Tunnel Structures subjected to Explosions

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1. INTRODUCTION

In order to evaluate how critical a structure or its elements are, many stages of analysis have to be carried out to lead to an evaluation of the object under consideration.

The first step of analysis is the identification of an essential and relevant threat and the risks arising from this threat for the structure under consideration. An important part of the subsequent risk analysis is the forecast of the extent of the damage to be expected to the structure under consideration or its elements as a result of the defined threat scenario. This event-related damage analysis can then be used to evaluate the risks to the structure concerning loss of load-bearing capacity and residual load-bearing capacity, and appropriate protection measures can be developed if required. The identification of the threat and its risks represent a complex problem right at the start of the analysis, and to help solve this the Terror Event Database (TED) has been developed at the Ernst-Mach-Institut. The database contains a collection of internationally documented events and enables a statistical evaluation regarding the type of structure, type of event and further registered parameters.

Explosions in tunnels have an extremely low probability of occurrence in comparison to other statistically certain events (wind, live loads), but at the same time an enormous damage potential for structure, life and environment. The scenario of explosions with a criminal, terrorist background is additionally subject to further, sometimes subjective, criteria so that the probability of occurrence has to be combined with a plausibility check and therfore a method categorised as deterministic has been chosen for the investigation and evaluation of the possible extent of damage. The following paper presents evaluation procedures in this context for the local and global structural safety of tunnel constructions in the event of explosions. The investigations were carried out by the authors as part of the SKRIBT (protection of critical road infrastructure, bridges and tunnels) and AISIS (automated information acquisition and protection of critical infrastructure in the case of a catastrophe) research projects sponsored by the Federal Ministry for Education and Research (BMBF) and supervised by the VDI Technologiezentrum GmbH.

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2. DEFINITION AND CALCULATION OF EXPLOSION EVENTS

The extent of the loading on structural components and structures from explosion events is mainly determined by the parameters charge quantity and distance of its detonation from the structure under consideration. The peak overpressure resulting from the detonation of contact charges reaches values of many Gigapascals acting for milliseconds, while distance charges typically reach peak overpressure values of the shock wave of many hundreds of kilopascals acting for many hundredths of a second. An initial engineering estimation of the type of loading resulting from a detonation can be obtained by using the so-called scaled distance Z, derived from the similarity laws according to Hopkinson – Cranz [Smi94].

A scaled distance of $Z > 0.5$ acting on flat structures of reinforced concrete elements, for example walls and slabs, leads to a global structural reaction in the form of bending of the element. In contrast, scaled distances of $Z < 0.5$ lead to predominantly shear and punching loading of the structural element. The exact limit value is of course dependent on the strength parameters of the loaded structure. Despite this, the accomplished application of the scaled distance enables a classification of the dominant mode of loading to be expected, which simplifies the choice of analysis tools for the detailed investigation of the influence of the action of the explosion on the integrity of the structural element.

In addition to the testing method at prototype or model scale, modern Finite Element Methods of the "Hydrocodes" class enable an analysis of the loading of the element and structure in which the modelling of the spread of waves in the element is of considerable importance, under the precondition that the short-term dynamic material behaviour is described by adequate material models. Using these complex numerical FEM simulations, complex geometries, discrete reinforcing layers and strengthening layers of metal, polymers or material fibres can be described and the effect of an explosion event on them can be analysed.

Simplified engineering procedures are also available, which enable a rapid analysis of standardised geometries and loading scenarios. The results for the standard geometries mentioned above have been validated with experiments [Geb04]. A differentiation has to be made in this case between engineering procedures for the local loading of an element resulting from shear or punching and the global loading of an element resulting from bending.

Both loading types have to be considered for the analysis of the safety and criticality of tunnels and are described below.

Local loading

Contact detonations or detonations at a very short scaled distance lead to very complex deformation phenomena. An almost discontinuous shock front with peak overpressures in the range of many GPa is introduced into the structure by the explosive. Wave reflections on the side away from the load lead to spalling of the element with flaking on the backside and the ejection of pieces of rubble. In addition, a crater of partially or totally destroyed material is created on the loaded side. If the depth of such a crater on the load side encounters the depth of spalling on the other side, then the element is broken through.

These complex processes are normally no longer possible to analyse for multi-dimensional structures. Their effects can, however, be described by empirical methods for concrete, reinforced concrete and also fibre concrete [Geb04]. The empirically described relationships are given in engineering codes (e.g. XPLOSIM [Geb04]).

It has been shown that good agreement can be achieved between the results of experiments and the calculations of the engineering procedure regarding the extent of the damaged area.

Global loading

The characteristics of the spread of a shock wave in a tunnel space are quite different from a detonation in the open air. The effect on the structural behaviour of the reflected shock wave after an internal detonation is greatly increased. There are multiple reflections, which reduce the sudden fall-off of overpressure typical in the open air and do not lead to a so-called suction phase. Fundamentally, two stages are to be differentiated: the very high peak pressures occurring at the start (many bar) with a short action time and the subsequently occurring gas pressure or the so-called quasistatic pressure, which on comparison to the peak overpressure has less pressure amplitude, but longer duration of action (many 100 ms) [May96, Bak83]. Figure 1 (small diagram) shows a typical pressure-time curve for a detonation in a tunnel

For the evaluation of the global loading and determination of the length of tunnel, which is more than critically loaded with regard to load-bearing capacity, a good estimation can be produced with a so-called pressure-impulse diagram with an iso damage curve.

Starting from an idealised mass-spring system, the behaviour of the structural element can be determined using such diagrams for any combination of peak pressure and loading impulse. If a critical deflection is given as a destruction criterion, this gives a destruction curve as limit value for the destruction of the structural element.

In order to use the pressure-impulse diagram in connection with the iso damage curve for a specific structural element, it is necessary to know the peak overpressure and impulse acting on the structure.

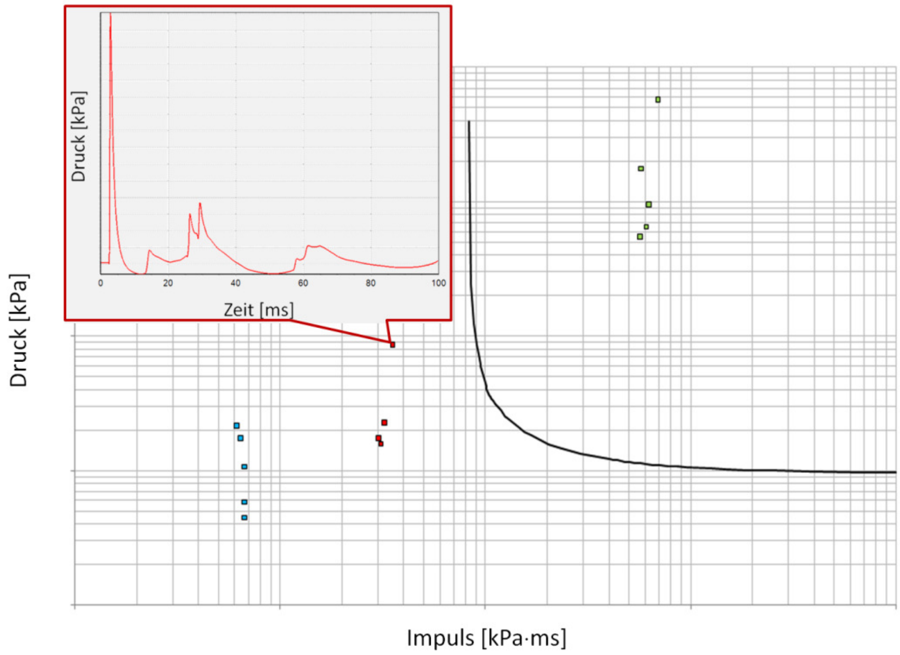

Figure 1: characteristic qualitative pressure-time curve following a detonation inside a tunnel (small diagram) and pressure-impulse diagram for a tunnel wall

For elongated volumes, like for example tunnels, there are a number of successive overlapped pressure waves, which according to [Smi94] run according to 4. This results in longer quasi-static loading. The duration of this quasi-static loading depends on the connecting and ventilation openings to other spaces and the geometry of the space. These values can be calculated for simple rectangular geometries, with the aid of an engineering tool (TUBLAC) developed at the EMI.

The connection of the calculated pressure and impulse values in combination with the destruction curve leads to an evaluation and valuation of the loading on the tunnel structure as shown in diagrammatic form in Fig. 1. If a pressure-impulse tuple lies above the line, then the structural element is destroyed; otherwise there is no destruction.

For more complex geometry and loading scenarios, the local and also the global loading of the tunnel can only be investigated with the aid of model tests and numerical simulations with the FE method. The equation solver of the FE method in this case is based on a so-called

Hydrocode formulation, which provides the simultaneous solution of the conservation equations for mass, impulse and energy, for stationary (Euler) and fixed-body (Lagrange) meshes and their interaction. The numerical simulation can be used in this case to model the global loading through the calculation of pressure and impulse values in a complex geometry as the result of a local detonation. Fig. 2 shows a possible scenario where an explosive charge is detonated directly above the intermediate slab of a tunnel constructed with a shield machine. The pictures show the spread of the shock wave resulting from the detonation, which propagates through the tunnel cross-.section. The pressure ordinates are shown at various times in the air, which are above 0.2 bar of excess pressure. With the aid of these calculated pressure and impulse ordinates, areas can then be determined and evaluated, in which the structural elements are loaded in bending as a result of the local detonation event.

For the case that the global loading of the tunnel does not result from simple bending of the wall and slab elements, but rather from other loading mechanisms, numerical simulation can then be used as well in order to simulate, analyse and evaluate the complete coupled structural reaction to an explosive charge detonated inside the tunnel. In these numerical simulations, the reinforced concrete segments are described with the aid of an RHT material model, the forecast capability of which has been validated in many short-term dynamic applications. For the numerical description of the non-cohesive ground, a material description is used, which has already been used successfully in the field of protection against mines, and whose applicability for the essential range of stresses in this case is currently being investigated through dynamic laboratory tests and their simulation. The simulation model also takes into account the fixed connection of the segments to each other under pressure.

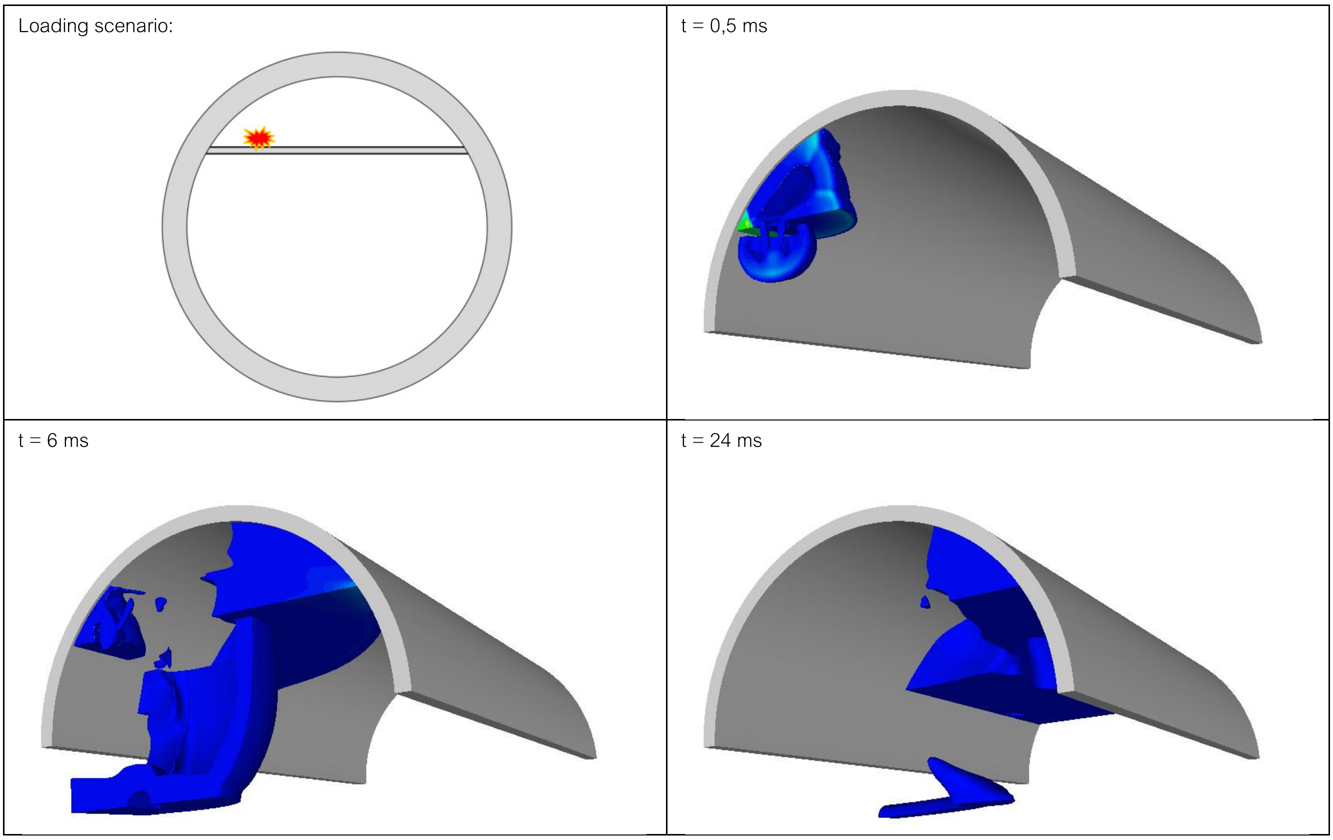

Figure 2: Propagation of the shock wave resulting from a detonation at the intermediate slab of a tunnel

3. EVALUATION OF THE DAMAGE RESULTING FROM AN EXPLOSION

The vulnerability calculation methods presented in chapter 2 provide the basis for the evaluation of tunnel damage. The local breaking-out of concrete can be used for the calculation of the residual structural strength of the overall tunnel cross-section in the form of missing areas or remaining residual cross-sections. A realistic determination of the residual load-bearing capacity of the tunnel cross-section can now be undertaken practically with the aid of the method of physical non-linearity of the construction material (concrete, fibre concrete, reinforcement) and the surrounding ground. The result of the calculation of residual load-bearing capacity can be summarised in the form of a capacity factor γ which is introduced factorizing the internal pressure caused by the explosion scenario.The magnitude of the capacity factor serves simultaneously as a criterion for the evaluation of the global degree of destruction and the robustness of the structure in section. As part of the SKRIBT research project, a five-stage classification has been chosen based on the comparable classification procedure according to e.g. DIN EN 1991-1-7. In contrast to DIN EN 1991-1-7, however, the results, as explained in chapter 1, can only be associated to a limited degree with probabilities of occurrence, but rather are to be interpreted as (deterministic) one-off events, and are to be classified as comparable to an exceptional action according to DIN 1055-100. In addition to the simple evaluation of structural safety, the evaluation of the degree of destruction of a structure serves to derive secondary effects as they affect the user and the operator. For example, the local destruction of a submerged tube tunnel (hole in the tunnel wall or at a joint) may not lead to immediate failure of the entire tunnel cross-section, but may well endanger the users and the rescue services through the immediate ingress of water.

In order to evaluate the global loading occurring at the same time as local destruction (see chapter 2), the non-stationary load-time functions of the shock wave must either be determined directly through a dynamic structural calculation at the level of the structure including consideration of the mass inertia effects and damping factors, or in the form of a equivalent stationary pressure in a structural calculation for the tunnel cross-section. The equivalent stationary pressure can be determined according to the natural frequency of the tunnel cross-section, the relevant action duration of the (positive) impulse phase and the ratio of the plastic to the elastic deformability of the structure. This procedure enables the "engineering" description of the overall structural behaviour of a tunnel cross-section taking into account the essential features of the action and the constraints. Together with the consideration of local damage, this can enable a realistic estimation of the residual load-bearing capacity and the robustness of the structure.

4. MEASURES TO IMPROVE SAFETY IN THE TUNNEL

The investigation of tunnel structures under the influence of exceptional events like explosions leads to the necessity of developing and demonstrating concepts to enable the avoidance of destruction and damage. Various scenarios can, however, lead to conflicts of interest of exceptional explosion and fire events.

Micro- and fibre-reinforced concretes, either as materials in new construction or as a subsequently applied protection layer, increase the overall energy dissipation capacity of a structure, as has already been shown in numerous experimental studies of columns and walls [Sta86, May09]. The effect of the damage resulting from explosion events in tunnel structures can potentially also be reduced by these measures. The fire resistance duration of these concretes is, however, considerably reduced and this can only be compensated through additional measures like the addition of polypropylene fibres [Bo07]. To ensure the suitability of these additional measures, there is a need for further research at the moment to look into the fire protection resistance capability of such high-performance materials.

Classic concepts like the sizing of the structure to resist the effects of explosions and construction in two skins are effective, but it should also be considered whether they are cost-effective, as with the use of newer, explosion-reducing materials. One concept to increase the safety in the event of explosion is the damping of the shock waves caused by an explosion with highly compressible damping layers of moderate compression-strength (polymer concrete with natural fibres), which considerably reduces the loading on the load-bearing structure behind.

Multi-cell and multi-tube construction with regular cross-cuts also leads to significantly increased safety in the case of exceptional events (global redundancy) for the users, rescue services and the tunnel structure overall including the road network above it.

A comprehensive analysis of the effectiveness of measures will be part of the further project work and deliver a foundation for the evaluation of this aspect.

5. SUMMARY

The investigations carried out and described above form the basis for a deterministic procedure for the evaluation of the local and global structural safety of tunnel structures in the event of explosion and enables a technical valuation of measures to improve tunnel safety. The presented investigation procedure offers the possibility of a realistic layout of tunnel structures and determination of the residual load-bearing capacity of existing structures.

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