A steel tube or a buffer zone for mitigating blast effects of a BLEVE on a building spanning an underpass

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1. Introduction

As a consequence of an ever-growing population, land is becoming scarcer, especially in urban areas. This has led to the development of design and construction techniques that make intensive and multiple use of the limited space possible. In the last decade, the space available above transport infrastructure - such as roads and railway tracks - and existing buildings has been exploited at a growing rate in city centres. Because the use of space is being intensified near and above locations with potentially dangerous activities (e.g. transport routes of hazardous materials), any accident may have serious consequences. Focussing on the local project scale, it can be stated that projects using land in multiple ways (realizing buildings above infrastructure) are generally complex. The safety considerations in multiple land-use projects should not be underestimated. Usually, a large number of people and several multiple risk interactions are involved. Due to the complexity and interrelationships of such a project, a small accident, like a fire in the building or on the covered infrastructure, can easily lead to a major disaster. In The Netherlands, some of these buildings are even realized above infrastructure with transport of hazardous materials where LPG (Liquefied Petroleum Gas) is transported (see Figure 1). An accident with a LPG-tank may result in a BLEVE (Boiling Liquid Expanding Vapour Explosion), causing injuries and large structural damage to the spanning building and the vicinity. Fortunately, such disasters hardly occurred in such circumstances. However, one should be aware of that such accidents may occur and potential consequences should be minimised. Generally, one may expect that realizing buildings above infrastructure along with the transport of hazardous materials will both increase in the future. However to quantify the consequences and risks, there is little background literature that addresses this type of problem, i.e. structural control of explosion effects on a building spanning an underpass at which the explosion occurs. Suddle [1] assessed risks quantitatively in order to determine physical safety in multiple use of space projects, including the analysis of structural safety measures to buildings above the infrastructure.

Van den Berg et al. [2] derived guidelines to assess the blast loading and response of a tunnel structure due to a gas explosion. The blast load is given as a function of the length of the gas cloud and the distance from the point of ignition. Recently, Van den Berg et al. [3] developed also a method to quantify the blast load from BLEVE accidents. Information on these methods is given in Section 2. Neither Suddle [1] nor Van den Berg et al. [2] provide specific analyses for structural control of explosion effects of buildings above infrastructure with transport of LPG. This has been the starting point of the research by Van Diermen [4]. Van Diermen [4] analysed some possibilities for the building structure above the infrastructure with the transport of LPG. His work has been extended and updated in the current study.

This paper gives an introduction analysis of possibilities of how to deal with structural control of explosion effects when realizing buildings spanning roads with transport of hazardous materials. In this regard, some types of the main bearing structure of the building above the infrastructure were inventoried, the explosion effect blast was modelled and the dynamic response of the structural elements and the main bearing structure of the building were analyzed using engineering techniques. Recommendations to limit and control the damage are given.

2. Explosion Hazards caused by LPG

The hazard scenarios that may occur on the infrastructure with transport of hazardous materials are collisions, fires, explosions, and leaks of toxic substances (consecutively decreasing in probability of occurrence and increasing in consequences; see Table 1).

Table 1: Frequency and consequences of hazard scenarios in multiple land-use projects with covered infrastructure [5]

	Consequences			
Frequency	Low	Medium	High	Extremely high
Extremely high	Local traffic accidents and small fires			
High		Fires on the infrastructure		
Medium			Explosions	
Low				Release of toxic gasses

These accidents can also be the starting points of others. A fire for instance can cause an explosion and vice versa. The release of toxic gasses hardly initiates other events. In this paper we constrain ourselves to the explosion hazard caused by the transport of LPG. Unfortunately quantitative risk analyses are not possible yet for the confined tunnel conditions because probability data on explosion and accidents in tunnels are not available. More background on the explosion scenarios can be found in Suddle [6].

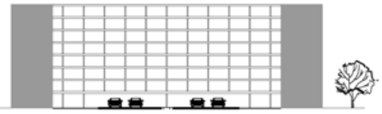
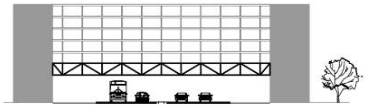
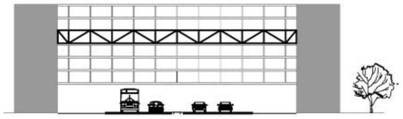
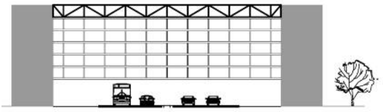
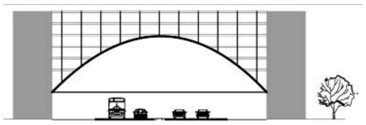
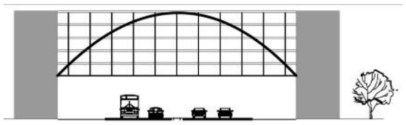
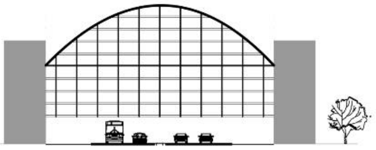
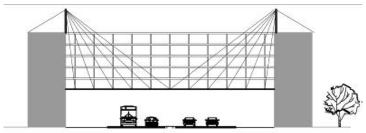
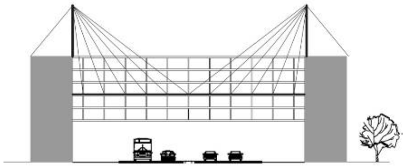
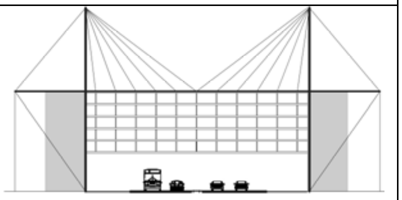
3. The bearing structure for building above infrastructure

The type of main bearing systems for buildings that cover highways have been inventoried and categorized. In the categorization the bearing structure is considered as an element of the structural safety measures to control explosion effects. The results are summarized in this section. For the current study the span of the structure is defined based on a two times two-lane-road, which resulted in a chosen reference span of 36 meter. Four types of span-structures are considered. In combination with the position of the span-structure in the building, ten types of structural design are distinguished; see Table 2 and Table 3. The structures are made of concrete and or steel.

Table 1 Ten types of span structures.

Span structure		Position		
		under	middle	top
Type	Column – beam	Type I		
	Framework beam	Type II A	Type II B	Type II C
	Bow structure	Type III A	Type III B	Type III C
	Stay structure	Type IV A	Type IV B	Type IV C

Table 2 Schemes of span structures

Type	A	B	C
I			
II			
III			
IV			

Comments to the bearing systems:
In this study the function of the bearing systems is to transfer the load of all floors to the towers beside the road.
Type II: The height of the beam-structure is set arbitrarily to the height of one level;
Type III: The structure consists of a pressure bow and tension rod.
Type IV: The tie rods are only designed to carry tensile forces. Consequently, the ties are not suited to resist the load of an explosion under the structure.

4. Case study

Structure type II has been selected to study the explosion effects and the structural response quantitatively to illustrate the phenomena and failure mechanisms that have to be covered. The selected building is depicted in Figure 4 and 5. The properties of the structural elements are given in [4]. This section on the case study is structured as follows. First the blast load of a representative gas explosion and a BLEVE are given. Next the effect on the building and the structural elements will be described qualitatively, supported with quantitative response data.

4.1 Loading of the building

To compute the loading of the building by a BLEVE of LPG of 326 K, a tank of 2.5 10 m2 was positioned in the centre of the space underneath the building. This location enables to limit the size of the numerical mesh by two planes of symmetry (figure 2). The building and the LPG vapour source have been configured in a mesh of 120 200 150 cells of 0.2 0.2 0.2 m3. Overpressure and impulse-time developments have been calculated at various target points at the ceiling in both lengthwise and lateral direction of the structure as well as at the facade.

The pressure-time records show a range of load levels (100 – 1700 kPa) and load profiles due to the reflections and rarefaction of the BLEVE blast wave. To simplify the problem and estimate the effect on the building quantitatively, we only consider the first part i.e. the expanding BLEVE blast wave. The load is schematized to triangular pulses and a positive phase duration based on the calculated impulse values. The blast load on the floor level will definitely result in structural damage, while window breakage will occur at the façade and the elevator core at ground level will be damaged.

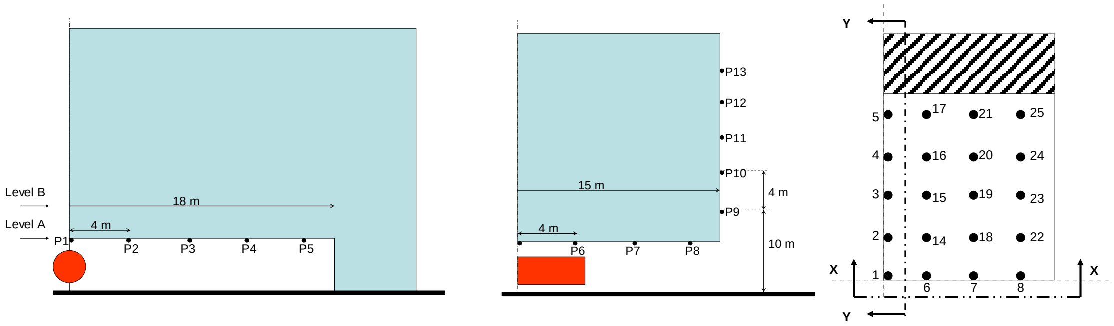


Figure 2: The geometric model of the building in two vertical cross-sections (X-X), (Y-Y) and the horizontal section at level A with target points.

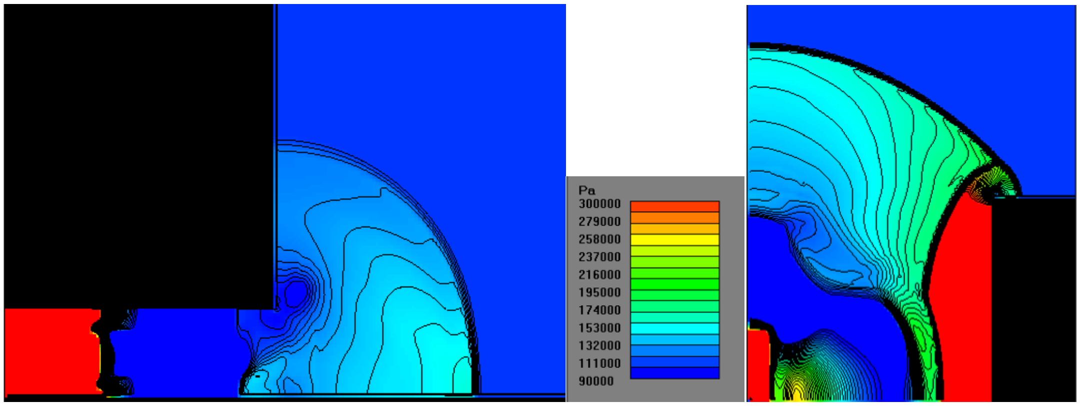
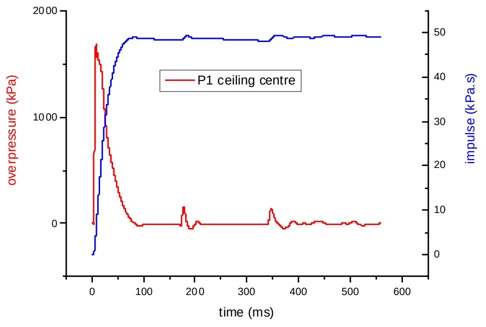
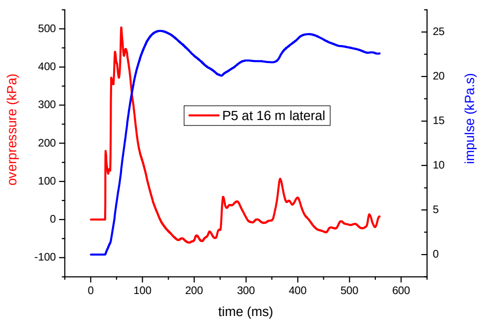


Figure 3: Blast profiles in vertical (left) and horizontal (right) cross-section.





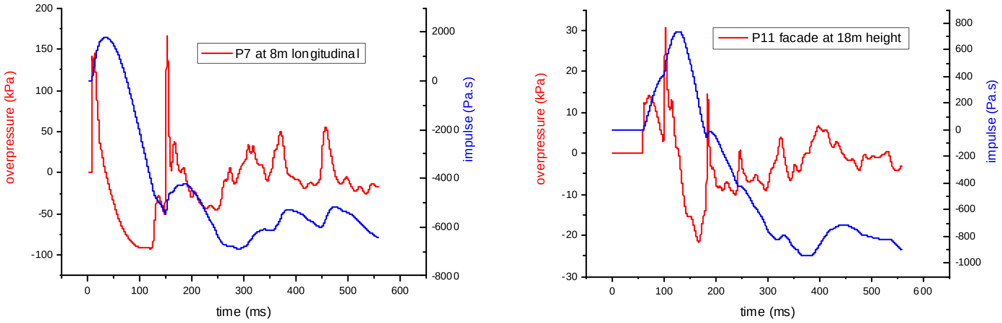


Figure 4: Predicted BLEVE blast loading on building positions 1, 5, 7 and 11.

4.2. Qualitative description of structure response

The blast load as predicted in the previous section ranges from overwhelming the structural strength (position 1) to window pane failure (double glass, strength in the order of 10 kPa). To illustrate the analysis procedure, building types 2a and 2c (see Table 3) are selected. The bearing system of the building consists of the primary and the secondary system as depicted in Figure 7. The secondary system consists of (i) columns, (ii) beams and (iii) floor panels. The six levels have a system height of 3.5 m, while the column grid is 3.5 x 10 meters. The primary bearing system consists of 4 beams at an intermediate distance of 10 meters. The elements, i.e. floor panels, beams, columns and primary beam structure were designed by Van Diermen [4] using Dutch guidelines, static floor load of 6 kN/m2 and floor weight of 3 kN/m2.

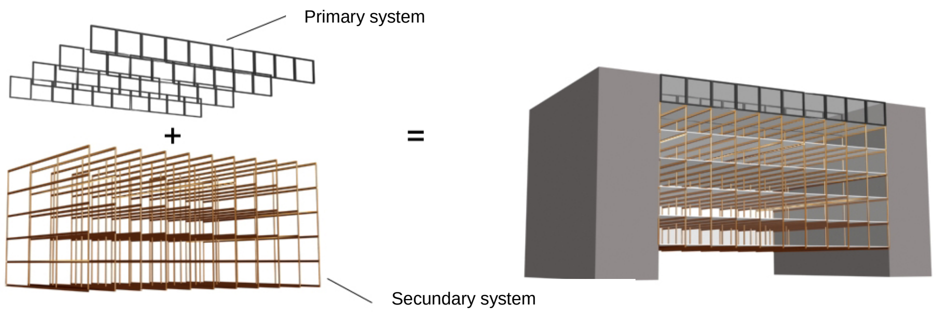


Figure 5: Primary and secondary bearing system

The upwardly directed blast will load the structure and can cause damage after the vertically directed gravity loads are compensated and exceeded. The effect of primary fragments and also thermal damage due to fire are not considered in the current study. The focus is on blast damage. The loading and response sequence due to blast loading is as follows (e.g. building type II C):

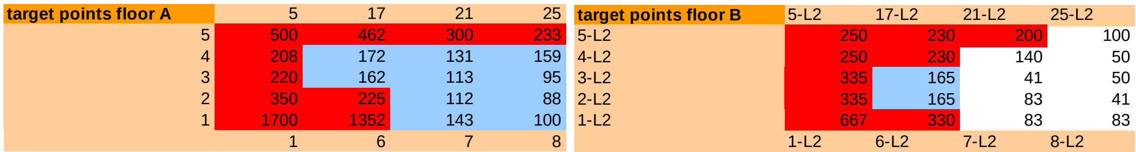
- The panels of the lower floor (level A, see Figure 2) are loaded by the blast (100 – 1700 kPa) and transfer the load to the supporting beams. When the panels fail during the loading phase of the explosion, only a part of the loading is transferred to the beams. Furthermore, the blast will penetrate the building and load the second floor (level B) and the internal walls. The load and response and failure sequence has to be analysed as a function in time.

- The beams are supported by the columns. Therefore, the load transfer sequence from panel to beam, to column to principle bearing system has to be determined.
- The location of the main span structure governs the initial element loading conditions during service life time and consequently the effect of the accidental explosion load.

4.3 Summary quantitative results on damage analysis

All steps mentioned in section 4.2 were analyzed quantitatively. It is evident that due to the extremely high blast load parts of the building will fail. From the chain of load transfer it emerges that the load on the last element, the primary bearing structure, will increase with increasing strength of the previous links, i.e. the columns, supporting beams and floor panels. To prevent building collapse, or partial failure, one of the preceding links has to be sacrificed. The damage to the building can be controlled by the strength and failure time of the elements in the load transfer chain.

The reference building was only designed for static loading (floors: design load 6 kPa; weight load 3 kPa). The blast loading on the panels at level A, leads to shear or bending failure. Because of the short rise time and high amplitude of the load, the dynamic resistance of the panels is exceeded at a very early stage. The load transfer to the supports is limited and the load impulse is transferred to kinetic energy of the panels. The panels are launched into the first building level and the remaining blast load can partly enter the first level also. The tables in Figure 8 give the load distribution on the floors at level A and B, the colours indicate the shear or bending failure mode. Bending failure occurs at a later stage of the response and consequently will result in lower blast pressures on the next floor level. The threshold for bending failure of the floor panels is about 150 kPa.



target points floor A	5	17	21	25
5	500	462	300	233
4	208	172	131	159
3	220	162	113	95
2	350	225	112	88
1	1700	1352	143	100
	1	6	7	8

target points floor B	5-L2	17-L2	21-L2	25-L2
5-L2	250	230	200	100
4-L2	250	230	140	50
3-L2	335	165	41	50
2-L2	335	165	83	41
1-L2	667	330	83	83
	1-L2	6-L2	7-L2	8-L2

Figure 6: Load distribution and failure mode of floor panels at level A (left) and level B (right). Location tank at target points 1-6. The target points correspond with figure 4. The peak load is given in kPa; red and blue indicate shear and bending failure resp.

For the building, designed for static loading conditions, the BLEVE accident will lead to complete failure of floor level A and a considerable part of level B. The windows at all levels will fail and will be blown into the building. The additional dynamic loading on the secondary and primary bearing system is very limited and the system will definitely survive. Evidently, the consequences of such a BLEVE accident are not acceptable from safety point of view. Three obvious countermeasures are (i) design the windows for 15 kPa, (ii) the lower level should not be used for offices but storage and supporting facilities with a low population density and (iii) a balanced design of the system at level A so that failure occurs at a later stage and level B does not fail and the dynamic resistance capacity of the bearing system (level A) is used.

6. Safety measures against peak overpressure

As presented in the previous chapters, without countermeasures, a BLEVE or a gas explosion occurring in the covered infrastructure may cause demolition or severe damage of the building above. The design of countermeasures depends on the considered explosion type and –strength, and thus the load on the structure. Nonetheless, one may consider structural countermeasures that reduce the effects of an explosion towards the building above. To illustrate the possible mitigating measures, we present globally the analysis of two optional countermeasures.

The first option is adding two extra stories to the building, in which the first two lower floors are designed to be severely damaged under explosive loading forming a buffer zone between the infrastructure and the building above. These first two lower floors shouldn't be used as office rooms or for vital functions but as an area with a low population density, such as a parking garage or storage. Applying such a measure enables a low people exposed to the risk of the explosion (see figure 7).

The second - a more progressive - option to prevent damage to the building above is to implement an explosion resistant structures to shield the building above. An example of a simple explosion resistant structures is implementing a steel tube. The protective sub-structure may be heavily damaged, which is acceptable when it can be easily repaired or substituted and still protecting the building above and the infrastructure (see figure 8).

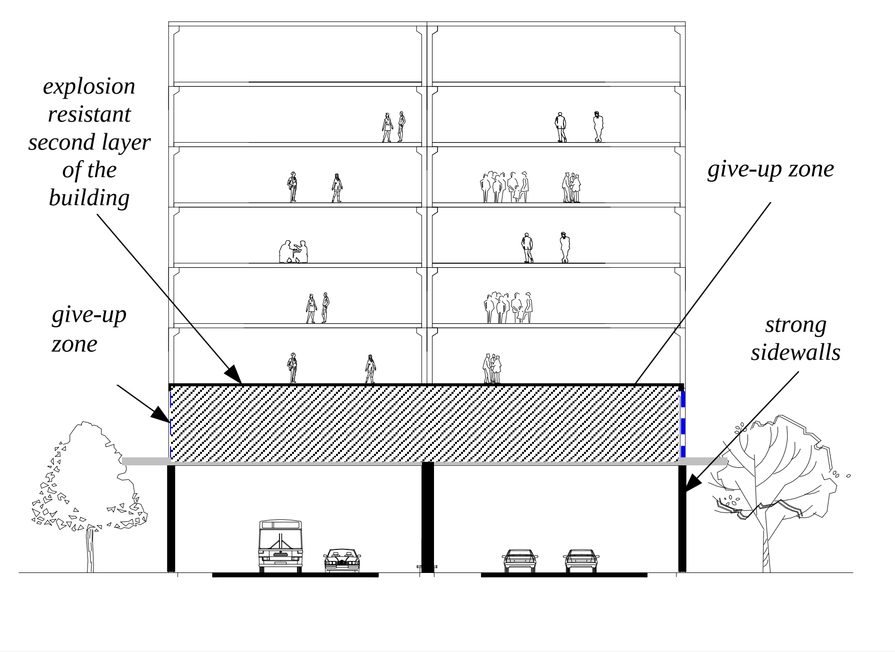


Figure 7: Illustration of the buffer zone concept to protect the building above.

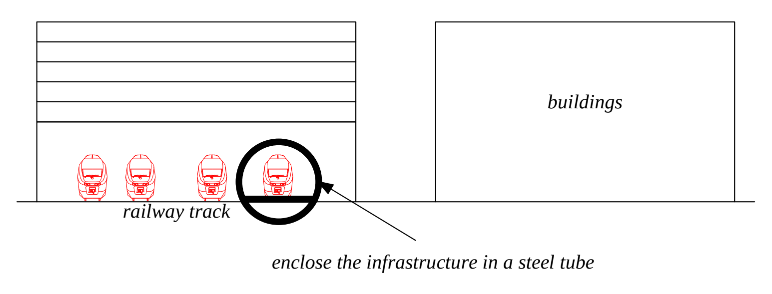


Figure 8: Enclosing the infrastructure in a steel tube.

7. Conclusions & Recommendations

The reported study shows that controlling explosion effects in multiple use of space projects is important and complicated. The explosion blast loads and the dynamic response up to failure of the elements and the overall building system have to be modelled to classify the risks quantitatively. The reported study shows that the potential consequences of an accident with LPG can be quantified using relatively simple models that were developed. The presented models and approach can be used to estimate the potential consequences of an LPG-accident as an input for risk analysis and identify countermeasures and subsequently to integrate these measures into both structural and building design. For the considered building the consequences of the accident and recommended countermeasures are:

- (i) no damage to the primary and secondary bearing system, (ii) first floor completely fails (iii) secondary floor partly fails, (iii) windows breakage at all levels, (iv) human risks too high at all building levels;
- (i) safety integrated design engineering (structural and functional) (ii) design the windows for blast loading, (iii) the lower level should not be used for offices but storage and supporting facilities and (iv) a balanced design for the floor system at the first level, so that damage is limited to the first level and the dynamic resistance capacity of the bearing system is used.

Though, the cost-effectiveness of countermeasures are not considered in this paper, we may expect that the investments in safety measures will be relatively high related to their human risk reduction. However, incorporating the buffer zone concept in the safety integrated engineering offers perspective. In this regard, we recommend to investigate the cost-effectiveness of such safety measures.

Furthermore, safety integrated design on the scale of the building is related to the functional and structural design of the building. Designing structures and the positioning of building functions in relation to possible accident scenarios should be implemented as safety measures in the building design. This can control the effects of the accidents on the building and its users considerably. This is not a common way of thinking yet. However as shown in this paper, it is inevitable to implement such a strategy. We recommend therefore to analyse more safety integrated design measures.

6. References

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