SAFETY IN NUMBERS

ANSYS Autodyn helps to determine effectiveness of alternative transit tunnel security measures.

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Terrorist attacks on transit tunnels in Madrid, London, Moscow, and other cities have resulted in enormous cost in loss of life, injuries, property damage, and economic consequences. A blast in a transit tunnel is particularly dangerous because of the confined underground space and the potential for ground collapse, as well as water entry into the tunnel (if it is constructed under a body of water). Parsons Brinckerhoff used ANSYS Autodyn to perform three-dimensional coupled Euler–Lagrange (fluid–structure interaction) nonlinear finite element blast analysis to simulate explosions in a generic transit tunnel and predict the potential damage. Engineers analyzed the effectiveness of conventional protective measures, such as increasing the thickness of concrete lining or the amount of reinforcement steel, versus alternative protection measures to reduce damage to the lining and determine costs. As transportation agencies or authorities balance multiple demands, this information can assist in the decision-making process.

The Federal Highway Administration (FHWA) and the American Association of State Highway and Transportation Officials (AASHTO) formed a Blue Ribbon Panel on Bridge and Tunnel Security after the terrorist attacks in the United States in 2001. The Panel identified more than 200 transit tunnels in the United States. Many of these tunnels serve transit systems carrying millions of passengers daily. Transit tunnels can be attractive terrorist targets because of easy accessibility, the presence of large concentrations of people, and the potential for costly damage to infrastructure and disruption of economic activity.

Photo courtesy Parsons Brinckerhoff

▲ Inside a transit tunnel

Parsons Brinckerhoff used ANSYS Autodyn blast analysis to simulate explosions in a generic transit tunnel and predict potential damage.

To improve the safety and security of infrastructure facilities, Parsons Brinckerhoff performed extensive in-house research [2] and developed a systematic approach named TARIF [3]. This approach has five steps and has been applied to the design of several tunnels and underground facilities.

Examples of Terrorist Attacks on Transit Systems [1]

Date	Location	Attack	Losses
December 29, 2013	Volgograd, Russia	Suicide bomb detonated at train station	Fatalities, injuries and structural damage in all cases
March 29, 2010	Moscow, Russia	Double suicide bombing at two subway stations	
July 7, 2005	London, UK	Four explosions on public transit network	
March 11, 2004	Madrid, Spain	10 explosions on commuter train system	
February 6, 2004	Moscow, Russia	Bombing in subway station	

BASE CASE STUDY

Explosive charge weight and stand-off distance are two important parameters used to define a blast threat. The charge weight is usually measured in equivalent pounds of TNT, and the stand-off distance is the distance from the charge's center of gravity to the bearing surface of the structure. A backpack bomb with a conservative estimate of 100 pounds of TNT and a stand-off distance of 2 feet was selected as a reasonable potential threat for this study.

The generic transit tunnel was modeled with a precast concrete segmental lining that is 11 inches thick and has an internal diameter of 20 feet. Neighboring segments are connected by radial bolts; adjacent rings are connected by steel dowels.

Parsons Brinckerhoff engineers selected the Jones–Wilkins–Lee equation of state for high explosives within Autodyn to model the detonation wave that propagates through the unreacted material and transforms the explosive into detonating products. The RHT strain-rate-dependent concrete model was used to model the extent of damage to concrete materials under explosive loads. The STEEL 4340 model from the Autodyn material library was used to model the steel rebar, plate, bolts and dowels. This material model uses the Johnson–Cook strength model, which represents the strength behavior of metals subjected to large strains, high strain rates and high temperatures. The Drucker–Prager strength linear model was used to represent the behavior of soils and rocks.

Engineers analyzed the effectiveness of protective measures to reduce damage to the lining and determine costs.

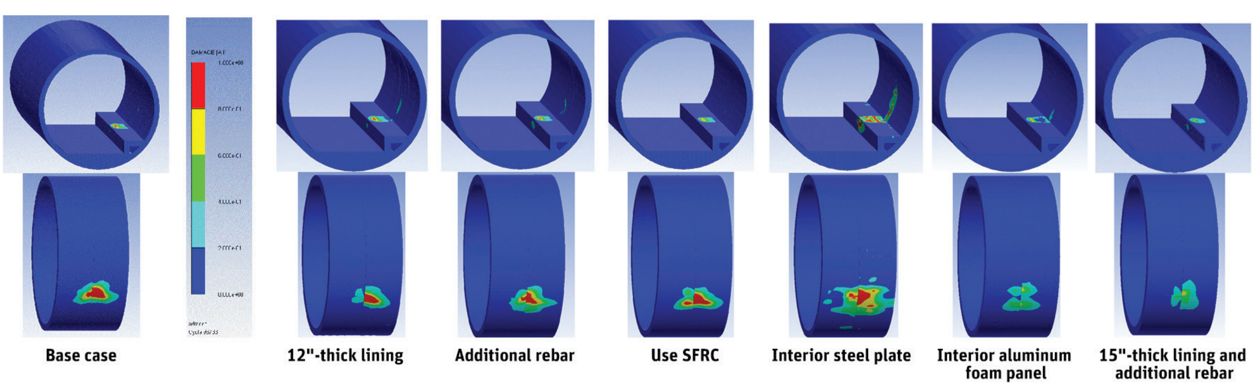
The simulation incorporated nonlinear dynamics, large strains and deformations, fluid–structure interactions, explosion, shock and blast waves, contacts, and interactions among structures. In the base scenario, the simulation predicted that an area in the lining of about 2.6 square feet would suffer severe damage.

PROTECTIVE MEASURES SIMULATION

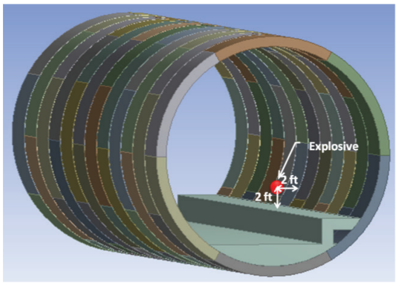
Parsons Brinckerhoff engineers considered several different protective measures in the cost-effectiveness study [4]. The first was increasing the tunnel lining from 11 inches to 12 inches. Compared to the base case, the damage was reduced by 35 percent to 1.7 square feet. The cost of the lining increased by 5 to 10 percent.

The second measure considered was to double the number of steel reinforcing bars. The damage to the tunnel lining in this scenario was reduced by 45 percent, relative to the base case, to 1.4 square feet. The cost of the lining was estimated to increase approximately 20 to 40 percent compared to the base scenario.

The third protective measure consisted of using steel-fiber–reinforced concrete (SFRC) with a dosage of 80 pounds of steel



▲ Damage simulation for all six protection measures. Blue indicates undamaged and red indicates fully damaged.



▲ **Finite element analysis model**

Protection Measure	Damage Reduction (%)	Lining Cost Change (%) Increase +; Saving –
Increase thickness of tunnel lining to 12 inches	35	+5 to +10
Double number of reinforcing bars	45	+20 to +40
SFRC	14	–15 to –20
Add steel plate	Not effective	+30 to +35
Aluminum foam panel	99	approximately+250
Increase thickness of tunnel lining to 15 inches and reduce rebar spacing	99	approximately +100

▲ **Cost and effectiveness of tunnel protection measures considered.**

fiber per cubic yard of concrete for the tunnel lining and interior structures. SFRC was modeled with a smeared model in which steel fibers were assumed to be uniformly distributed throughout the concrete elements. Based on information from literature, it was assumed that the steel fibers increased the strength and improved the ductility for the concrete members with corresponding steel fiber dosage. The damaged area was reduced to 2.3 square feet, 14 percent lower than the base case. Based on data from similar tunnels using SFRC, engineers estimated that this approach would cost about 15 to 20 percent less than the base case due to reduced labor and simplified manufacturing process.

The investigation demonstrates a major advantage of engineering simulation: to find the right balance between cost and safety.

Another measure considered was bonding a 1-inch-thick steel plate to the tunnel wall. The simulation showed that the concrete lining suffered more damage compared to the base case. This model demonstrated that the 1-inch plate did not provide substantial impact energy absorption and that the impact of the plate on the lining increased the destructiveness of the blast. The plate could increase the cost of the lining by 30 to 35 percent.

Parsons Brinckerhoff engineers looked at applying a 4-inch-thick aluminum foam panel, with a sandwich structure consisting of two metallic cover sheets and an aluminum foam core, to the bearing face of the inner lining for high-impact energy absorption. This study used the P-alpha compaction model to describe dynamic compaction of the foam panel. The simulation showed that porous foam is an effective shock attenuator. Damage to the lining was reduced by more than 99 percent compared to the base case. On the other hand, the addition of the foam panel could increase the cost of the lining by 250 percent.

The last protective measure considered in this study was to increase the thickness of the concrete lining to 15 inches and reduce the spacing of the reinforcing steel bars. This protective measure also reduced the damage to the lining by about 99 percent. The cost of the tunnel lining, including the additional excavation, increased by 100 percent.

Simulation reveals that it is possible to reduce the blast impact to the structure of the tunnel to almost nothing, for example by bonding an internal aluminum porous panel, but the cost is high and can be affordable for critical structures only. However, a conventional measure, such as an increase in the lining thickness with design optimization using steel rebar can also significantly reduce the damage at a smaller cost increase. This kind of information is valuable to those setting safety guidelines. The investigation demonstrates a major advantage of engineering simulation: to find the right balance between cost and safety, especially when applied to problems that are difficult or costly to study experimentally.

RE-ENGINEERING WITH CONFIDENCE: THE CRITICAL ROLE OF PHYSICS-BASED SIMULATION
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