Final Report

Possibility of Sidewall Collapse of Underground Structures due to Loss of Lateral Support under Internal Blast Loading

Performing Organization: City University of New York (CUNY)

March 2014

University Transportation Research Center - Region 2

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The UTRC was established in order to support research, education and the transfer of technology in the field of transportation. The theme of the Center is "Planning and Managing Regional Transportation Systems in a Changing World." Presently, under the direction of Dr. Camille Kamga, the UTRC represents USDOT Region II, including New York, New Jersey, Puerto Rico and the U.S. Virgin Islands. Functioning as a consortium of twelve major Universities throughout the region, UTRC is located at the CUNY Institute for Transportation Systems at The City College of New York, the lead institution of the consortium. The Center, through its consortium, an Agency-Industry Council and its Director and Staff, supports research, education, and technology transfer under its theme. UTRC's three main goals are:

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The research program objectives are (1) to develop a theme based transportation research program that is responsive to the needs of regional transportation organizations and stakeholders, and (2) to conduct that program in cooperation with the partners. The program includes both studies that are identified with research partners of projects targeted to the theme, and targeted, short-term projects. The program develops competitive proposals, which are evaluated to insure the mostresponsive UTRC team conducts the work. The research program is responsive to the UTRC theme: "Planning and Managing Regional Transportation Systems in a Changing World." The complex transportation system of transit and infrastructure, and the rapidly changing environment impacts the nation's largest city and metropolitan area. The New York/New Jersey Metropolitan has over 19 million people, 600,000 businesses and 9 million workers. The Region's intermodal and multimodal systems must serve all customers and stakeholders within the region and globally.Under the current grant, the new research projects and the ongoing research projects concentrate the program efforts on the categories of Transportation Systems Performance and Information Infrastructure to provide needed services to the New Jersey Department of Transportation, New York City Department of Transportation, New York Metropolitan Transportation Council , New York State Department of Transportation, and the New York State Energy and Research Development Authorityand others, all while enhancing the center's theme.

Education and Workforce Development

The modern professional must combine the technical skills of engineering and planning with knowledge of economics, environmental science, management, finance, and law as well as negotiation skills, psychology and sociology. And, she/he must be computer literate, wired to the web, and knowledgeable about advances in information technology. UTRC's education and training efforts provide a multidisciplinary program of course work and experiential learning to train students and provide advanced training or retraining of practitioners to plan and manage regional transportation systems. UTRC must meet the need to educate the undergraduate and graduate student with a foundation of transportation fundamentals that allows for solving complex problems in a world much more dynamic than even a decade ago. Simultaneously, the demand for continuing education is growing – either because of professional license requirements or because the workplace demands it – and provides the opportunity to combine State of Practice education with tailored ways of delivering content.

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UTRC's Technology Transfer Program goes beyond what might be considered "traditional" technology transfer activities. Its main objectives are (1) to increase the awareness and level of information concerning transportation issues facing Region 2; (2) to improve the knowledge base and approach to problem solving of the region's transportation workforce, from those operating the systems to those at the most senior level of managing the system; and by doing so, to improve the overall professional capability of the transportation workforce; (3) to stimulate discussion and debate concerning the integration of new technologies into our culture, our work and our transportation systems; (4) to provide the more traditional but extremely important job of disseminating research and project reports, studies, analysis and use of tools to the education, research and practicing community both nationally and internationally; and (5) to provide unbiased information and testimony to decision-makers concerning regional transportation issues consistent with the UTRC theme.

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16. Abstract

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Possibility of Sidewall Collapse of Underground Structures due to Loss of Lateral Support under Internal Blast Loading

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Abstract:

For some immersed tube tunnels, the horizontal slab contributes to the structural integrity. If a train running on the slab were subjected to an explosion, which then failed a large area of the horizontal slab, the sidewall might yield under the lateral earth and water pressures. In this study, a three-dimensional Finite Element (FE) model was established to analyze the problem. The dimension and structural characteristics of the model tunnel was taken from a published literature. Three different failure scenarios were analyzed to investigate the risk of side wall collapse. It was found that for a well-designed immersed tube tunnel with sufficient lining thickness and reinforcement, the possibility of sidewall collapse is very small.

Keywords: Underground structure; Blast loading; Loss Lateral Support; Finite Element Method

Introduction

Underwater tunnels connecting Manhattan and the surrounding regions are crucial to New York City. Consequently, their protection against malicious attack is of paramount importance. Collapse of any of those tunnels might result in flooding of the city for weeks. Some of these tunnels are immersed-tube tunnels, while one particular immersed tube, the East 63rd street tunnel, has a cross-section that consists of four sub-sections, as illustrated in Fig. 1.
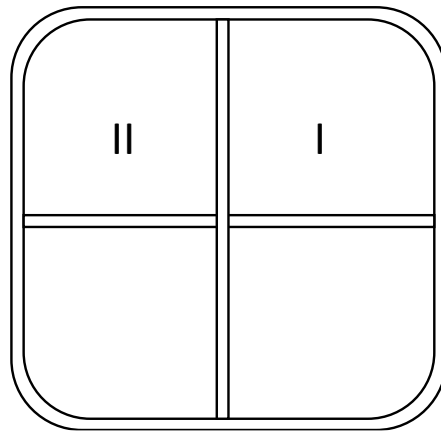

Fig. 1 Illustration of a tunnel with lateral support

The structural integrity of such tunnels depends on the lining, the center wall and the horizontal slab. If a train running in the tunnel-section I or II were subjected to an explosion, which then failed large area of the horizontal slab and also significantly weakened the sidewall, the sidewall might collapse under the lateral earth and water pressures. Due to the fact that if such explosion ever occurred, the train load would also aggravate the progressive failure of the platform, and that the earth and water pressure might be much larger due to dynamic effect, simple calculation using static lateral pressure and simplistic structural analysis would not lead to reliable conclusion.

In this study, a three-dimensional Finite Element (FE) model was established to analyze the problem. The FE model was based on the FE program ABAQUS, which took into account the dynamic effect due to explosion, the possible damage of concrete, the possible yielding and failure of steel, and the dynamic and elasto-plastic response of surrounding soil. The material properties and model dimension was generic, based on publically available information of similar underground structures.

Generic Model Tunnel

The model tunnel has a cross-section as shown in Fig.2, which is based on an immersed tube tunnel discussed in Gursoy (1995). The lining was reinforced with #8 (ϕ25 mm.) rebar at 30 cm spacing longitudinally and #6 (ϕ19 mm.) rebar at 30 cm spacing transversely. The reinforcement layers were assumed to be 5 cm away from the inner surface. The center wall had two layers of reinforcement that had the same rebar layout as the lining. It was assumed that the horizontal slab did not have reinforcement so that it could easily fail under blast loading. The tunnel was encased by a steel shell with a thickness of 9.5 mm.
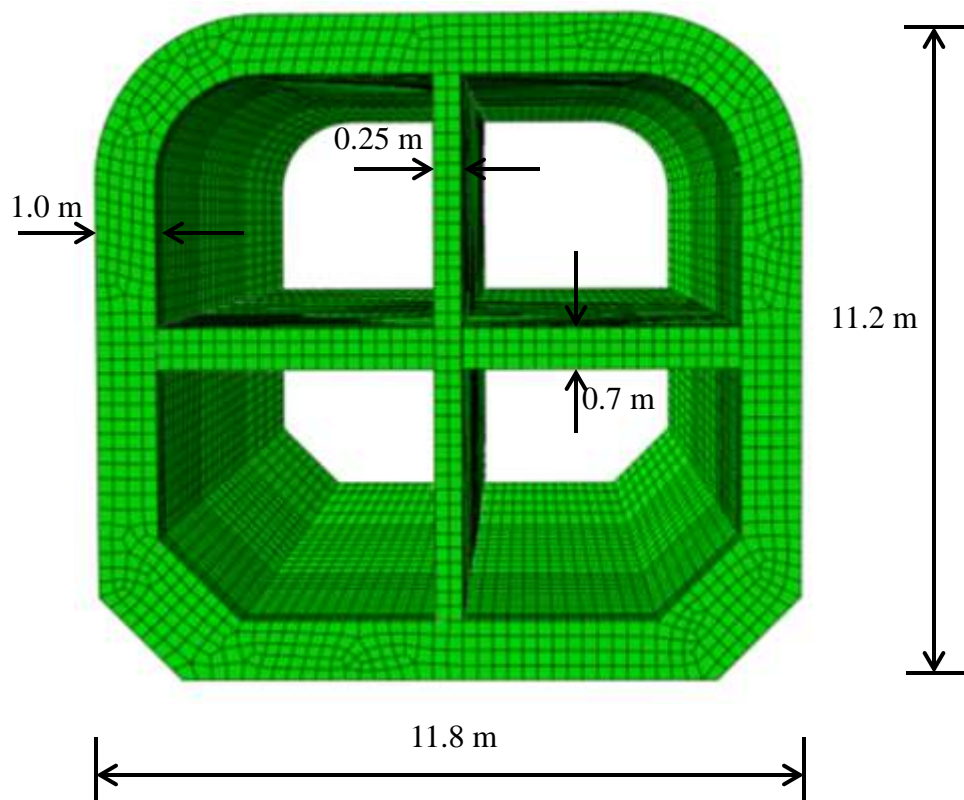
Fig.2 Illustration of tunnel cross-section

The tunnel was assumed to be 29 m below the river bed, while the soil was assumed to be saturated at a unit weight of 22 kN/m^3. The depth of water above the river bed was assumed to be 30 m when the blast occurred, which was converted to a normal pressure of 294 kPa applied on top of the riverbed.

The compressive strength of concrete was assumed to be 32 MPa, while that of steel, including rebar and steel shell, was assumed to be 455 MPa (Grade 60 Steel). The strengths

of concrete and steel were increased in the Finite Element model to take into account the rate effect, as will be discussed in the subsequent section.

Finite Element Model

Considering symmetry in the longitudinal direction, the three-dimensional Finite Element model had a length of 25 m in the longitudinal direction, while large soil domain was used in the model to minimize the boundary effect. Fig. 3 shows the Finite Element mesh. Blast loading was assumed to occur in section I (Fig. 1) of the tunnel and close to the front boundary. The Finite Element model was fixed at the base, while roller boundaries were used on the four sides.
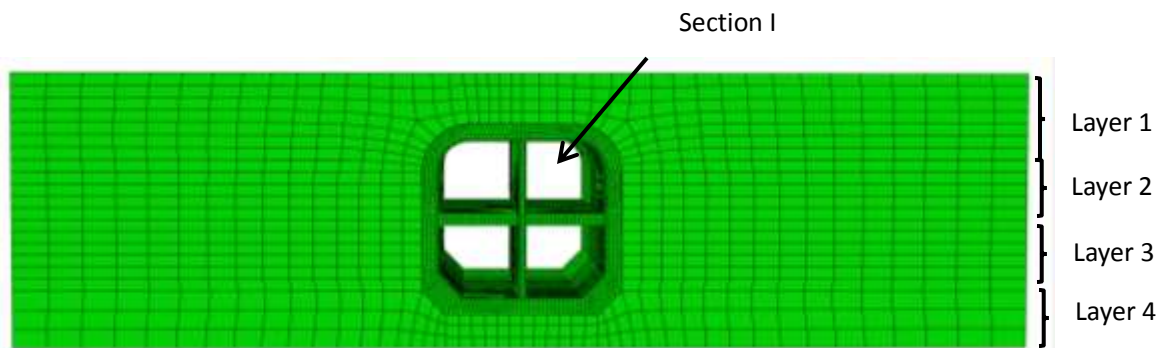
Fig. 3 Finite Element mesh

The concrete materials were simulated using a Concrete Plasticity Model that is available in Abaqus (2004). The compressive strength of the concrete was increased to 34.5 MPa to take into account the rate effect, as recommended by UFC 3-340-02 (2008). The concrete Young's modulus was assumed to be 30.875 GPa, according to UFC 3-340-02 (2008). The tensile strength of the concrete was assumed to be 10% of the compressive one. Fig. 4 shows the idealized concrete behavior under uniaxial compression and tension, respectively. The Poisson's ratio and unit weight of concrete were assumed to be 0.18 and 24 kN/m^3, respectively.

Non-associated flow rule is assumed in the Concrete Damaged Plasticity model, which is defined by a dilatancy angle ψ. In this study, the dilatancy angle was assumed to be 30° , which was based on Iqbal et al. (2012) for similar concrete.

Elasto-plastic model following von Mises yielding and isotropic hardening was used to describe the steel shell and steel rebar. Fig. 5 shows the steel behavior in uniaxial tension.

The increase of steel strength due to high-rate loading was based on UFC 3-340-02 (2008).
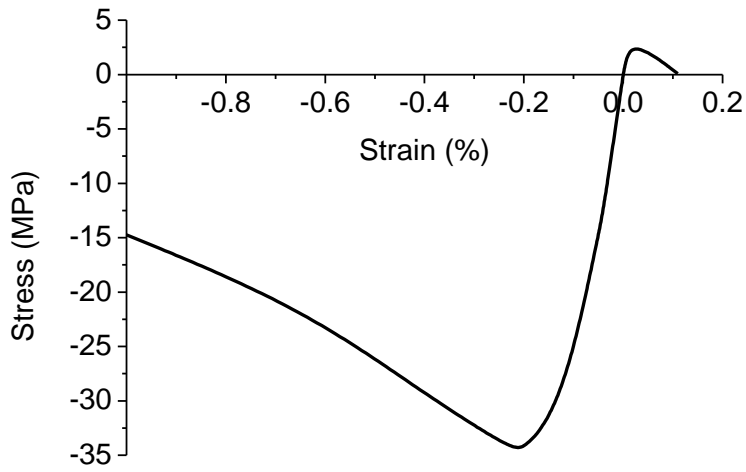
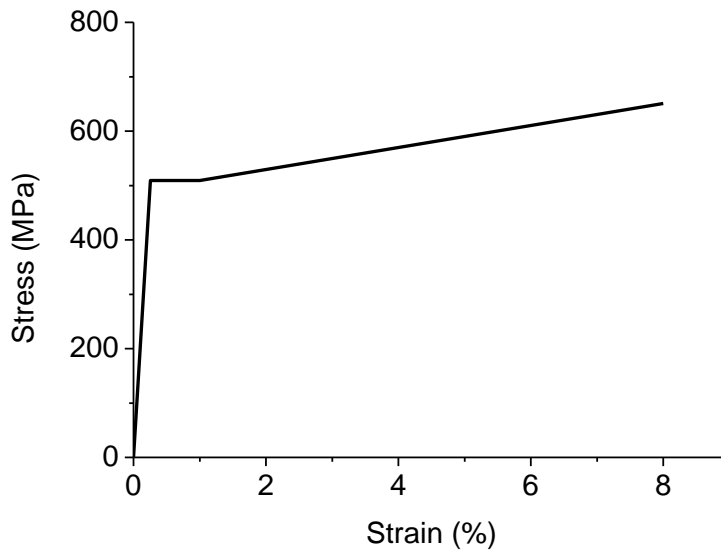Fig.4 Uniaxial stress strain relationship of concrete

Fig.5 Uniaxial stress-strain relationship of steel

The saturated soil was modeled using Drucker-Prager elasto-plastic model. The soil was divided into 4 layers, so that the increase of soil stiffness with depth could be considered in the Finite Element model. Table 1 shows the model parameters of soil, which is based

on the generic values of saturated dense sand. The Poisson's ratio of the saturated soil was assumed to be 0.48, so that the possible compression of saturated soil under large compressive loading could be taken into account (Fragaszy and Voss 1986).

Table 1 Soil properties

Soil layer from top	Layer 1	Layer 2	Layer 3	Layer 4
Thickness (m)	5.8	3.5	3.5	3.4
Modulus of elasticity (MPa)	26	48	60	72
Friction angle (°)	47.5	47.5	47.5	47.5

In the Finite Element analyses, the gravity load and water pressure was applied first, followed by the loading induced by the blast. Explicit dynamic analyses were employed in both steps, hence longer time of analysis and larger damping were employed in the first step so that before the blast loading, the response of the soil-tunnel system had stabilized.

Due to the limitation of the Finite Element model, spalling of concrete due to blast loading was not considered in this study. The spalling simplified as reduction of concrete strength and stiffness in one of the models, as will be discussed in the subsequent section.

Analyzed Cases

In the first stage of this study, explosion of 1000-kg TNT was assumed to occur 1 m above the horizontal slab. The blast pressures on the lining, the slab and the center wall were obtained as per UFC 3-340-02 (2008). It was found that damage to the tunnel mainly occurs in the center wall and the horizontal slab, and the increase of stress in the lining was not significant. Limited area of horizontal slab failed, the size of which is approximately 1 m by 1 m, but it had very small effect on the side wall.

Therefore, in the second stage of the study, the approach of blast loading simulation was not used. Instead, the effect of blast was simulated by sudden failure of horizontal slab.

Three cases were analyzed: 1) the length of slab failure in the longitudinal direction was 6.5 m; 2) the failure of horizontal slab was significant and was removed below section I in Fig. 3; 3) the failure of horizontal slab in Case 2 occurred together with reduction of strength and stiffness of the lining concrete close to section I. Half of the lining concrete was assumed to experience damage with only half of strength and stiffness remaining.

The results of these three cases will be discussed in the subsequent section.

Results

Fig. 6 shows the maximum principal stress of concrete in the tunnel in Case 1. Also shown is the deformation that is enlarged 50 times. The limited failure of horizontal slab induced tensile stress in the concrete lining that was close to the tensile strength, but the damage was rather modest.
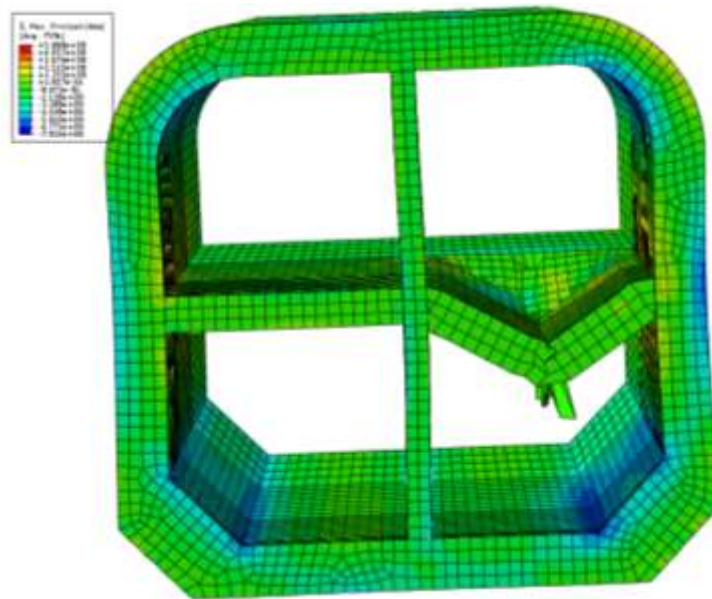
Fig.6 Maximum principal stress in the concrete and deformed mesh of Case 1
(deformation enlarged 50 times)

Fig. 7a shows the maximum principle stress of concrete in the tunnel in Case 2. For this case, large tensile stress that was close to the tensile strength occurred at the upper corner and the middle section that is close to the collapsed horizontal slab. But still the damage was rather modest. Fig. 7b to Fig. 7d shows the maximum tensile stresses in the lining reinforcement, the steel shell and the reinforcement in the center wall. The maximum tensile stresses in the steel elements were smaller than the yield strength of steel.
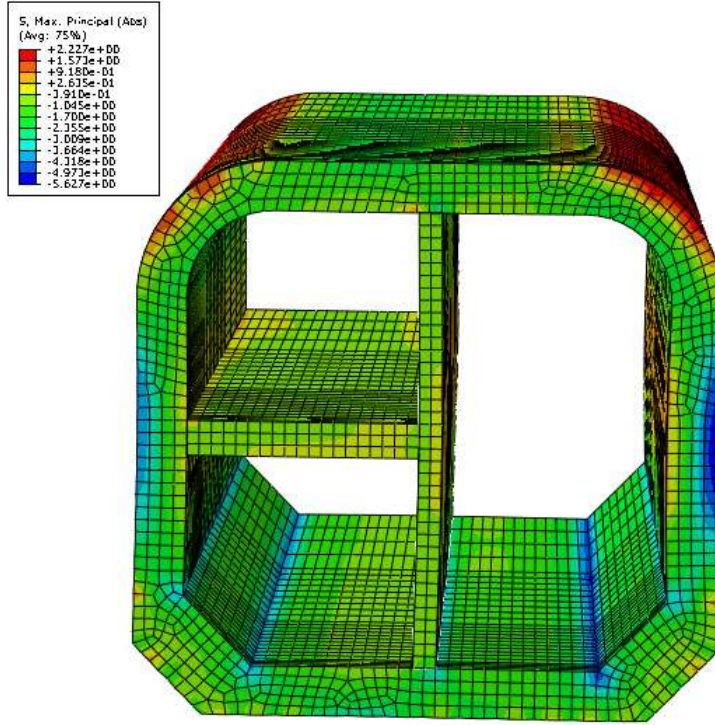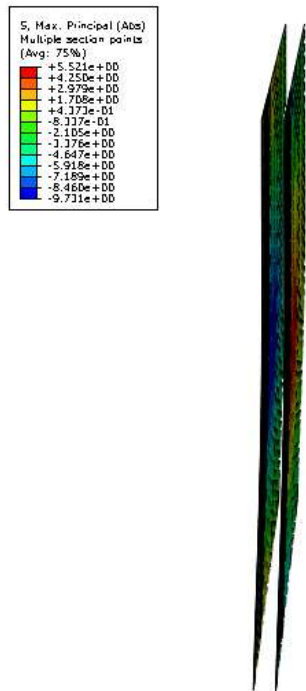
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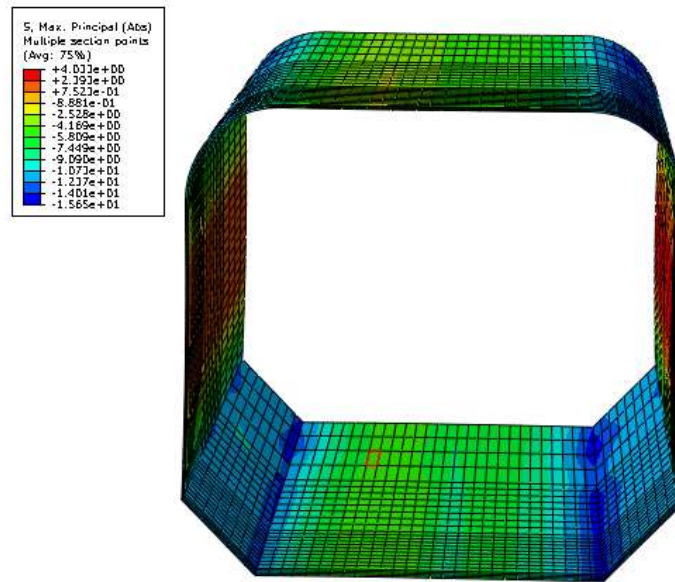
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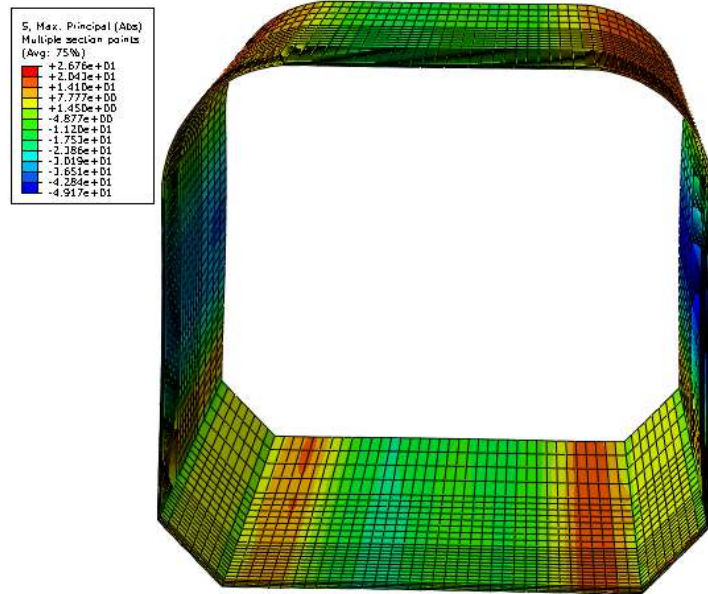
(c)

(d)

Fig.7. Maximum principal stresses in the tunnel of Case 2: (a) concrete; (b) lining reinforcement; (c) steel shell; (d) center-wall reinforcement

Fig. 8a shows the plastic strain of concrete in the tunnel in Case 3. In this case, some failure

of concrete in the lining can be observed, but catastrophic failure of the side wall is not expected. Fig. 8b to Fig. 8d shows the maximum tensile stresses in the lining reinforcement, the steel shell and the reinforcement in the center wall. The maximum tensile stresses in the steel elements were still smaller than the yield strength of steel.

Summary

A generic tunnel with a horizontal slab and a center wall was analyzed for possible collapse of side wall due to failure of the horizontal slab under blast loading. The tunnel model followed one tunnel section that was discussed in Gursoy (1995). It is an immersed tube tunnel including reinforced concrete lining and steel shell. Three extreme cases were analyzed. The analyses showed that even for the most severe case, in which the horizontal slab failed extensively and the side wall lost its support from the slab, the model tunnel could still survive, provided that the concrete and steel in the lining were not significantly damaged.
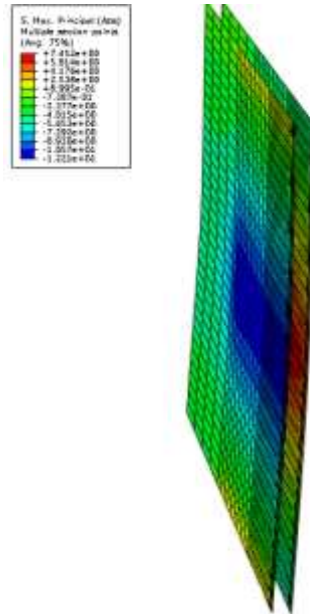
The study shows that the main concern associated with blast loading inside such a tunnel should be on the damage, including concrete spalling and rebar cutting, in the lining. The -loss of support from the horizontal slab is not a concern.
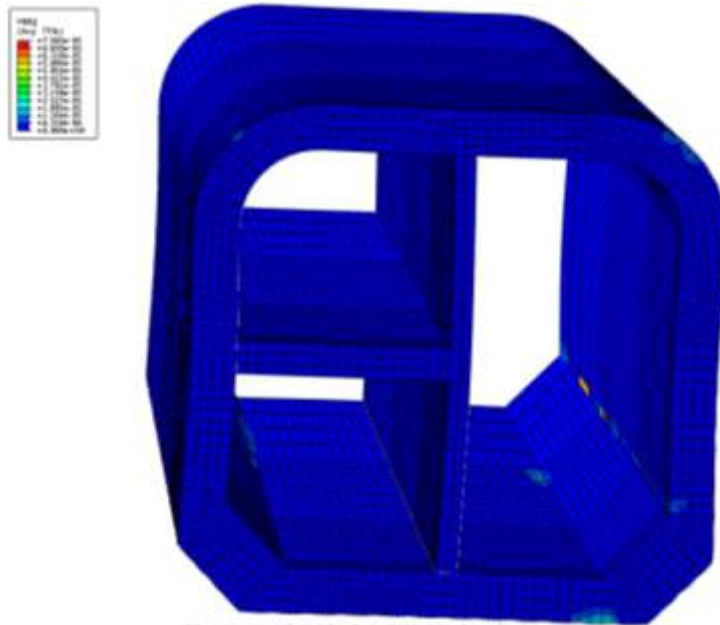
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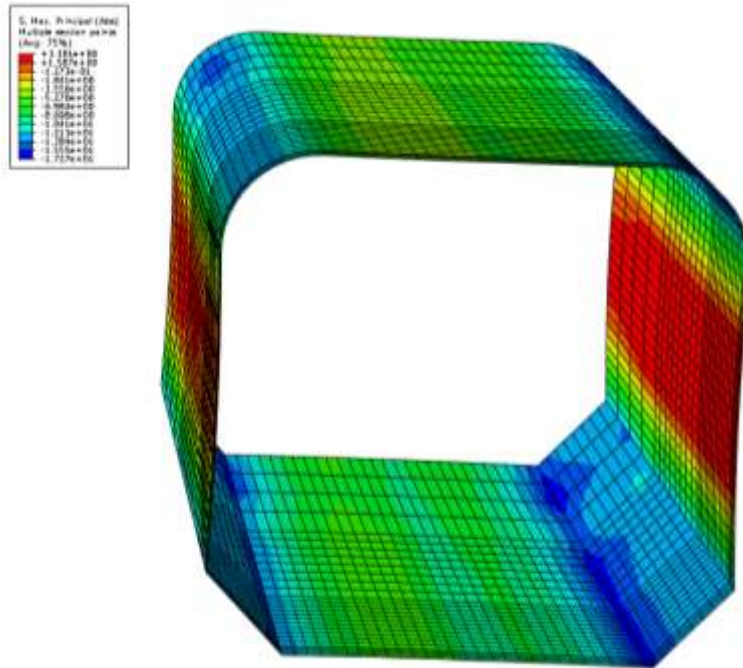
(b)

(c)

Fig.8 Plastic strains and stresses in the tunnel of Case 3: (a) plastic strain in concrete; (b) maximum principal stress in lining reinforcement; (c) maximum principal stress center-wall reinforcement

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