied charge weight (W = 7500 kg and 10000 kg) the tensile stresses of shotcrete lining with $t_c/R \leq 0.088$ was greater than the allowable tensile strength.

For tunnel radius R= 6 m

As shown in Fig.(11-a), for applied charge weight (W = 7500 kg) the compression stresses of shotcrete lining with $t_c/R \geq 0.033$ was less than the allowable compressive strength. For applied charge weight (W = 10000 kg) the compression stresses of shotcrete lining with $t_c/R \leq 0.067$ was greater than the allowable compressive strength. As shown in Fig. (11-b), for applied charge weight (W = 7500 kg and 10000 kg) the tensile stresses of shotcrete lining with $t_c/R \leq 0.067$ was greater than the allowable tensile strength.

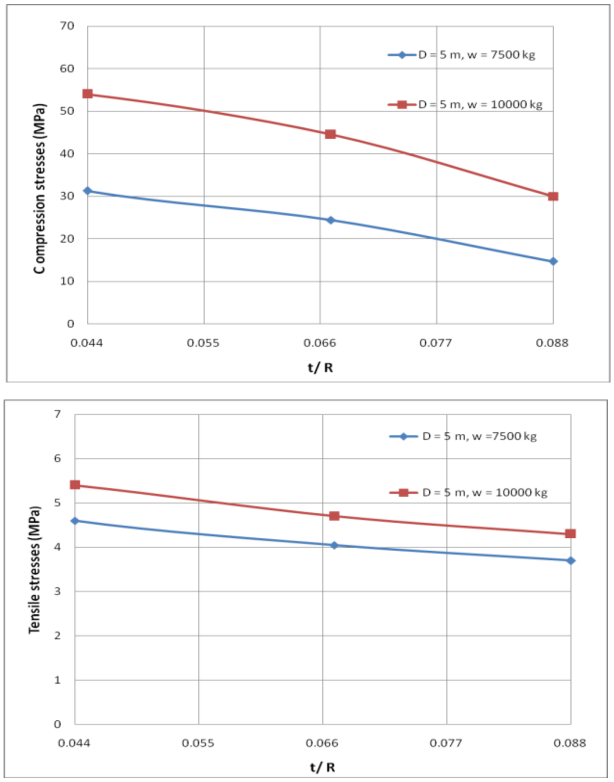

Fig.(10) Peak values of induced compression and tensile stresses in shotcrete lining at tunnel crown versus the (t_c/R) for R = 4.5 m and RMR = 60

ANALYSIS OF SHOTCRETE LINING FOR HARD ROCK TUNNEL (RMR = 80)
(COMPRESSION AND TENSILE STRESSES)

To study the behavior of shotcrete lining with this type of rock mass, 24 numerical model of shotcrete lining were analyzed under the effect of charge weight (W = 7500 kg and 10000 kg) for RMR= 80. These charges were located at crown-detonation distance (D = 5 m).

For tunnel radius R= 3 m

From Fig. (12-a), for applied charge weight (W = 7500 kg) the compression stresses of shotcrete lining with $t_c/R \geq 0.055$ was less than the allowable compressive strength (f_c = 35 MPa) which indicates no damage occurs in the lining. For applied charge weight (W = 10000 kg) the compression stresses of shotcrete lining with $t_c/R \geq 0.1$ was less than the allowable compressive strength. As shown in Fig. (12-b), for applied charge weight (W = 7500 kg and W = 10000 kg) the tensile stresses of shotcrete with $t_c/R \leq 0.13$ was greater than the allowable tensile strength.

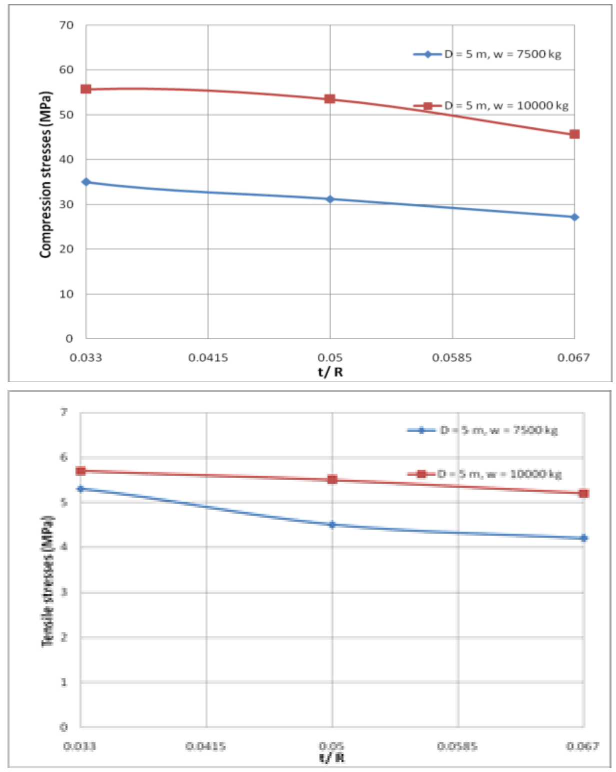

Fig.(11) Peak values of induced compression and tensile stresses in shotcrete lining at tunnel crown versus the (t_c/R) ratio for R = 6 m and RMR = 60

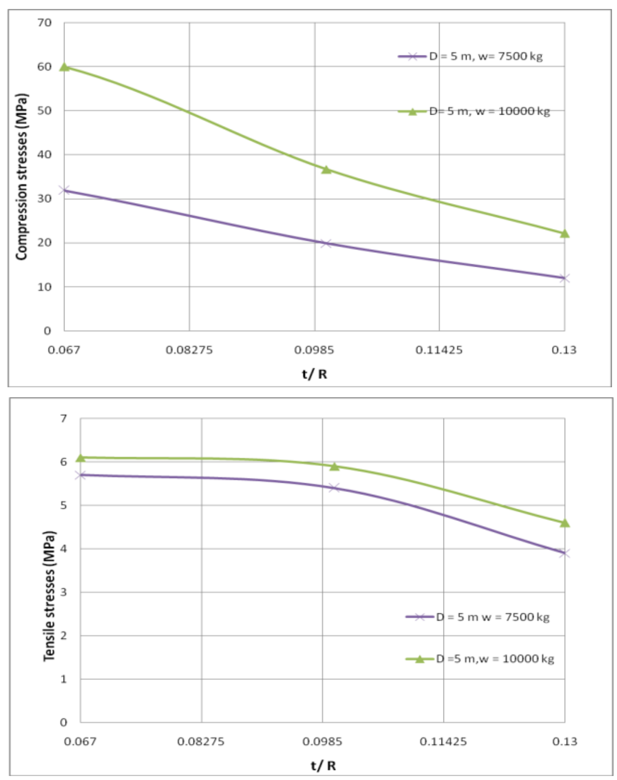

Fig.(12) Peak values of induced compression and tensile stresses in shotcrete lining at tunnel crown versus the (t_c/R) ratio for R = 3 m and RMR = 80

For tunnel radius R= 4.5 m

As shown in Fig. (13-a), for applied charge weight (W = 7500 kg) the compression stresses of shotcrete lining with $t_c/R \geq 0.067$ was less than the allowable compressive strength. For applied charge weight (W = 10000 kg) the compression stresses of shotcrete lining with $t_c/R \geq 0.088$ was less than the allowable compressive strength. As shown in Fig.(13-b), for applied charge weight (W = 7500 kg and W = 10000 kg) the tensile stresses of shotcrete lining with $t_c/R \leq 0.088$ was greater than the allowable tensile strength.

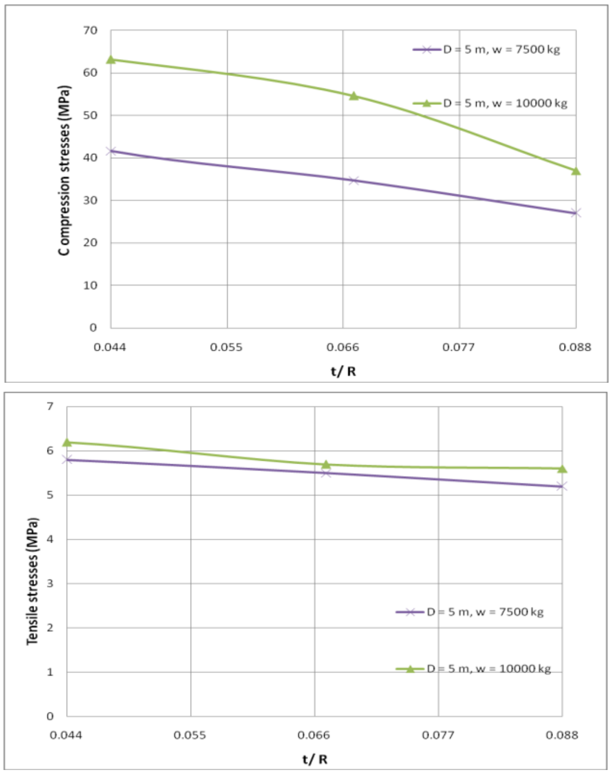

Fig.(13) Peak values of induced compression and tensile stresses in shotcrete lining at tunnel crown versus the (t_c/R) for R = 4.5 m and RMR = 80

For tunnel radius R= 6m

As shown in Fig.(14-a), for applied charge weight (W = 7500 kg) the compression stresses of shotcrete lining with $t_c/R \geq 0.067$ was less than the allowable compressive strength. For applied charge weight (W = 10000 kg) the compression stresses of shotcrete lining with $t_c/R \leq 0.067$ was greater than the allowable compressive strength. As shown in Fig. (14-b), For applied charge weight (W = 7500 kg and W = 10000 kg) the tensile stresses of shotcrete lining with $t_c/R \leq 0.067$ was greater than the allowable tensile strength.

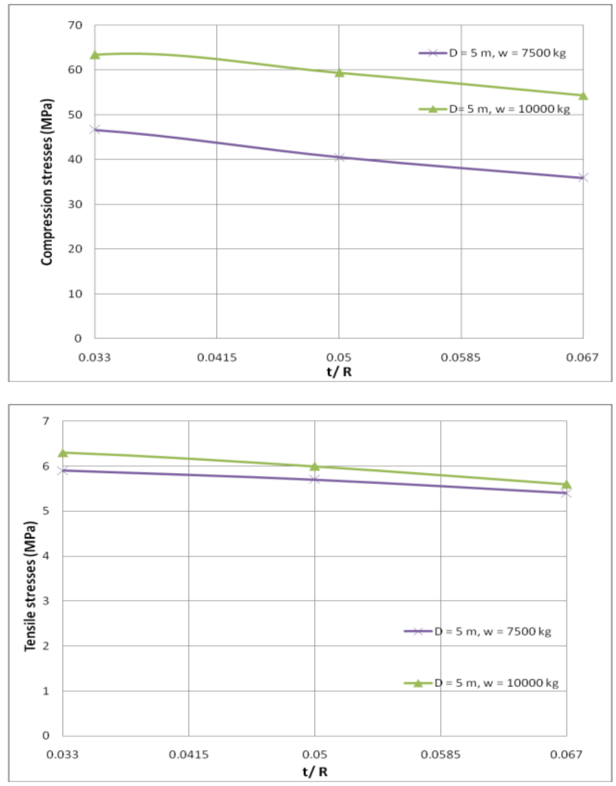

Fig.(14) Peak values of induced compression and tensile stresses in shotcrete lining at tunnel crown versus the (t_c/R) for R = 6 m and RMR = 80

RATIONAL ANALYSIS

The commercial software Data Fit [7] is used to determine the best-fit parameters for a model by minimizing a chosen merit function. The process is to start with some initial estimates and incorporates algorithms to improve the estimates iteratively. The new estimates then become a starting point for the next iteration. These iterations continue until the merit function effectively stops decreasing.

A numerical simulation of ground shock from detonations in rock is extremely demanding, requiring hydrodynamic computer codes, combined with non-linear dynamic codes based on discrete elements, discrete fracture and finite elements, which is a very complex approach. In the last decades, a general trend towards quantitative tunnel design is observed, in order to guarantee safety and stability of the tunnel at every stage of construction. This has demand for a more reliable method to quantify the properties of rock mass.

This section gives an overview of simpler approach, based on the use statistically treated results of the finite element with physical principles and analytical solutions to idealized cases.

In this study, simple design equations are developed for different responses of rock tunnel in different parameters based on a regression analysis of the results of the numerical models.

Analysis of tensile stresses for vertical-side-wall rock tunnels, shotcrete lining are performed utilizing different parameters that have been used in the numerical simulation.

The following symbols are used in the predicted equations:

R	: The tunnel radius for vertical side wall (VSW) tunnel (m) as defined in Fig.(2).
tc / R	: Shotcrete lining thickness to tunnel radius ratio.
W	: Charge weight (kg).
D	: The crown-detonation distance (m).
W/ D	: Charge weight to crown-detonation distance ratio.
RMR	: Rock Mass Rating.
σ_t(shotcrete)	: Maximum tensile stresses in shotcrete Lining (MPa).

TENSILE STRESSES

The studied responses for shotcrete lining is tensile stresses σ_t(shotcrete), at tunnel crown. The induced tensile stresses in shotcrete lining at crown of vertical side wall tunnel due to explosion loads could be predicted from Equation (1), it is clear that the induced tensile stresses value is decreased by the increasing of (t_c/R) ratio and decreasing of (W/D) ratio.

$$\sigma_{t(shotcrete)} = e^{(0.00592\,RMR + 0.000276\,W/D - 6.21t/R + 1.14)} \qquad (1)$$

Fig.(15) shows the results obtained from predicted tensile stresses equation for shotcrete lining plotted against the numerical results from AUTODYN, it can be seen that a very good correlation is observed between the two results. This equation was used to form design charts to predict the induced tensile stresses in shotcrete lining depending on different RMR, W/D and R.

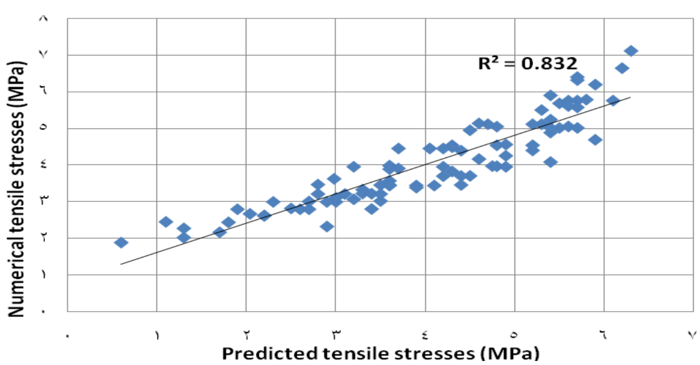

Fig.(15) Correlation graph between predicted tensile stresses and numerical results from AUTODYN for shotcrete lining

Fig. (16) show the design charts which introduce the relation between the predicted tensile stresses in shotcrete lining at tunnel crown and (t_c/R) for RMR= 50 according to different W/D ratio using Equation (1).

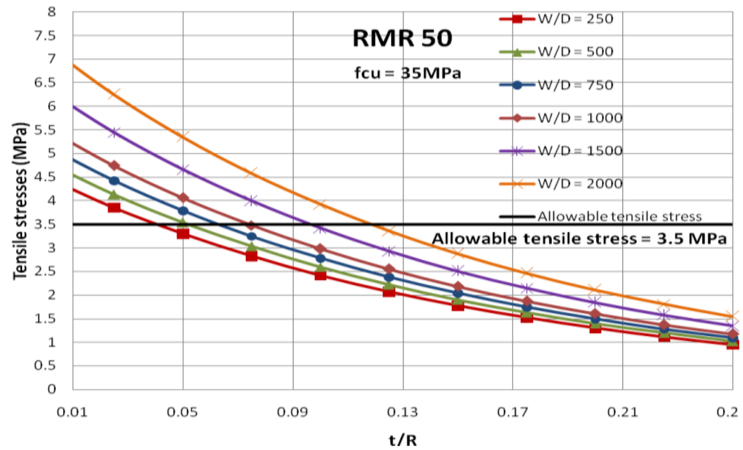

Fig.(16) Predicted tensile stress in shotcrete lining tunnel RMR = 50

CONCLUSIONS

The induced compression stresses in shotcrete lining increased by increasing Rock Mass Rating, tunnel radius and charge weight, whereas, the decreasing crown-detonation distance the increasing induced compression stresses in shotcrete lining.

The induced compression stresses in shotcrete lining decreased by increasing the shotcrete lining thickness.

For RMR = 60, the induced compression stresses were higher than the corresponding values for RMR = 40 by an average percentage 10%, 37.1% and 29.8% for tunnel radii R = 3, 4.5 and 6 m respectively, under effect of applied charge weight W = 7500 kg and 5 m crown-detonation distance.

For RMR = 60, the induced compression stresses were higher than the corresponding values for RMR = 40 by an average percentage 37.4%, 41.8% and 39.5% for tunnel radii R = 3, 4.5 and 6 m respectively, under effect of applied charge weight W = 10000 kg and 5 m crown-detonation.

For RMR = 80, the induced compression stresses were higher than the corresponding values for RMR = 40 by an average percentage 42.8%, 57.7% and 46.4% for tunnel radii R = 3, 4.5 and 6 m respectively, under effect of applied charge weight W = 7500 kg and 5 m crown-detonation distance.

The induced tensile stresses in shotcrete lining increased by increasing Rock Mass Rating, tunnel radius and charge weight, whereas, the decreasing crown-detonation distance the increasing induced compression stresses in shotcrete lining.

The induced tensile stresses in shotcrete lining decreased by increasing the shotcrete lining thickness.

For RMR = 60, the induced tensile stresses were higher than the corresponding values for RMR = 40 by an average percentage 5%, 8% and 10% for tunnel radii R = 3, 4.5 and 6 m respectively, under effect of applied charge weight W = 7500 kg and 5 m crown-detonation.

For RMR = 60, the induced tensile stresses were higher than the corresponding values for RMR = 40 by an average percentage 6%, 9% and 11% for tunnel radii R = 3, 4.5 and 6 m respectively, under effect of applied charge weight W = 10000 kg and 5 m crown-detonation.

For RMR = 80, the induced tensile stresses were higher than the corresponding values for RMR = 40 by an average percentage 33.6%, 27% and 24.4% for tunnel radii R = 3, 4.5 and 6 m respectively, under effect of applied charge weight W = 7500 kg and 5 m crown-detonation.

For RMR = 80, the induced tensile stresses were higher than the corresponding values for RMR = 40 by an average percentage 23%, 20% and 17% for tunnel radii R = 3, 4.5 and 6 m respectively, under effect of applied charge weight W = 10000 kg and 5 m crown-detonation.

The predicted tensile stress equation shows a compatibility percentage with numerical results equal to 83%.

The rational analysis approach mostly ends up in easy-to-use closed-form prediction equations, which thus constitute a rational tool for practical solution of commonly encountered ground shock problem.

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