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Nonlinear Finite Element Stability Analysis of Tunnel in Sandstone against Blast Load

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Abstract. Underground space utilization has increased globally, which in turn has made tunnels an indivisible part of the development. The stability and safety of urban tunnels has always been a concern while designing and maintaining these projects. The increased unrest in the world has resulted in targeting of these strategic structures occasionally. In a previous couple of decades, underground structures especially tunnels, were targeted. Hence, the consideration of blast resistivity is an integrated part of design of tunnels and other underground structures. The stability of a rock tunnel against the blast load of 5m diameter tunnel enclosed in 30m by 30m of the surrounding sandstone rock mass has been considered. The tunnel has a reinforced cement concrete (RCC) lining of 0.35m thickness which is reinforced with steel reinforcement. Finite element analysis has been carried out to study the rock tunnel response due to blast load of TNT explosive charge of 100kg. The TNT has been modelled as a material using Coupled-Eulerian-Lagrangian (CEL) modelling technique. The Mohr-Coulomb constitutive material model has been incorporated for simulating the elastoplastic response of sandstone rocks. Kota sandstone, Jamrani sandstone, Singrauli sandstone and Jhingurda sandstone are different type of sandstone rocks considered in the present study. Also, Concrete Damage Plasticity (CDP) model has been used for concrete, and the Johnson-Cook model for steel reinforcement modelled is considered in the study. The TNT and air inside the tunnel have been modelled as a Eulerian model, and the other parts of the simulation were adopted as the Lagrangian model. The damage and displacement for each case has been observed and its contours are discussed in detail. The rock tunnel constructed in Jhingurda sandstone is found to be the most vulnerable in reference to blast resistance capacity.

Keywords: Rock tunnel; Sandstone; Trinitrotoluene; Blast; Coupled-Eulerian-Lagrangian.

1 Introduction

The underground structures especially tunnels have been prone to terror events. A terror attack on a tunnel in Afghanistan (1982)had resulted in several casualties that left 1000-3000 people dead [1]. A Similar type of event was witnessed in London underground metro tunnel (2005), where 52 deaths were reported [2]. Moreover, similar events were reported in different parts of the world. Therefore, the study of underground tunnel has attracted scientists and researchers to study and design underground structures [3–9]. The tunnels have been constructed in both the soil and the rock. Therefore, both types of materials have to be considered to understand the response of tunnels when exposed to internal blast loading.

The amount of explosive charge, type of material surrounding the tunnel and thickness of the tunnel lining are some of the important factors that govern the tunnel stability against blast load [10, 11]. A study was carried out for different parameters of the tunnel, i.e., tunnel diameter, distance between the super-structure & the tunnel, and loading density of tunnel. It was concluded that the distance between the tunnel and the super-structure had high effect on the stability as compared to other factors [12]. Moreover, propagation of blast waves in the soil and the jointed rocks differs in various aspects. Also, the attenuation of shock waves was concluded as a function of weight of explosive, angle of incidence and the distance of propagation [13]. Further, the tunnels in weak rocks were found to have higher magnitude of damage, therefore, properties of rocks should be considered precisely for the study of tunnel stability against blast load [14]. Further, there are numerous studies carried out for the study of tunnel when subjected to blast loading [15–17].

However, it has been concluded that majority of the authors have carried out studies for soil tunnels and rock tunnels which rarely have been studied. In addition, the literatures dealing with the study of tunnel subjected to internal blast loading are infrequently available. Moreover, the coupled-Eulerian-Lagrangian (CEL) methods of modeling for TNT explosive charge and air inside the tunnel have hardly been considered in the available literatures. Furthermore, air inside the tunnel has been considered by some authors but neglected in most of the studies.

In this study, a three-dimensional finite element study has been carried out by using Abaqus. Moreover, an advanced method of modelling, i.e., CEL method has been incorporated to model the TNT explosive charge and the air inside the tunnel. In addition, four-different sandstones found in the Indian region have been considered to understand the best choice for blast-resistant tunnel.

2 Numerical Modelling

The nonlinear elastoplastic analysis has been carried out in the present study. A finite element analyses has been carried out using Abaqus [18]. The rock has 30m x 30m of cross-section and its length is 35m. A tunnel having 5m of diameter has been considered at the center with 12.5m of overburden depth. The tunnel has a concrete liner of 0.35m in thickness [19]. The detailed model used for the study of internal blast loading is shown in Fig. 1.

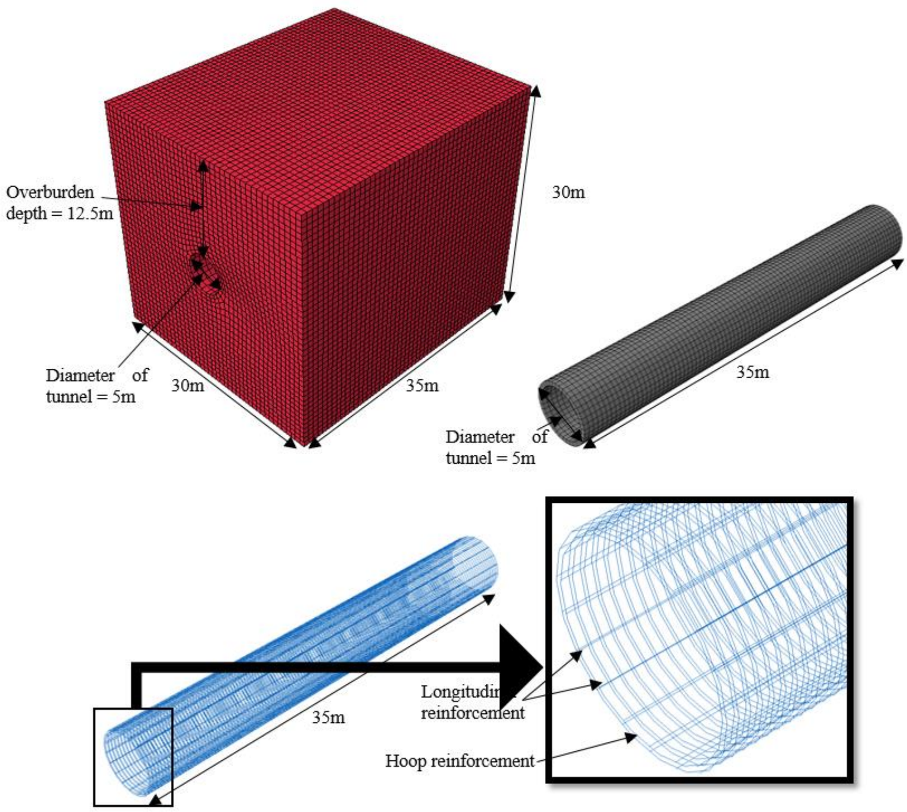


Fig. 1. Different parts of the finite element model.

There are four different sandstones, i.e., Jhingurda, Singrauli, Jamrani and Kota, which are compared for their blast-resistant response. The Mohr-Coulomb material model has been considered for the elastoplastic response of the sandstone rocks. Table 1 shows the input parameters of elastoplastic model used in the present study.

Table 1. Properties of different rocks considered in the study [20].

Rock (Sandstone)	Mass Density (kg/m^3)	Young's Modulus (GPa)	Poisson's Ratio	Friction Angle (Degree)	Cohesion (MPa)
Jhingurda	1670	2.84	0.25	21.34	3.68
Singrauli	2310	4.31	0.29	27.11	10.47
Jamrani	2480	5.29	0.22	37.79	11.17
Kota	2310	14.02	0.21	43.42	20.93

The tunnel has concrete liner of M30 grade and the properties used in this study are shown in Table 2 [21]. Moreover, Fe415 grade of steel has been used as a reinforcement for concrete liner [22]. The steel bars in the longitudinal direction have 10mm of diameter having spacing of 850mm in the hoop direction. Moreover, double hoop reinforcement has been used and the spacing between the internal and external hoop reinforcement is 250mm [19]. The hoop reinforcement has 12mm of diameter steel bars that are spaced at 250mm in the longitudinal direction. The properties of the Fe415 grade steel bars used in the present analyses are shown in Table 3 and Fig. 2 [21].

Table 2. Property of M30 grade concrete tunnel lining [21].

Density (kg/m^3)	Young's Modulus (GPa)	Poisson's Ratio	Dilation Angle	Eccentricity	fb0/fc0	K
2500	26.6	0.2	31	0.1	1.16	0.67

Concrete Compressive Behavior		Concrete Compressive Damage	
Yield Stress (MPa)	*Inelastic Strain*	*Damage Parameter (c)*	*Inelastic Strain*
15.3	0	0	0
19.2	0.000048249	0	0.000048249
22.5	0.000119844	0	0.000119844
25.2	0.000214786	0	0.000214786
27.3	0.000333074	0	0.000333074
28.8	0.000474708	0	0.000474708
29.7	0.000639689	0	0.000639689
30.0	0.000828016	0	0.000828016
29.7	0.001039689	0.01	0.001039689
28.8	0.001274708	0.04	0.001274708
27.3	0.001533074	0.09	0.001533074
25.2	0.001814786	0.16	0.001814786
22.5	0.002119844	0.25	0.002119844
19.2	0.002448249	0.36	0.002448249
15.3	0.002800000	0.49	0.002800000
10.8	0.003175097	0.64	0.003175097
5.7	0.003573541	0.81	0.003573541
Concrete Tensile Behavior		Concrete Tensile Damage	
Yield Stress (MPa)	*Cracking Strain*	*Damage Parameter*	*Cracking Strain*
3.00	0	0.00	0
0.03	0.001167315	0.99	0.001167315

Table 3. Property of steel reinforcement embedded in concrete [22].

Density (kg/m^3)	Young's Modulus (GPa)	Poisson Ratio	A (MPa)	B (MPa)	n	C	Strain Rate (s^{-1})
7800	210	0.3	360	635	0.114	0.075	100

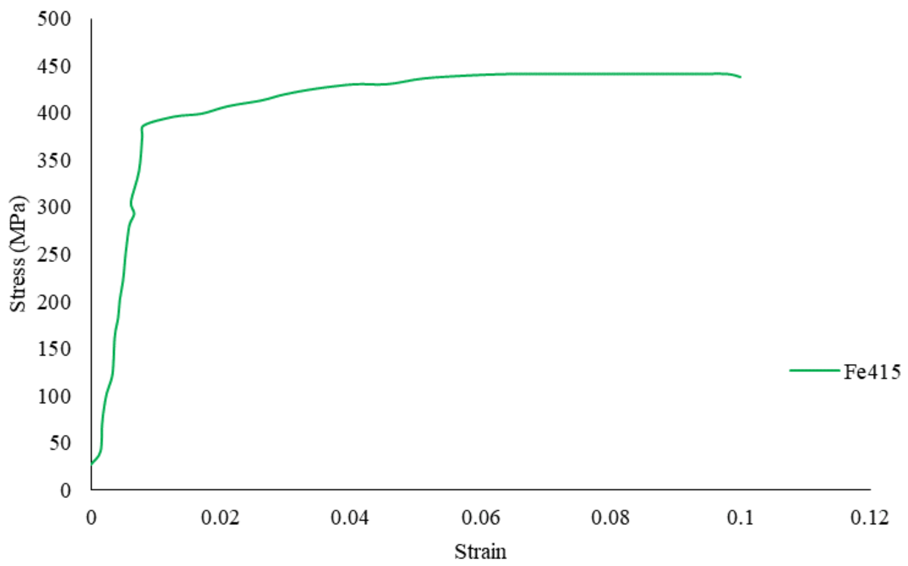


Fig. 2. Stress-strain behaviour of Fe415 steel grade [22].

A 100kg of TNT explosive has been used for simulating the internal blast loading in different sandstone rocks considered in the present study. Jones-Wilkins-Lee (JWL) material model of equation of state (EOS) has been used and the input parameters are shown in Table 4.

Table 4. Property of TNT explosive charge used for internal blast loading [23].

Density (kg/m^3)	Detonation Wave Speed (m/s)	A (MPa)	B (MPa)	ω	R_1	R_2	Detonation Energy Density (kJ/kg)
1630	6930	373800	3747	0.35	4.15	0.9	3680

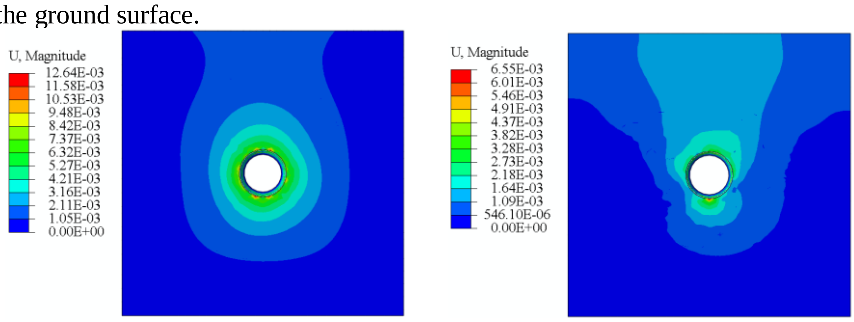
The rock and the tunnel lining have been meshed using C3D8R element type and steel bars have meshing of B31 element type. Moreover, the Eulerian parts of the model have been meshed using EC3D8R element type. The interaction between the different parts of the model has been assigned using general hard contact in terms of normal and tangential contact. Moreover, a penalty has been assigned for the contact between the rock and the tunnel lining. The base of the tunnel has been assigned a fixed boundary condition and the sides of the model have roller support.

The Eulerian-volume-fraction (EVF) tool available in Abaqus has been used for coupled-Eulerian-Lagrangian (CEL) modelling of TNT and air inside the tunnel. The value of EVF ranges from 0 to 1, where 0 stands for empty elements and 1 stands for completely filled Eulerian elements. In the present cases, EVF = 0.8 has been used for filling the air in the Eulerian elements lying inside the tunnel. Moreover, EVF = 1 has been assigned for filling the Eulerian elements with TNT explosive material. In CEL, method of modelling, the Eulerian material can flow through the Lagrangian elements that create deformation in the Lagrangian elements.

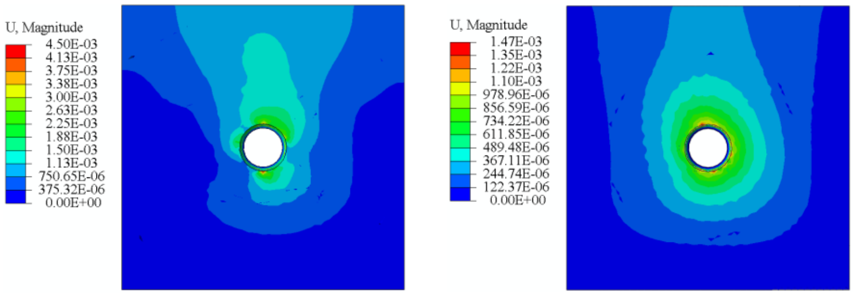
3 Results and Discussion

The response of rock tunnels constructed in four different sandstones has been analyzed. TNT explosive charge having 100kg of weight has been assumed at the center of the tunnel and the analysis has been carried out for 30 milliseconds. The TNT and the air inside the tunnel have been modelled through CEL technique in Abaqus. Deformation in the rock, tunnel lining and steel reinforcement has been compared for different rocks. In addition, failure of tunnel lining in terms of compression and tension has also been analyzed.

The magnitude of deformation in the rock tunnel gives an idea about its safety and serviceability. Fig. 3 show the contours of deformation when a rock tunnel has been subjected to internal blast loading. It has been observed that Jhingurda sandstone is the most unsuitable choice for blast resistant tunnel construction. However, Kota sandstone has higher stability against internal blast loading. Moreover, the deformations are concentrated at the internal surface of the tunnel in case of Jhingurda, Singrauli, and Jamrani sandstones but Kota sandstone has larger radius of influence. Further, Jhingurda sandstone has 12.64mm of deformation at internal surface that has 6-times higher value than the deformation at the ground surface. Similarly, Singrauli, Jamrani and Kota sandstone has 6.55mm, 5.50mm and 1.47mm of deformation at the internal surface of the tunnel, which is 4-times higher than the deformations observed at the ground surface.



(a) (b)



(c) (d)

Fig. 3. Deformation contours of (a) Jhingurda, (b) Singrauli, (c) Jamrani, and (d) Kota sandstone tunnel.

Fig. 4 and Fig. 5 have been plotted for the comparison of deformation variation with time at the ground surface and the internal surface of the tunnel respectively. At the ground surface heaving and spike formation at the internal surface have been observed from these figures. Moreover, the deformation varies in an arbitrary manner at the internal surface of the tunnel. However, an orderly variation of the deformation with time has been observed at the ground surface. Further, Kota sandstone shows a decline in the deformation and therefore, a recovery of failure has been witnessed. Consequently, Kota sandstone has been found as a better choice for blast resistant tunnel construction.

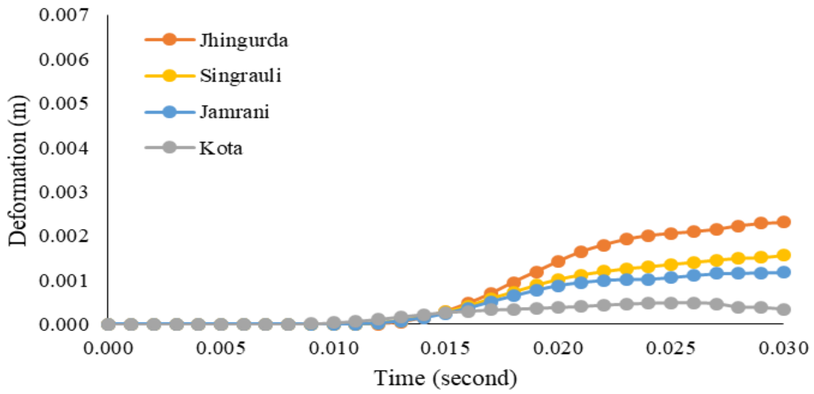


Fig. 4. Variation of deformation at the node on ground with time when subjected to 100kg TNT explosive charge for 30 milliseconds of time period

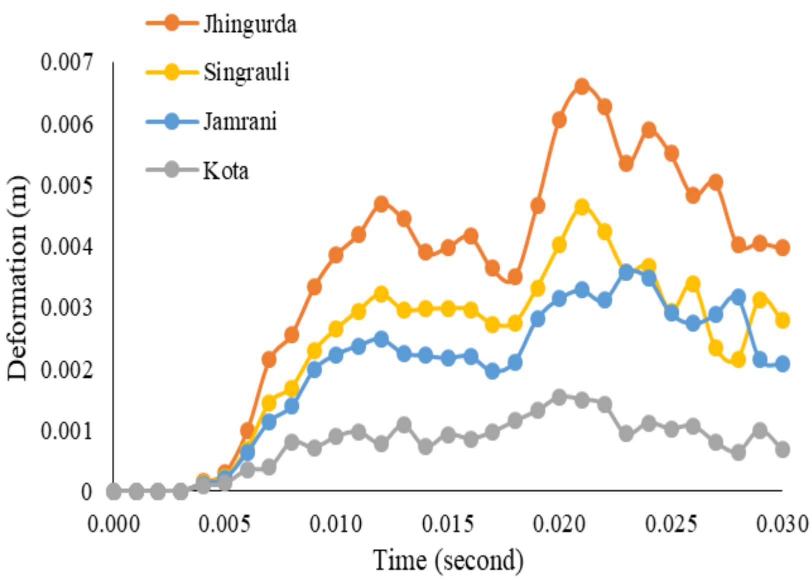


Fig. 5. Variation of deformation at the node on crown of tunnel with time when subjected to 100kg TNT explosive charge for 30 milliseconds of time period

The deformation in the tunnel lining has been compared in Fig. 6 for different sandstones considered in this study. The maximum deformation of value 331mm has been noted for Jhingurda sandstone tunnel lining. The deformation in case of Singrali, Jamrani, and Kota sandstone is 303mm, 302mm and 299mm respectively. In all the different cases, crown and invert are the most vulnerable regions of a tunnel lining.

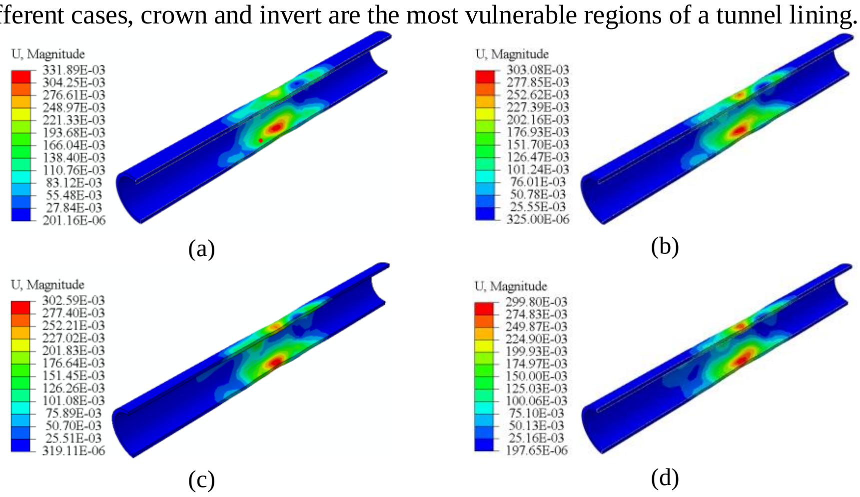


Fig. 6. Deformation contours of tunnel lining in case of (a) Jhingurda, (b) Singrauli, (c) Jamrani, and (d) Kota sandstone tunnel.

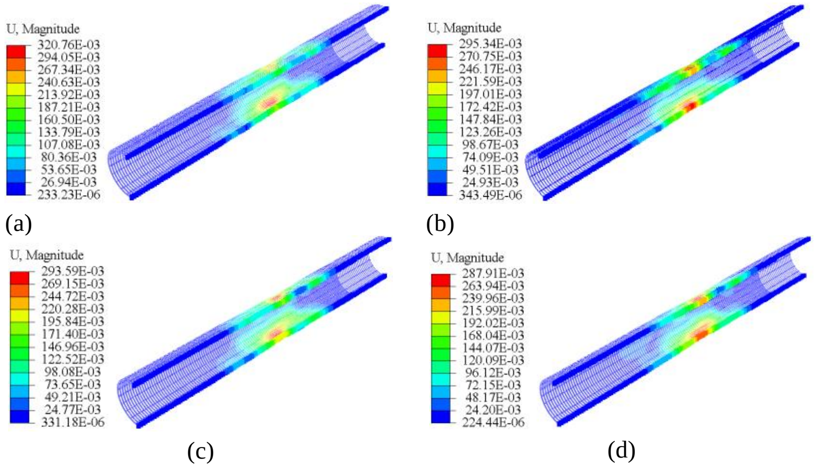


Fig. 7. Deformation contours of steel reinforcement for (a) Jhingurda, (b) Singrauli, (c) Jamrani, and (d) Kota sandstone tunnel.

The deformation contours in the steel reinforcement have been compared in Fig. 7 for sandstones considered in the present study. The steel reinforcement in case of Jhingurda sandstone experiences 320mm of deformation at crown and invert of the tunnel. Moreover, the reinforcement steel in case of Singrauli, Jamrani, and Kota sandstones has 295mm, 293mm and 287mm deformation respectively. Therefore, it has been observed that blast-resistant designing of Jhingurda sandstone requires higher amount of money while the cost reduces for Kota sandstone tunnel.

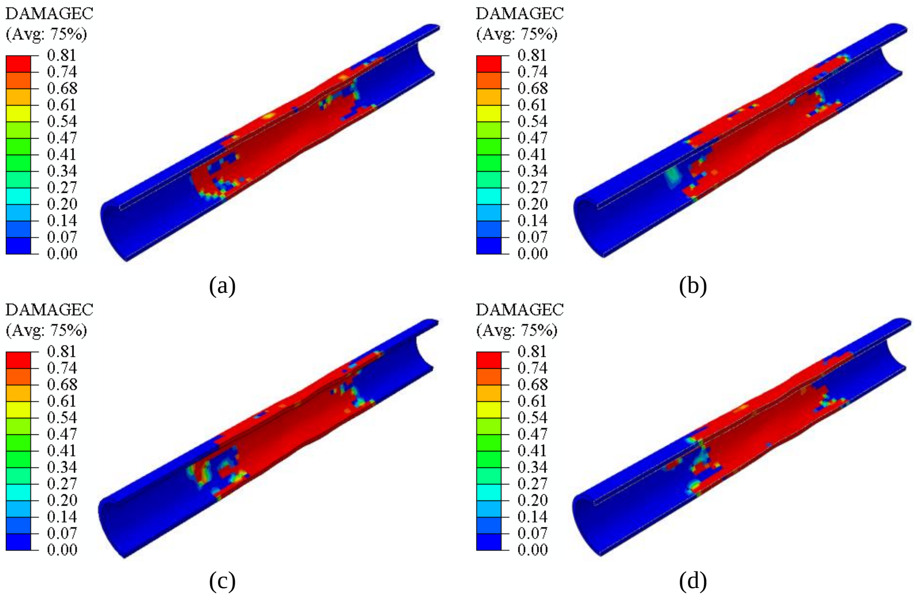


Fig. 8. Compression damage failure in tunnel lining for an internal blast load of 100kg TNT

for (a) Jhingurda, (b) Singrauli, (c) Jamrani, and (d) Kota sandstone tunnel.

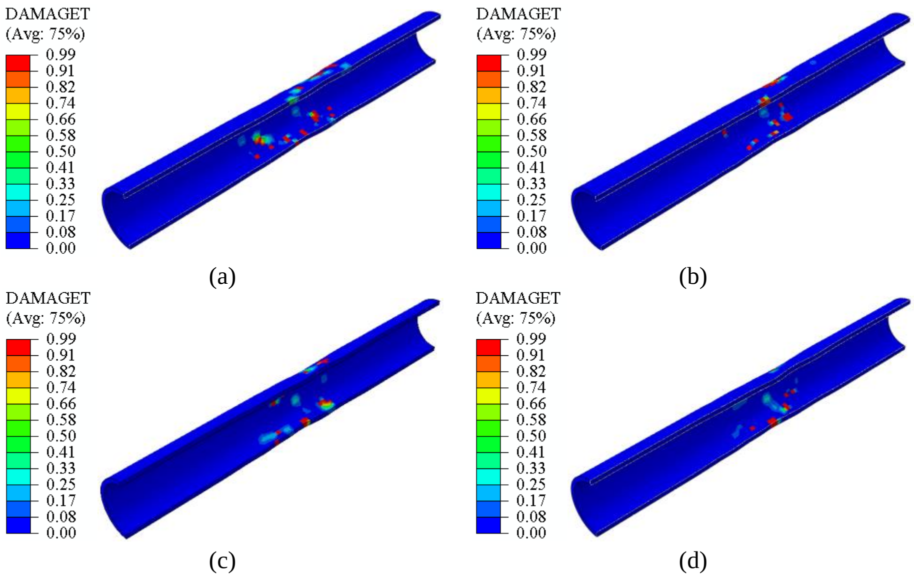


Fig. 9. Tension damage failure in tunnel lining for an internal blast load of 100kg TNT for (a) Jhingurda, (b) Singrauli, (c) Jamrani, and (d) Kota sandstone tunnel.

Fig. 8 and Fig. 9 present contours of compression and tension damage in the concrete liner of tunnel. Minor failure has been observed in terms of tension damage and it is concentrated at the internal surface of the tunnel lining. Therefore, the tension damage doesn’t propagate through the thickness of tunnel lining. However, the compression damage has propagated through the tunnel lining thickness and resulted in failure of half of the lining. Moreover, a complete crushing has been observed that makes the tunnel lining unserviceable and therefore, higher strength of concrete has to be used.

4 Conclusions

The three-dimensional finite element analyses have been carried out in this study using Abaqus. Moreover, Coupled-Eulerian-Lagrangian which is an advanced method of blast modelling has been adopted. Jhingurda, Singrauli, Jamrani and Kota are the four different sandstones subjected to the blast with a 35mm RCC lining as nonlinear elasto-plastic analysis. The major conclusions determined from this study are-

1. Kota sandstone is the most suitable among the rocks considered in this study for blast resistant designing of tunnel.
2. Kota sandstone is 8.6-times safer than the Jhingurda sandstone during an event of internal blast loading.
3. Heaving has been observed at top surface of rock tunnel of present study and spike formation has been noted at inside face of the tunnel.

4. Maximum deformation in tunnel lining and steel reinforcement has been observed at the position of crown and invert.
5. Negligible tension damage has been observed in the tunnel lining while half of the tunnel lining has damaged due to compression in all the sandstone. Therefore, tunnel lining fails in compression irrespective of the type of sandstone.
6. It has been concluded that the stability of the tunnel in this types of sandstone rock is directly proportional to the angle of internal friction and cohesion of the rock surrounding the tunnel.

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