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EXPLOSION MITIGATION TECHNIQUES IN TUNNELS AND THEIR APPLICABILITY TO SCENARIOS OF HYDROGEN TANK RUPTURE IN A FIRE

V. Shentsov[1], L. Giuliani[2], W. Liu[2] and F. Markert[2]

[1]Ulster University, Newtownabbey, BT37 0QB, UK, v.shentsov@ulster.ac.uk
[2]Civil and mechanical engineering department, Technical University of Denmark, Brovej 118, 2800 Kgs.Lyngby, Denmark, lugi@dtu.dk, weliu@dtu.dk, fram@dtu.dk

ABSTRACT

This paper presents a comprehensive review of existing explosion mitigation techniques for tunnels and evaluates their applicability in scenarios of hydrogen tank rupture in a fire. The study provides an overview of the current state of the art in tunnel explosion mitigation and discusses the challenges associated with hydrogen explosions in the context of fire incidents. The review shows that there are several approaches available to decrease the effects of explosions, including wrapping the tunnel with a flexible and compressible barrier and introducing energy-absorbing flexible honeycomb elements. However, these methods are limited to the mitigation of the action and do not consider either the mitigation of the structural response or the effects on the occupants. The study highlights how the structural response is affected by the duration of the action and the natural period of the structural elements and how an accurate design of the element stiffness can be used, in order to mitigate the structural vulnerability to the explosion. The review also presents various passive and active mitigation techniques, aimed at mitigating the explosion effects on the occupants. Such techniques include tunnel branching, ventilation openings, evacuation lanes, right-angled bends, drop-down perforated plates or high-performance fibre-reinforced cementitious composite (HPFRCC) panels for blast shielding. While some of these techniques can be introduced during the tunnel's construction phase, others require changes to the already working tunnels. To simulate the effect of blast wave propagation and evaluate the effectiveness of these mitigation techniques, a CFD-FEM study is proposed for future analysis. The study also highlights the importance of considering these mitigation techniques to ensure the safety of the public and first responders. Finally, the study identifies the need for more research to understand blast wave mitigation by existing structural elements in the application for potential accidents associated with hydrogen tank rupture in a tunnel.

1.0 INTRODUCTION

Tunnel fire is a worst-case scenario for vehicles with on-board high-pressure hydrogen storage, In case of the TPRD failure to open for emergency release of the onboard high-pressure hydrogen storage tank, the consequences may be a blast wave and fireball providing the main hazards. Therefore, a reliable prediction of the explosion action is paramount, to be able to assess, prevent, and mitigate the effects of such an explosion on the structure and people.

With respect to the former aim, structural safety against accidental actions is obtained by putting in place several independent safety measures, for example:

- Reducing the occurrence of the accidental event: in particular, the occurrence of hydrogen tank explosions can be reduced by reducing the frequency as well as the severity of car accidents in the tunnel (e.g. by means of lower speed limits, the number of cars in the tunnel, better illuminations, larger emergency lanes, and prompt extinguishment systems for fires).
- Reducing the entity of the action (in this case the pressure wave caused by the hydrogen tank explosion), by means of mitigation measures aimed at reducing the intensity of the explosion and the associated blast wave and fireball.
- Reducing the vulnerability of the structure, i.e. by increasing the resistance of the structural elements to the accidental loads, either by increasing the strength or dimension of the single elements or by increasing the continuity of the structural system and thus the stress redistribution among the different structural members or parts. The first measure is often more effective in

tunnels, which typically have a high degree of structural continuity (let's think for example to the bearing walls of a drilled tunnel or the monolithic precast concrete section of a submerged tunnel).

- Reducing the progressive collapse susceptibility of the structure, so that a failure of one structural member or part does not lead to the failure of adjacent members or parts. In the case of tunnels, the collapse of one section of the tunnel should not lead to the collapse of subsequent sections. As for bridges, this requires an interruption of the structural continuity at pre-determined points along the tunnels.

The first two measures are aimed at preventing and mitigating actions. Thus, their implementation is paramount, as it also positively affects the safety of people.

The probability of occurrence of a hydrogen explosion as described above is assumed low, but still steady reductions will improve the low-risk level and the acceptability of hydrogen technologies. There is unfortunately no zero risk, but the major goal is to improve safety continuously by lowering the risk of accidents. Hereunder, there are accidents given a very low probability combined with catastrophic consequences. Such risks may be acceptable, but the consequences in terms of casualties as well as direct and indirect costs due to structural damage, repairs and downtime of the infrastructure are typically very high. Regarding the case of strategic and critical infrastructures e.g., tunnels such interruptions certainly have to be prevented.

In turn, the reduction of the progressive collapse susceptibility requires complex collapse analyses. It is often quite difficult to implement in the case of tunnels, and, although might avoid catastrophic consequences, do not eliminate the costs associated with downtime and repair, which might also be significant.

For the reasons above, the measures deemed more effective and more easily applicable to reduce the risk associated with hydrogen tank explosions in tunnels are the second and third ones. The following review is therefore focused on these two mitigation measures in particular.

Recent studies [1], [2] show the fire safety performance of road tunnels. According to [1] from 1992-2016 only in Australia, there were 78 fire incidents. The second study [2] analyses the database of 156 fire incidents over years in which more than half are due to spontaneous ignition of a vehicle due to various reasons e.g. engine, tyre, fuel leaks, electric problems etc. This confirms the non-zero probability of high pressure hydrogen tank rupture in a tunnel.

2.0 REVIEW OF MODELLING AND MITIGATION OF EXPLOSIONS

The study on the propagation of shock waves in a complex tunnel system [3] revealed that the series of shock waves emerging from the test section into an adjacent tunnel coalesce to form an even stronger wave and that the attenuation of the wave through this typical tunnel geometry is surprisingly small.

Work by Fondaw (1993) [4] has shown the shock mitigating effects of low-density foam. The optimal foam thickness depends on the length of the tunnel and how much shock mitigation is required. About 1.25 kg of C-4 explosive in a 2 m diameter tunnel provided the blast. The tunnel with 10 cm of foam shows over 50% reduction in the peak overpressure compared to the tunnel without foam. The tunnels with 20 and 30 cm of foam show even greater reductions of 70% and 78% respectively. In the plain tunnel, the overpressure exceeds the lung damage threshold (82 kPa) values for about the entire length of the tunnel. But with 10 cm of foam, the overpressure drops below this threshold at around 30 m and with 20 cm of foam it drops below at about after 25 m.

Hager and Naury (1996) [5] predicted the pressure dynamics for a storage chamber, a secondary tunnel, and a primary tunnel inside an underground storage facility; they determined the effects of tunnel length and effect of boundary conditions on peak shock pressures and time duration of pressures and also compared measured and predicted pressure time-histories with the following results:

a. For straight tunnels, the peak pressures attenuated slowly along the length of the tunnel. Responding media modelled by a cylinder in which the chamber and access tunnel are embedded was 7.8 m in radius and 115 m in length located along the tunnel walls causing a minimal change in the predicted peak pressures.

b. For the complex tunnel consisting of different tunnels and chambers, responding media reduced peak pressures by 10 to 30%.

c. Predicted peak pressures by Autodyne exceed the measured pressures by at least 100% in a nearfield meaning the increase reached ten times higher than the measured pressure at junctions, which could be explained by reflected pressures at the tunnel junction.

In the study performed by Smith et al. (1998) [6] a scaled model test of the blast wave propagation along straight tunnels of 50 mm width, 100 mm height and 500 mm length built of 3 mm thick steel plate was conducted. They revealed that the roughness of the tunnel walls has significant effects on the blast wave propagation. It was stated that the introduction of “discrete” roughness elements along the walls of a straight tunnel will produce a greater reduction in blast resultants than if the tunnel is smooth. The attenuation generally increases as the height of the roughness elements increases. For uniformly spaced roughness, the number of elements is closely related to the gap between them. In these cases, height to spacing ratio is an important influence on attenuation. They also cited from [7] that an example of a well-established form of passive attenuator is the incorporation of right-angled bends into a tunnel which will reduce overpressure by 6% for every bend.

The mitigating effect of a water wall on the generation and propagation of blast waves of a nearby explosive has been investigated using a numerical approach [8]. It was shown that the water-to-explosive weight ratio of 1–3 is practical for applications. This amount of water can reduce peak overpressure by about 30–60%.

Sklavounos and Rigas (2006) [9] performed a parametric study of the attenuation effect of the side vents of a branched tunnel, in which a shock wave develops and propagates after an explosion event. They found that with the increase of the number of vents or their diameters, the explosion wave attenuation has increased and hence enhances their protective role.

Finite element simulations have been carried out by Netherlands Organisation for Applied Scientific Research [10] for studying the effect of high rate loadings from a gas explosion and a BLEVE (Boiling Liquid Expanding Vapor Explosion) to see the effect expected on the wall and roof deformations. They used 3 existing tunnels (Caland tunnel consisting of 2 sections WxH=14.45x6.09m each, Drecht tunnel consisting of four 2 lane sections WxH=10.35x4.8 m each and Leidsche Rijn tunnel consisting of two 3-lane sections WxH=16.47x6.45 m each and two 4 lane sections WxH=21.67x6.45 m each) to perform the study to including realistic permanent and distributed loads to the walls and ceilings and properties of materials used in construction. They were looking into wall and ceiling deflections after explosion at loads of 5.13, 6.5 and 4.35 bar respectively for each tunnel. The load increases to a maximum value, where an exponentially decreasing load was assumed afterwards. In each case, the load is reduced to zero at t=160 ms. It was concluded that failure is not occurring for the Caland tunnel, cracking is expected for the Drecht tunnel and Leidsche Rijn tunnel failure may be expected. The report is very useful in terms of the material properties of the concrete and steel used as well as tunnel drawings.

Numerical simulation finite element three-dimensional nonlinear dynamic simulation analysis for an explosion experiment inside a tunnel was carried out in [11] and compared with experimental data. The overpressure peak attenuation formula was derived under different equivalents of TNT masses. Comparison of formula results with experimental results reveals that the overpressure peak can be predicted by the formula achieved in this paper when the scaled distance ($L \cdot m^{-1/3}$) is larger than 1, where L is the distance to the detonation point, and m is the TNT mass.

Kumar et al. (2009) [12] presented an extensive overview of the dispersion and explosion hazards research conducted as part of HyTunnel, together with other published work, and provided a better understanding of the potential hazards associated with hydrogen vehicles in road tunnels. In their study, Pennetier et al. (2012) [13] determined numerically and experimentally the position of this transition zone along the tunnel, when, during the wave propagation and after multiple reflections on the tunnel’s walls, it will behave like a one-dimensional wave using a scaled model.

A blast wave mitigation experimental study with a particulate foam barrier was performed in [14] and they found that particulate foam can reduce the ability of the real blast to cause damage and make it less hazardous.

Later, a numerical study [15] on the arrangement of baffles attenuating blast waves inside tunnels revealed that:

- The arrangement of baffles can reduce the blast wave propagation velocity, delay the blast wave arrival time and reduce the blast wave peak overpressure in the tunnel.
- When only one row of baffles is arranged along the tunnel, it was suggested that the type of symmetrical baffles is better to attenuate the blast wave.
- When two or more rows of baffles are arranged along the tunnel, it was suggested that the type of alternate baffles is better to attenuate the blast wave.
- The relative baffle width b and the relative baffle spacing c have significant effects on attenuating the blast wave, the value of overpressure attenuation ratio a increases with b and decreased with c. It is suggested to take $b>0.5$ and $c<0.5$.

De et al. (2013) [16] investigated numerically the role of compressible protective barriers (made of polyurethane foam) and rigid barriers (made of concrete) in reducing the impact of a surface explosion and showed beneficial effects of both compressible and rigid barriers.

Research of [17] suggested that the light weight but strong drop-down perforated barriers, triggered by a gravity motion detector, could be used to mitigate the effects of the blast wave.

Forecasting research on overpressure in subway tunnels was done in [18]. On the basis of experimental research, they established a calculation model of blast effects in a tunnel. Its applicability has been verified by comparing the numerical results and the experimental findings. Then the blast effects in a subway tunnel have been analysed. It has been found that such factors as the tunnel shape, charge position, and distance to the explosion centre all have a great influence on blast effects. The overpressure of the blast in the subway tunnel is summarized and the formula was also proposed.

Studies [19], [20] numerically investigated the effect of the surface explosion above the buried tunnel on different depths. They were looking into the amount of TNT that can be safely exploded above tunnel surface and the modelling techniques could be useful in the application for the internal explosions too.

A design procedure based on a simplified Finite Element model for underground tunnels subjected to internal explosion and possibly preceded by fire accidents was proposed by Colombo et al [21]. The FE model was tested under static serviceability loads (soil pressure). Once the model has been tested, several dynamic analyses were carried out in order to reproduce the blast scenario in a metro line tunnel of 8.15 m internal diameter. Different material properties were considered in the analysis to conclude that segments made of conventional reinforced concrete and a new solution, in which a layered precast tunnel segment made of different fibre-reinforced cementitious composites, have better performance under static loadings, in the case of fire and subject to an internal explosion.

A series of in-situ tests were carried out in [22] in far field to study the blast mitigation effect of a water filled plastic wall. Test results show that the mitigation effect of water filled plastic wall is remarkable. The numerical simulations were also performed with water wall scaled height and water/structure scaled distance on the overpressure reduction are discussed and analysed.

The behaviour of a full-scale porous Glass Fibre Reinforced Polymer GFRP barrier under blast loads [23] has shown that a porous barrier composed of GFRP pipe elements mounted on a precast concrete showed the capability of the barrier in disrupting the shock wave generated by an explosion and consequently reducing the induced loads on a target placed beyond the barrier. The explosive charge of 4 kg of equivalent TNT explosive was used, and the distances between the charge and the barrier were set at 5 m, 3 m, and 0.5 m, respectively. The total impulse reduction factors of 6% and 25% and pressure reduction of 11% and 36% were experienced in two tests ad distances of 5 and 0.5 m respectively.

A shock wave impact study on open and closed cell foam obstacles was completed in [24] to assess attenuation effects with respect to different front face geometries of the foam obstacles. Five different types of geometries were investigated while keeping the mass of the foam obstacle constant. The front face, i.e., the side where the incident shock wave impacts, were cut in geometries with one, two, three or four convergent shapes, and the results were compared to a foam block with a flat front face. Results from the experiments show no significant difference between the five geometries, nor the two types of foam.

The blast mitigation effect of the foamed cement-base sacrificial cladding for tunnel structures has been investigated experimentally and numerically by Zhao et al (2015) [25]. A comparison is made of the effective stress of the tunnel vault for three structures: without cladding, with a 6 cm thickness of foamed cement-based cladding, and with a 10 cm thickness of foamed cement-based cladding. As shown in Figure 1 for the three structures, the effective stress peak values are 2.49 MPa, 0.52 MPa and 0.25 MPa respectively.

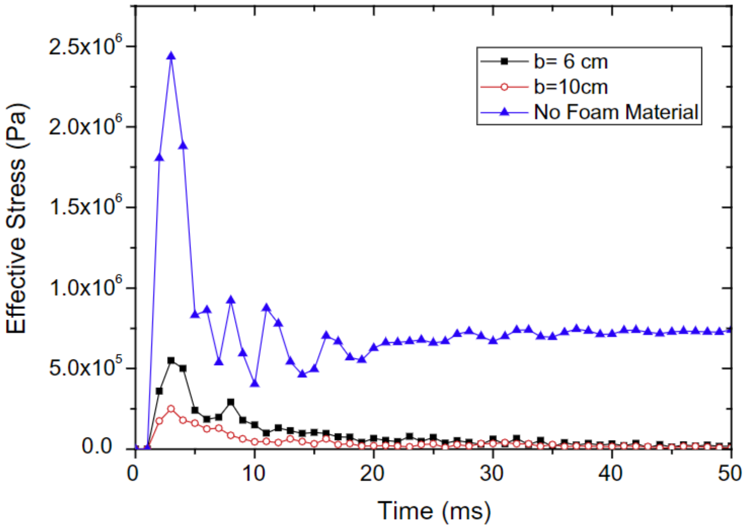

Figure 1. The effective stress of the tunnel structure without, with 6 cm, 10 cm-thickness cladding. Reproduced from [25].

In an experimental study [26] authors found that wall roughness amplifies the maximum impulse in proximity to the blast source, contradicting the generally held belief that wall roughness primarily attenuates the blast wave impulse compared to the smooth walls.

The study on the attenuation of a blast by foam barriers was performed both experimentally and numerically in [27]. Conventional shaving foam was used for making the foam barrier. The density of the samples was ρ≈100 kg/m3, which corresponds to a volume liquid fraction of α=0.1. They found that the overall rate of attenuation was much faster compared to the rate of blast decay in air. In case of single barrier, overall pressure reduction in the range of 86%–96.5% was observed for various configurations. An underlying process responsible for the reduction of peak pressure of the shock wave propagating in foam is the “catching up” of the rarefaction wave with the wavefront, thereby effectively attenuating it. This process is also aided by the very low speed of sound in foam (~40 m/s), providing sufficient time for the rarefaction wave to catch up with the wavefront at shorter distances.

Coupled fluid-structure-interaction study of internal blast resulted from 44 kg of TNT in circular and square tunnels of 5.5 m characteristic size and its effects of underground tunnels in soils [28]. The paper revealed several factors that affects the structural integrity of the tunnel as follows. The stiffer soil around the buried tunnel reduces the structural damage. In the tunnels with low burial depth (low confinement from the ground) lining strain is large and the structure could be damaged. A circular tunnel would be more affected compared to a square one with a height and width equal to the diameter. Location of the charge is also important and has a significant effect, wall location is the worst compared to the centre.

A later work by Colombo et al [29] presents an experimental investigation of an important situation in case of an internal tunnel explosion i.e. the response of panels made of high performance fibre reinforced cementitious composite (HPFRCC) applied to the internal walls of new or existing tunnels. The panels are conceived as a countermeasure for tunnels under blast events; they also improve tunnel performance under fire conditions. In this situation, there is an air interspace between the lining and the applied panels (Figure 2). The panels have limited sizes (0.5–1 9 0.5–1 m) in order to allow easy handling; moreover, they have a limited thickness (20 mm) for cost and space reasons.

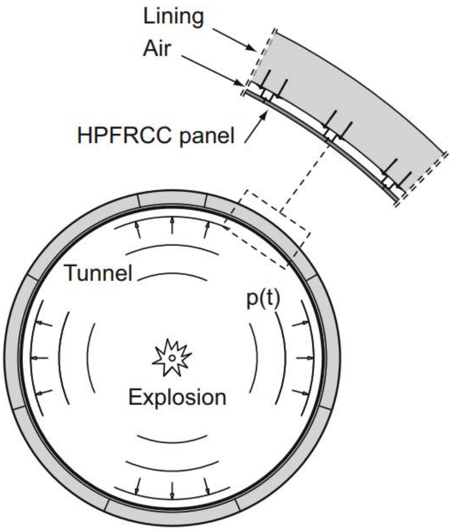

Figure 2. Schematic layout of the HPFRCC panel applied to the intrados of the tunnel. Reproduced from [29].

It was concluded that the experimental tests carried out by means of shock tube on concrete specimens confirm that thin HPFRCC panels could break at blast pressures of 0.3 MPa, with anchor spans of about 40 cm, in case of air space is used to reduce thermal effects on the segment of tunnel. It was observed that the panel failure reduces the acceleration transmitted by 50 %, which means a higher energy dissipation due to plastic strain and cracking of the panel.

Work by Pavan Kumar et al. (2017) [30] shows numerical research on the shock wave propagation through the shock tube and the interaction of the wave with perforated plates. It was demonstrated that the shock wave pressure drops, as it passes through the perforated plates. The percentage pressure drops varied from 43.75% to 26%. Hence, the perforated plates can be used to attenuate shock/blast waves. The effectiveness of blast mitigation with lightweight claddings was also assessed theoretically in [31].

Small scale tests were performed in [32] to study mitigation effect from water in a bag placed inside the tube to reduce the blast wave, caused by an explosion. The blast pressure outside the tube was measured and examined. The results demonstrated that the peak overpressure was mitigated for 33-45% by the water bag. It was concluded that the information obtained from the research can be extensively applied to the explosion in closed places, such as subsurface magazines, underground magazines, and tunnels, for mitigation of blast waves.

Experimental results on shock wave attenuation characteristics of aluminium foam sandwich panels subjected to blast loading in [33] show that the wave attenuation rate on the mild steel structure is only 11.3%, whereas the wave attenuation rate on the sandwich structure can exceed 90%.

A case study on the attenuation characteristics of the blast waves in a long road tunnel was performed by a Chinese group recently [34]. They modified the decay equation proposed in [35] and applied it to the Micangshan highway tunnel in China, by this demonstrating that the field tests in a tunnel for the modified equation is more suitable to describe the attenuation of the blast waves in the tunnel than the original one.

A recent CFD study presented in [36] and [37] simulated the decay of a blast along a tunnel without mitigation measures, they highlighted that the most of energy from the blast is used to demolish the car rather than displace it. Therefore, in order to reduce the blast wave strength in the near field due to loss of mechanical energy of compressed gas, the simulation of vehicle destruction after tank rupture is required and is a subject of ongoing research. The CFD fireball model validation was done in [37] against a stand-alone experiment. The model prediction has shown that the fireball size in the test and simulations of both the size and the shape of fireball are well reproduced. An interesting observation was detected in a tunnel during simulations, which shows a standing (not moving in space) combustion zone at the beginning of the blast up to about 9 ms, contrary to the case of the open atmosphere, when the fireball propagates outwards in all directions.

3.0 EFFECT OF LAYBYS ON THE MITIGATION OF THE BLAST WAVE IN TUNNEL

A CFD simulation study on the effect of laybys on the mitigation of the blast wave in a tunnel has been performed in this paper to assess if the presence of laybys affects the reduction of the overpressure. ANSYS Fluent was used as a computational fluid dynamics (CFD) engine with pressure-based solver, combined with the PISO pressure-velocity algorithm. The numerical model employed involves using large eddy simulation (LES) to handle turbulence, utilizing the Smagorinsky-Lilly for simulating sub-grid scale turbulence, and employing the EDC for combustion with a one-step reaction. The governing equations are derived from the filtered conservation equations for mass, momentum, and energy in their compressible form. The tunnel walls and floor are specified as non-adiabatic to allow heat transfer from the combustion, and no-slip wall conditions are applied. The external non-reflecting boundary is defined as a pressure outlet with zero-gauge pressure. To enhance the accuracy of the simulation for compressible flows, the second-order upwind discretization scheme is used for pressure, while the second order upwind scheme is used for convective terms. Time advancement is carried out using a first-order scheme. In order to conserve the mechanical energy of compressed hydrogen, the simulated tank volume with "ideal gas" is reduced compared to the actual tank volume. This reduction is determined using the equation $V_{ideal} = V_{real} - mb$, where V represents volume (m^3), m is the mass (kg), and $b=7.69\cdot10^{-3}$ is the co-volume constant (m^3/kg). The original time step adaptation technique is employed to maintain a constant Courant-Friedrichs-Lewy (CFL) number of 0.2. All calculations are performed with 20 iterations per time step. The CFD model is based on [37] and full validation and description is given there.

The dimensions of the tunnel and laybys were taken from the Norwegian Road tunnels: standard [38], the tunnel of 500 m length and a hydrogen storage tank of 120 L at 700 Bar located 50 m from the entrance of the double-lane tunnel was simulated and can be seen from Figure 3.

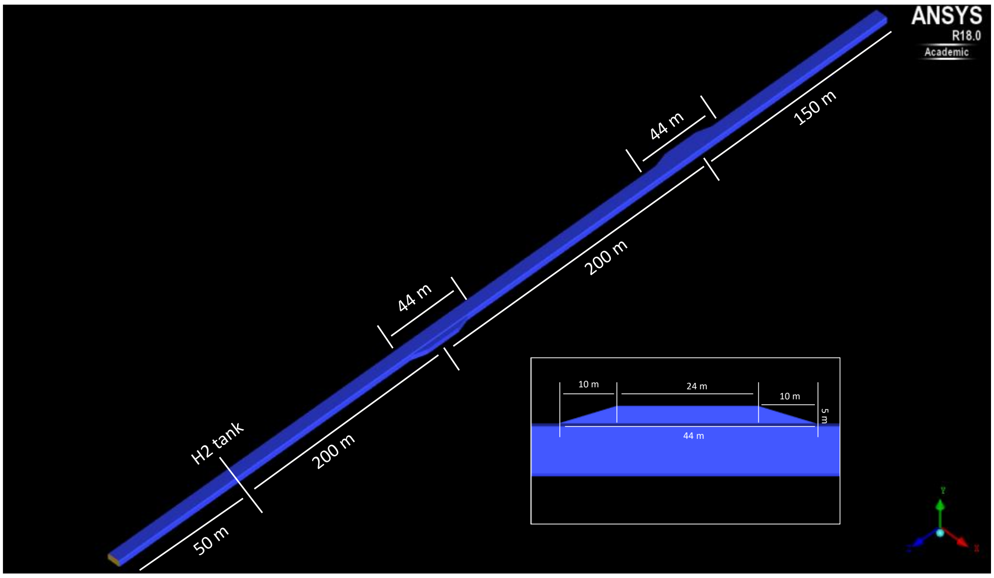

Figure 3. Simulated tunnel with laybys.

The maximum pressure peak was recorded along the tunnel length for a straight tunnel and with laybys. As can be seen from Figure 4 that the pressure curves overlap in the area of the straight zone and drop in the laybys zone, showing practically no effect on the overpressure reduction after leaving the laybys zone. This leads to the conclusion that widening of the tunnel preserved the conservation of energy inside the tunnel and does not act as a mitigation measure.

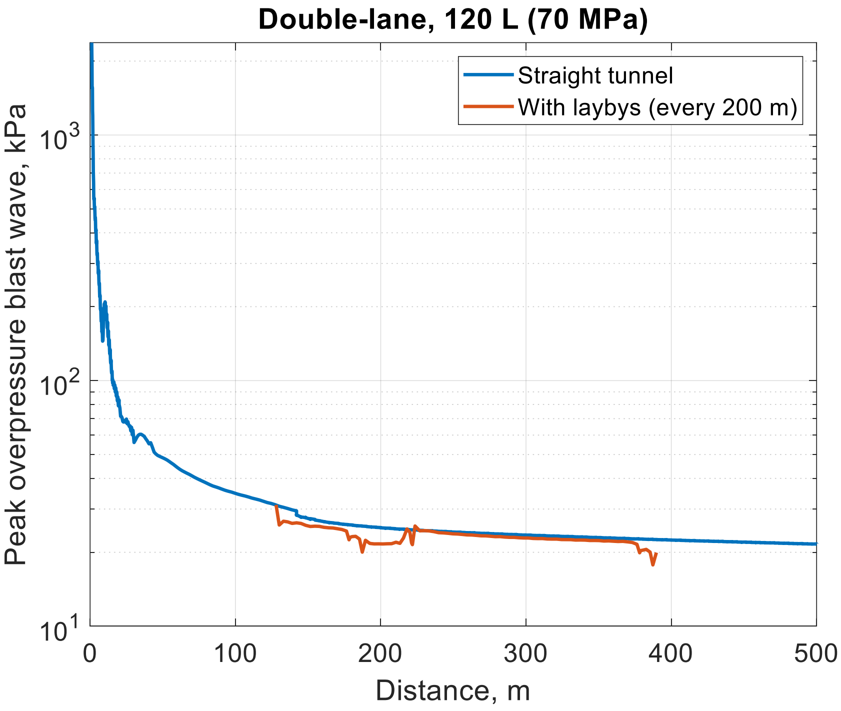

Figure 4. Simulated maximum pressure peak along the tunnel with and without laybys.

4.0 STRUCTURAL VULNERABILITY TO HYDROGEN TANK EXPLOSIONS

Hydrogen tank rupture in a tunnel can cause severe damage to the structure due to the semi-open geometry of a tunnel. To reduce the vulnerability of tunnels under a blast, the passive mitigation technique is one of the popular measures. The passive mitigation techniques of the tunnel against blast consider the tunnel itself, such as tunnel geometries, boundaries, materials, etc. The tunnel vulnerability could be decreased by changing the natural period and energy dissipation of the structure in passive mitigation techniques. Up to now, changing tunnel components, adding flexible support, and using high-performance materials are three typical passive mitigation techniques of tunnel structures [39].

With reference to the HyTunnel project [40], the peak pressure of an unmitigated blast wave caused by a hydrogen tank explosion is above hundred kPa. For example, [41] reports an overpressure peak of 150 kPa (see Figure 5) on the ceiling slab of a tunnel having a cross-section area equal to 38 m^2 caused by the explosion of a hydrogen tank of 62.4 L capacity, pressurized at 70.0 MPa. A maximum overpressure peak of 265 kPa and a duration of 10 ms have been observed in an experimental study by Park et al. (2023) [42], where a hydrogen tank Type IV of size 870 mm × 363 mm and filled with a pressure of 70.7MPa was detonated in a cylindrical explosion test space with a diameter of 20 m and a height of 15 m.

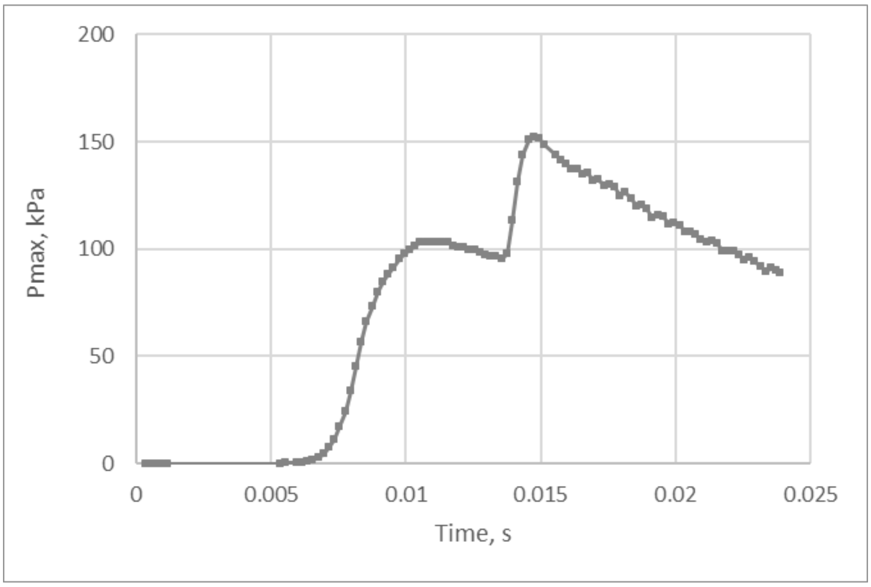

Figure 5. Overpressure history on the tunnel ceiling above the hydrogen tank explosion. Reproduced from [41] with permission of the authors.

Such pressures are much higher than the pressure load capacity of a tunnel ceiling slab carrying the ventilation system and are designed for ordinary conditions. This means that were this pressure applied quasi-statically, it would cause the collapse of the slab. Nevertheless, the duration of such overpressure is very short and possibly significantly lower than the natural vibration period of a long structural element in bending, such as the above mentioned concrete slab. For example, in the first referenced study, the overpressure is dissipated after ca. 40 ms, while, in the second study the overpressure last less than 20 ms. In comparison, the natural vibration of a 10 m long simply-supported slab, having a minimum thickness of 350 mm and made of ordinary concrete reinforced by 16Ø steel bars @ 150mm is ca. 10 ms.

Depending on the efficiency of the mitigation measures, the value of the peak pressure can be significantly reduced. Although such reduction is paramount for people's safety and to reduce the distance at which the occupants are safe [43], they might not prove to be equally effective in mitigating the structural consequences, as the duration of the overpressure is hardly reduced by such measures.

A more effective structural measure would be to design sacrificial stiffening elements (such as restraining rods) that would break during an explosion, thus increasing the natural period of vibration of tunnel slab or other critical elements. For example, a full-scale test of tunnel segmental linings under internal explosion is performed by Yuetang Zhao [44], and the failure patterns and mechanical capacity of the tunnel lining are analyzed. Based on these analyses, a mitigation measure is made, namely adding flexible damping cushions on the lining joints. The allowance deformation of the tunnel structure can increase, and the dissipation of energy in the tunnel is more efficient with this mitigation measure [44].

The influence of high-performance material on tunnel blast resistance was investigated by Colombo (2016) [29]. In this study, two different materials are considered, high-performance fiber reinforced cementitious composite (HPFRCC) and steel fibre reinforced concrete (SFRC). Based on the test results, the single-layer specimens with HPFRCC store more energy compared to the multi-layer specimen with HPFRCC and SFRC, under the same input energy. And the multi-layer specimen can transfer more energy to the soil and has a higher natural period. It is worth noting that high-performance materials with high stiffness and low mass can lead to a higher natural frequency or natural period of a structure. However, if the stiffness of the high-performance material is too high and the mass is too low, it can result in a lower natural period, which may not be desirable for certain applications.

5.0 CONCLUSIONS

Among blast impact mitigation measures there are several approaches available in the literature to decrease the vulnerability of structural integrity, i.e. wrapping the tunnel with a flexible and compressible barrier consisting of a layer of polyurethane foam or introducing energy absorbing flexible honeycomb elements between radial joints of the tunnel. These two methods are possible during construction, at the engineering stage and not applicable for the already working tunnels. Both these measures are directed to save the structural integrity of the tunnel from the external explosion rather than internal, and therefore there is practically no mitigation effect towards people.

As for the mitigation of the blast strength on the people, this could be achieved by compressible low density porous foams, sandwich foam panels, wall roughness, tunnel brunching, ventilation openings and presence of evacuation lanes to route the blast way, use of drop-down perforated plates for blast shielding, baffles, right-angled bends, and high performance fibre reinforced cementitious composite (HPFRCC) panels applied to the walls of new and existing tunnels. The level of congestion is also affecting the strength of the blast, so this also has to be considered.

Passive mitigation measures such as: tunnel brunching, ventilation openings, presence of evacuation lanes and right-angled bends could be already built structures implemented during construction stage and cannot be changed for already existing tunnels. While, porous foams, sandwich foam panels, wall roughness, drop-down perforated plates, baffles and HPFRCC are part of active mitigation strategies they could be introduced later for tunnels that are in operation.

Among the measures listed above implementation of drop-down perforated plates or HPFRCC panels seems to be one of the simplest engineering solutions to implement in terms of material and activation time. Porous foams need to be released in the vicinity of the accident before tank rupture and the amount of the foam should be sufficient to fill the entire area of the tunnel and this is practically not realistic in a short time and a huge amount of foam should be ready to release at all times. Foam sandwich panels should be located along the tunnel same as baffles should be a part of the structure taking extra space, especially height for baffles. While the drop-down perforated plates and HPFRCC are relatively lightweight, do not occupy lots of space.

Based on the information obtained by the literature review, it seems important to advance the modelling capability to predict the decay of the blast using CFD-FEM analysis, to simulate the blast decay with and without combustion and including passive vehicle displacement from the original location and destruction, as well as an active as drop-down perforated plates or HPFRCC for blast shielding. The choice of including the drop-down plates is aimed not only at highlighting the effect of the blast mitigation but also at minimising hot products and smoke dispersion. The model will be used to develop an engineering tool for the assessment of blast wave strength and thermal hazards in a tunnel after a hydrogen tank rupture in a fire.

6.0 ACKNOWLEDGEMENTS

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