Dynamic Analysis of Tunnels in Urban areas With and Without support systems

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***Abstract*— ANSYS is a powerful numerical simulation tool for analyzing a structure and calculating its stresses and deformations. It comes handy in the static and dynamic analysis of Bangalore underground metro tunnels. In this paper, the influences of various static loads and in-situ stresses on underground Bangalore metro tunnel are analyzed along with the respective images. Similarly, 30kg TNT blast effect on the entrance of one of the twin tunnel with lining is also analyzed. All these analyses are performed using elasto-plastic analysis after proper validation of the software for the same using references and the results are tabulated.**

Keywords—underground metro tunnel; ANSYS; numerical simulation; blasting effects; static analysis

I. INTRODUCTION

In cities like Bangalore, traffic congestion and environmental factors are creating a demand for greater utilization of underground spaces. Underground Metro Rail satisfies the need for effective means of transportation by reducing a lot of travelling time and fuel consumption. The main aim of the project is to analyze the 4.8 km of underground east-west section subjected to various static and dynamic loads. In addition to the experimental work carried out, the results obtained will be compared with finite element software which gives a visual representation of failure pattern at various points of interest. Thus the tunnel stability and deformations are checked for various loading criteria using a powerful numerical simulation tool called ANSYS. It follows a meshing technique to split the structure into smaller pieces and analyze them separately for gaining accuracy. Terrorist attack inside underground structures is also a major topic and has a lot of scope for research. The time-varying influence of blast load inside a single and twin tunnel due to 30kg TNT is analyzed. In this project, detailed elasto-plastic analysis is performed to validate for static loading and blasting effects both in 2D and 3D models along with the comparison analytical and numerical results.

II. OBJECTIVES

The main objectives of this project are:

- To review the literature related to tunneling and non-linear analysis in ANSYS.
- To study in detail, the construction of underground metro tunnel for generating an exact model similar to field conditions.
- To validate and explore the possibilities of implementing ANSYS for static and dynamic analysis of Bangalore underground metro tunnel.
- To obtain various parameters affecting the tunnel and tunnel failure pattern by providing different static loading conditions.
- To analyze the longitudinal extent of blast effect for a 30m long tunnel without confinement.
- To analyze the blasting effects for tunnel with and without support systems and influence of blast load on nearby tunnel due to 30 kg TNT explosion.

III. LITERATURE SURVEY

- P Anbazhagan et al (2008) describes the properties of the soil layer with various depths using MASW component. MASW is used to study the behavior of soil and embankments. This paper describes the methodology of Multichannel Analysis of Surface Waves to obtain the soil properties such as density, Poisson's ratio and young's modulus for different layers of soil situated in and around Bangalore. Rayleigh surface waves generated in this are captured by using SURFSEIS software package to arrive at the soil properties for the location.
- M. Sekhar et al (2009) explains in detail about the topography, groundwater level, depth of hard rock and the tunnel alignment along the east-west section of the metro rail project. It deals about the impact of groundwater system for proposed metro tunnel. From the studies, it has been concluded that the ground water table will be at a depth of 5m approximately which will have a greater influence on the stresses acting on the underground tunnel.
- B.S.Sudhir Chandra (BMRC) explains the salient features of twin tunnel construction along the east – west corridor of 18.1kms and north-south corridor of 24.2kms. In a total length of 42.3kms, the elevated section is 33.48kms and underground section is 8.82kms. The dimension of the tunnel's inner diameter is 5.6 m and boring diameter is 6.44 m with a reinforced concrete lining thickness of 280mm. The depth of the tunnel from the ground level is 15 to 18.3m approximately and centre to centre distance of

the twin tunnel is 15.04m. Tunneling is done by using slurry TBMs and earth pressure balanced TBM method and cut and cover method is used for stations. Two drilling machines namely Helen and Margarita are used for tunneling this section which has a drilling capacity of 11m per day.

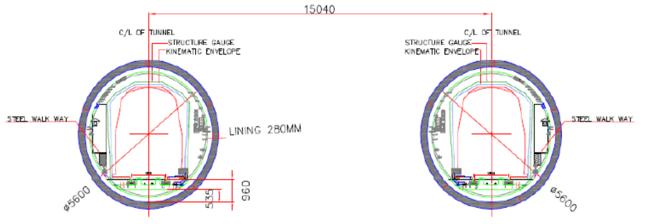


Fig. 1. Cross-section of Bangalore Metro Underground Tunnel.

TABLE I. SOIL PROFILE OF BANGALORE METRO TUNNEL

Layers and its Depth (m)	Density (Kg/m^3)	Young's modulus (N/m^2)	Poisson ratio	Cohesion (KPa)	Friction angle (deg)
Clayey sand 0 to 3.2m	2000	3.25×10^8	0.3	5	35
Clayey sand+Gravel 3.2 to 8m	1900	1.11×10^8	0.3	20	30
Silty sand+Gravel 8 to 28.5m	2000	4.08×10^8	0.3	15	35
Hard rock > 28.5	2000	5.23×10^8	0.2	4000	42

- Huabei Liu et al (2009) investigates various factors that influence the magnitude of damage on an underground tunnel based on the explosive weight, burial depth, type of soil layers and the characteristics of blast pressure. The dynamic ground-structure interaction, structure damage, nonlinear response of ground media, three dimensional effects, and fluid–structure interaction defines the complicated characteristics of the problem.

IV. VALIDATION OF ANSYS FOR ELASTO-PLASTIC ANALYSIS

The theoretical model proposed by John Bray (1967) states that, in case of soft or weak soil, the stress developed exceeds the yield strength and hence formation of both elastic and plastic zone occurs. The plastic zone is also known as "yield zone". If r_0 is the radius of the tunnel, r_p is the plastic zone radius, r is the radial distance, Φ is the angle of internal friction, C the cohesion, P = P_0 is the insitu stress considered, then

Radial stress, $\sigma_r = m_3 . r\ (m_1 - m_2)$ (1)

Tangential stress, $\sigma_\theta = m_4 .\ r\ (m_1 - m_2)$ (2)

Where,

$m_1 = 2 \sin\Phi / (1-\sin\Phi)$

$m_2 = C \cos\Phi / \sin\Phi$

$m_3 = m_2 / r_0\, m_1$

$m_4 = m_3 (1+\sin\Phi) / (1-\sin\Phi)$

The plastic zone equation is given below:

$r_p = r_0[(P+C.\cot\Phi)(1-\sin\Phi \quad /(C.\cot\Phi)](1-\sin\Phi)/2\sin\Phi$ (3)

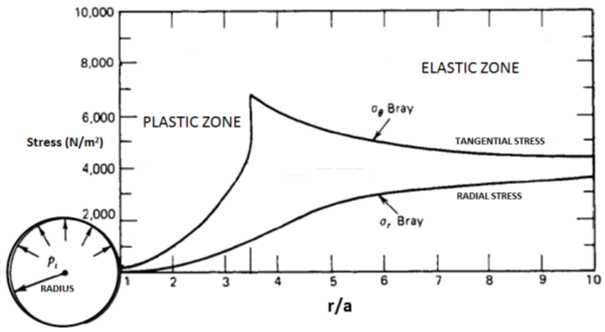
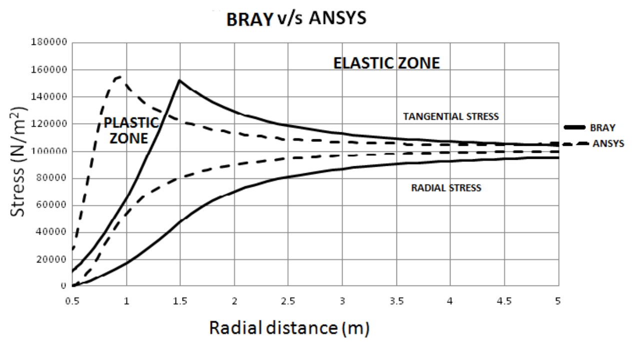


Fig. 2. John Bray's solution graph (1967).

By using the equations of theoretical Bray's solution, the validation of ANSYS is done by comparing the results for a solved example problem. The problem is about a square plate with a hole having dimension of 5m on all sides and radius is 0.5m. The young's modulus and Poisson's ratio are 10,000MN/mm^2 and 0.25 respectively. Its density is 1900kg/m^3 while the angle of internal friction is 30^0, cohesion is 3.45MPa and dilatancy angle is 0^0. The results obtained from theoretical equations and ANSYS are plotted using excel and a graph is obtained. Thus, it is verified from the validation of a simple 2D example problem that Drucker-Prager model in ANSYS can be used to model the elastic and plastic stresses and deformations.



Comparison of Bray vs. ANSYS graph from results

V. ACCURACY IN MESHING AND BOUNDARY CONDITIONS

There are four types of meshing available for a 2D problem in ANSYS. They are Tri-Free meshing, Tri-Mapped meshing, Quad-Free meshing and Quad-Mapped meshing. Though, there may be a slight variation in all the cases, "quad-free" meshing of smart size = 2 gives the exact result as such when compared with the example problem. For the optimum dimension to be adopted in the model, we take three dimensions of tunnel boundaries based on its diameter. They are 2.5d, 3d and 4d where d represents the diameter of the underground tunnel which is 6.44m. In 2.5d, the influence of stress is going out of the boundary and hence it cannot be used for modeling. In 4d, there is more extra space for the boundary influence. So, the modeling will become more complex to solve. Therefore 3times the diameter is taken as the optimum dimension on all sides and is used in further calculations.

VI. STATIC ANALYSIS OF TWIN TUNNELS

In-situ stresses exist in the ground prior to any excavation, which is one of the major influential factors for underground construction. The tunnel is considered as a thin cylindrical opening in an infinite medium of soil mass. Non-linearity in a FEM tool like ANSYS can be simulated with the help of some soil models. **Main Menu> Preprocessor> Material Props> Material Models> Structural> Nonlinear** is used to define the type of non-linear model to be used in ANSYS. Drucker-Prager model proves to be more advantageous for soil modeling because of its accuracy and sensitivity. Apart from the elastic properties like young's modulus, Poisson's ratio and density, the input for this model will consist of three constants namely cohesion, angle of friction and dilatancy angle. PLANE42 element is used for 2-D modeling of soil profile. This element can be used as a plane stress, plane strain or as an axi-symmetric element. Similarly, SOLID65 element type is used for the three-dimensional modeling of soil. It is also useful for concrete applications like reinforced composites such as fiberglass. This element has eight nodes with 3 degrees of freedom at each node. Quarter analysis is done to get the displacement vectors and stress contours on the tunnel face and to generate a graph along the horizontal (0^0). **Main Menu> Solution> Define Loads> Apply> Structural> Inertia> Gravity> on global** is used to specify the gravity load acting on negative Y-direction with a value of **9.81m/s^2**. For live load due to traffic, **Main Menu> Solution> Define Loads> Apply> Structural> pressure>on line** command is used and a value of **6kN/m^2** is specified. The bottom layers are subjected to hydrostatic pressures and a value of **29.43KN/m^3** is applied for the second layer and **166.67KN/m^3** for the third layer. As fourth layer lies below the tunnel, its hydrostatic pressure will not affect the tunnel. The thickness of concrete lining provided is 280mm with a young's modulus of 3e10N/m^2 and a Poisson ratio of 0.2.

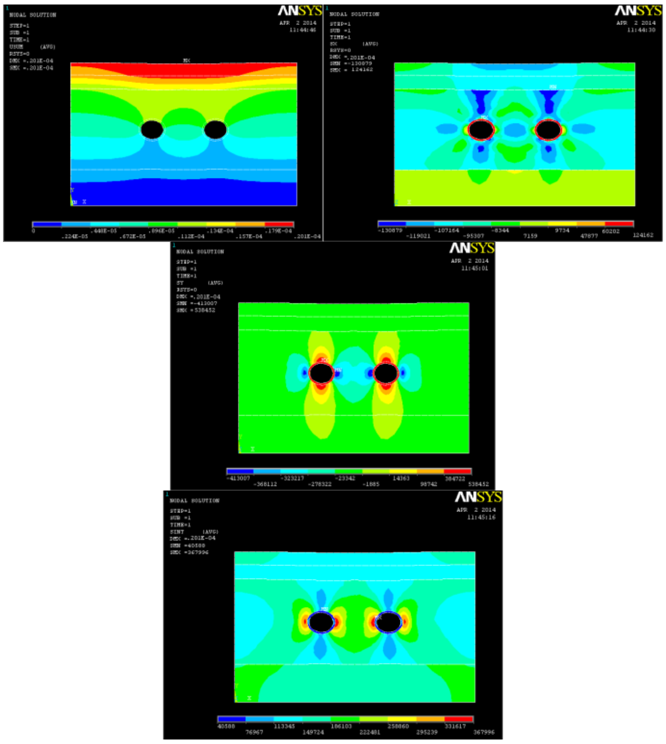


Fig. 3. Displacement, Radial stress, Tangential stress and Stress intensity images for 2D twin tunnel with lining

Three types of analyses are carried out for static loads.

- Effect due to gravity
- Effect due to gravity and hydrostatic pressure
- Effect due to gravity, hydrostatic pressure and live load due to traffic movement

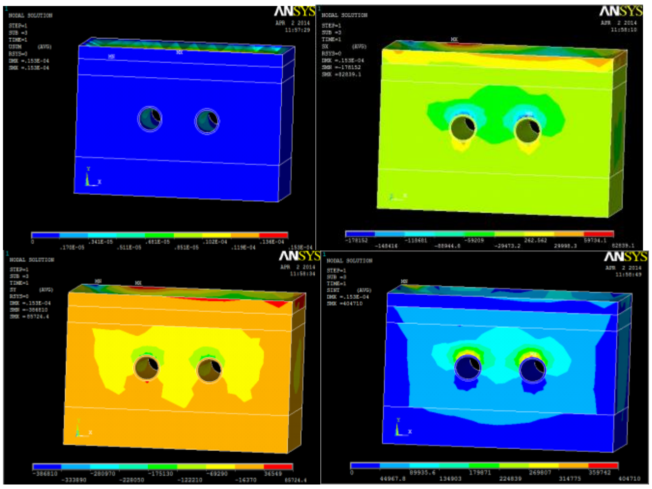


Fig. 4. Displacement, Radial stress, Tangential stress and Stress intensity images for 3D twin tunnel with lining

TABLE II. STATIC LOADS ON TWIN TUNNEL WITH LINING

Results for 2D twin tunnel with lining	**Gravity**	**Gravity + Hydrostatic**	**Gravity + Hydrostatic + Live load**
Max. Displacement (m)	0.967X10^{-6}	0.195X10^{-4}	0.201X10^{-4}
Max. Radial stress (N/m2)	376.605	123538	124162
Max. Tangential stress (N/m2)	432.149	526494	538452
Max. Stress intensity (N/m2)	24917	359986	367996
Results for 3D fully bored twin tunnel with lining (30m section)	**Gravity**	**Gravity + Hydrostatic**	**Gravity + Hydrostatic + Live load**
Max. Displacement (m)	0.671X10^{-6}	0.150X10^{-4}	0.155X10^{-4}
Max. Radial stress (N/m2)	3812.86	87888.9	89469.9
Max. Tangential stress (N/m2)	3699.42	87293.8	89069
Max. Stress intensity (N/m2)	16493	448020	462802

VII. VALIDATION OF ANSYS FOR DYNAMIC ANALYSIS

Huabei Liu et al (2009) analyses a finite element model which was referred for numerical validation. Keeping a twin tunnel in New York City (Ghaboussi et al 1983) as a reference, a finite element model was constructed on the ANSYS. The two tunnels buried 9m underground, with a simplified inner diameter of 5m each, were noted to be 8 m apart with respect to their centers. The model was extended to 50m in the longitudinal direction, having length and height as 100m and 50m respectively. The unit weight of the soil considered was 18.9KN/m3. The materials and its properties were used in the model from the same reference. A cast iron lining was provided to the tunnel model with a young's modulus and a Poisson's ratio of 1.4e5MPa and 0.2. A 50 Kg TNT was considered to induce the blast pressure on the first segment of the tunnel section. Load steps derived from the above graph by extrapolation for the ANSYS Model.

The von mises stress graph of reference paper was compared with those results obtained in ANSYS and a graph for it was plotted. From the below image it is clearly proved that the simulation of blasting effect for 50kg TNT using ANSYS is exactly matching with those results from ABAQUS and can be used for progressing further into this topic.

TABLE III. TIME-VARYING PRESSURES FOR 50KG TNT BLAST

Time in seconds	**Pressure in MPa**
0.005	3.33
0.009	6.67
0.01	10
0.013	9
0.058	7.5

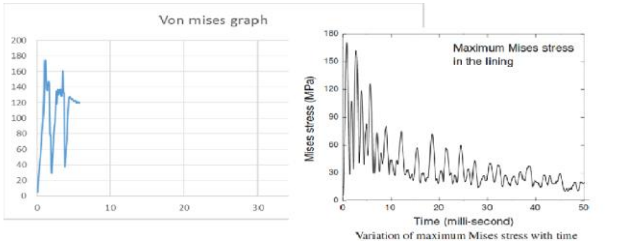


Fig. 5. Comparison of Von Mises graph obtained from ANSYS and example problem

VIII. BLAST EFFECTS ON BANGALORE UNDERGROUND METRO TWIN TUNNEL

With increase in terrorist attacks in the present day, it is not only interesting to study the significant damage caused by explosives, but also essential to understand its consequences on structures. The impact of TNT blast on underground structures using transient analysis in ANSYS is studied for 30kg TNT along with static in-situ stresses and live load due to traffic. PLANE42 element is chosen for 2D analysis and SOLID65 element type is adopted for 3D analysis. The time loads are specified in separate LS files and solved together. Analysis includes both positive and negative phase (suction phase). But the suction phase is not taken into account here. The blast pressure is uniformly distributed on the outer lines of the tunnel face. The blast pressure increases gradually and reaches the peak at 1 millisecond as soon as the blast is initiated. Then it gradually reduces and becomes nil at about 8.2 milliseconds. The 30m longitudinal volume is split into 2 parts of 1m and 29m sections and the blast pressure is applied on the 1m section. The images for blast loads at various time instances for 2D and 3D twin tunnel with lining is given below.

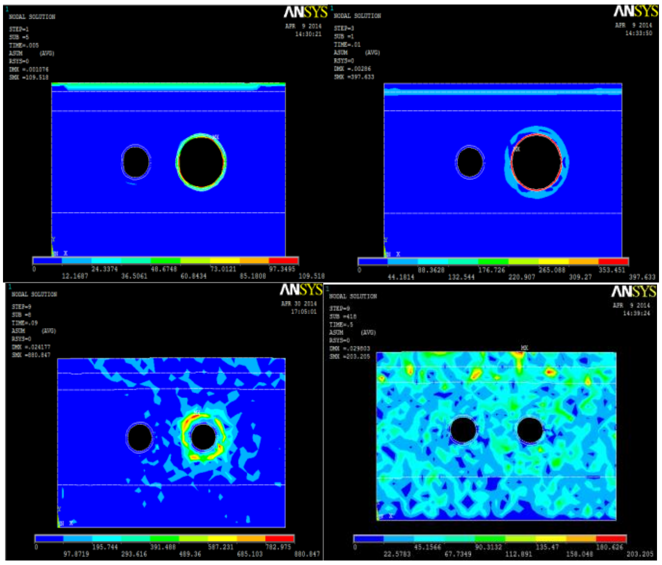


Fig. 6. Acceleration images of 2D twin tunnel with lining at 0.5ms, 1ms, 9ms and 50ms.

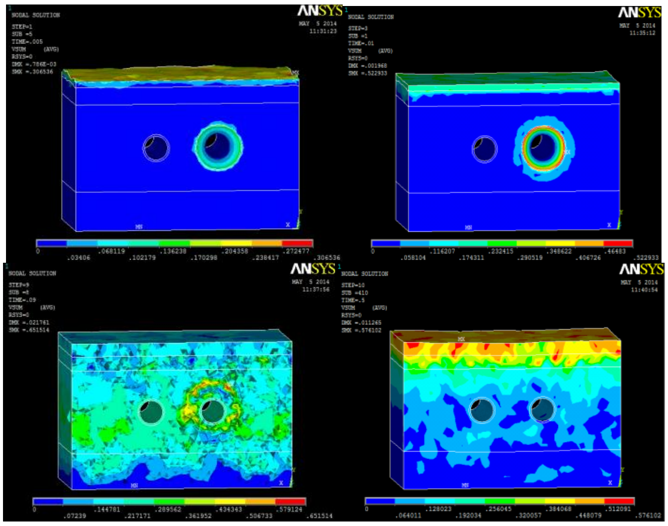


Fig. 7. Velocity images of 3D twin tunnel with lining at 0.5ms, 1ms, 9ms and 50ms.

TABLE IV. BLAST EFFECTS ON 2D TWIN TUNNEL WITH LINING

RESULTS	0.5 ms	1 ms	9 ms	50 ms
2D Twin tunnel with lining				
Max. Displacement (m)	0.001	0.0028	0.0241	0.0298
Velocity (m/s)	0.3046	0.7479	0.988	0.4689
Acceleration (m/s^2)	109.518	397.633	880.847	203.205
Max. Radial stress (N/m^2)	0.112×10^8	0.295×10^8	0.539×10^7	0.658×10^7
Max. Tangential stress (N/m^2)	0.112×10^8	0.295×10^8	0.276×10^7	0.104×10^7
Max. Stress intensity (N/m^2)	0.131×10^8	0.355×10^8	0.238×10^8	0.293×10^8
Max. Von Mises stress (N/m^2)	0.122×10^8	0.330×10^8	0.213×10^8	0.264×10^8

TABLE V. BLAST EFFECTS ON 3D TWIN TUNNEL WITH LINING

RESULTS	0.5 ms	1 ms	9 ms	50 ms
3D Twin tunnel with lining				
Max. Displacement (m)	0.0078	0.0019	0.0217	0.0112
Velocity (m/s)	0.3065	0.5229	0.6515	0.5761
Acceleration (m/s^2)	74.641	313.213	557.943	123.457
Max. Radial stress (N/m^2)	0.776×10^7	0.192×10^8	0.639×10^7	0.397×10^7
Max. Tangential stress (N/m^2)	0.8×10^7	0.200×10^8	0.435×10^7	0.131×10^7
Max. Stress intensity (N/m^2)	0.109×10^8	0.277×10^8	0.450×10^7	0.320×10^7
Max. Von Mises stress (N/m^2)	0.958×10^7	0.244×10^8	0.411×10^7	0.296×10^7

We can clearly see from the images that the neighboring tunnel also deforms even if lining is provided. The longitudinal effect of 30kg TNT blast will travel more than 20m. When the analysis was performed for 30kg, 50kg and 75kg TNT blast, it showed that Bangalore underground metro with lining failed at 75kg TNT. Thus, a sufficient thickness of lining should be provided for safety from blasting failure due to terrorist attack. A very large boundary condition is required on either side of the tunnels such that the effect experienced at the boundary is nil. It is noticed that the blast load is absorbed by the soil and the ground surface will be severely affected in case of shallow tunnels. The von mises graph with a time duration of 50 milliseconds obtained for the full blasting effect is shown below for our reference.

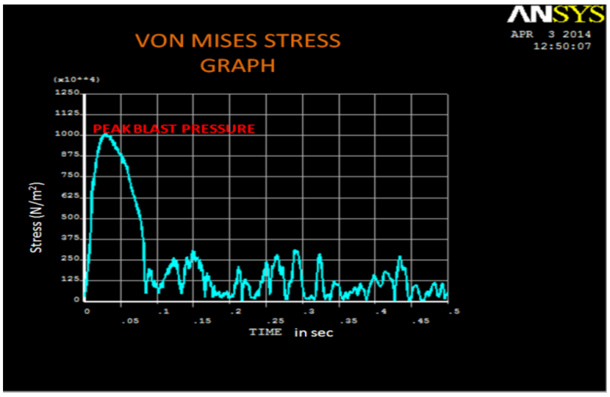


Fig. 8. Von Mises graph for 30kg TNT blast

IX. CONCLUSION AND RECOMMENDATIONS

The effect of improper boundary condition may affect the analysis to a great extent. A full transient analysis includes many types of nonlinearities which require an iterative solution at each point of time known as equilibrium iterations. Smaller time steps helps to converge and solve the iterations quickly. But, nonlinearities such as plasticity, creep and friction are non-conservative in nature which is complex to solve. Seismicity induced due to the blast may affect the foundation of the nearby buildings if it is a shallow tunnel. This should be taken care in the designing stage itself. Dynamic transient analysis for blast effect includes modeling for both positive and negative phase of the blast. But the suction or negative phase is not considered here because it is very complex to model. The tunnel deformations for 30kg TNT blast is analyzed with a peak blast pressure of 6MPa. Apart from this, excessive heat may be generated during blasting and the temperature may rise drastically more than 1000C. This may also lead to tunnel failure and should be included in the calculation. Finer the meshing, the more accurate will be the results obtained and time taken to solve also increases in ANSYS. One of the major limitations of this software is that it takes enormous amount of time to solve a simple geometry in dynamic analysis. Moreover, the accuracy in results for practical field problems is greater in ANSYS when compared with other finite element softwares.

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