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# ARCHITECTURAL LAYOUT DESIGN FOR RAILWAY STATION PLATFORMS TO MITIGATE PASSENGER HAZARD RISK DUE TO TERRORIST EXPLOSIONS

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**Key words:** Passenger safety, explosive blast, physical and cyber threats, hazard risk, railway systems, platform layout design; layout optimization.

**Abstract.** The first priority in operating transportation and transit systems is public safety. Generally, operators are expected highly to assure the reliable and safe day-to-day journeys of public transports. However, based on recent factual evidences, extreme physical and cyber threats are no longer uncommon and these unpreventable measures are even more dangerous to the public's daily lives. Such clear examples are the terrorist attacks in Saint Petersburg in 2017, in London in 2017, in Stockholm in 2017, in Brussels in 2016, in Nice in 2016, and so many more. These examples have one thing in common. The transportation and transit system hubs are the clear target: either on rail, bus, car or truck, etc. This research establishes a novel and innovative development and optimization of architectural layout design on the railway platform in order to improve safety, manage risks, and mitigate uncertainties where perspectives from the humanities and the operations are fully considered. Computational multi-physics simulations have been used to simulate blast effects from terrorist attacks at a railway platform. Birmingham Grand Central railway station has been selected for case study modelling using LS-Dyna. A platform layout design as structural wave barriers has been used to illustrate the hazard risk mitigation for train passengers due to explosive blast pressures. The reflected air blast from a simulated terrorist bomb has been calculated using LS-Dyna CFD in comparison with the US Army guideline. The new insight will guide a new platform layout design to minimize damage and hazard risks to rail passengers. This research aligns with United Nation's Sustainable Development by creating novel engineering solutions enabling a safer built environment.

## 1 INTRODUCTION

Since the 1970's, terrorist attacks in Western Europe have remained a constant threat [1]. The number of attacks and fatalities can be seen in Figure 1. Therefore, it is of paramount importance to consider blast attack resistance in all design processes of new built environments and the assessment of existing ones in order to mitigate risks and minimise hazards to the public. To put the physical and cyber threats into context, areas of high importance and potential targets include train stations, airports, shopping centres, sport stadiums, malls, concert halls and theatres. In other words, anywhere that could have a large number of casualties or have a detrimental effect on transport and infrastructure networks or the economy [2].

There are currently no official standards governing the testing or specification of blast-resistant structures in Eurocodes [3]. However, there are accepted technical manuals for blast-resistant design, including but not limited to:

- EN 1990: Eurocode - Basis of structural design
- GSA-TS01-2003: US General Services Administration Standard Test Method for Glazing and Window Systems Subject to Dynamic Overpressure Loadings
- ASTM F2912 – 11: Standard Specification for Glazing and Glazing Systems Subject to Air blast
- UFC 3-340-02: Structures to resist the effects of accidental explosions.

Railway assets are a critical infrastructure that requires active monitoring and protection against man-made hazards (such as terrorist attack, severe vandalism, derailments, and human errors). The loading actions and design criteria are complex in nature with strict considerations for systemic and sub-systemic compatibility [3-7]. With the active engagement in overseas military missions, Europe's critical infrastructures remain at high risk of terrorist attack, especially at crowded railway stations as shown in Figure 2. Based on a critical literature review, most studies into blast effects are focussed on the damage on built environments or on building structures. In fact, the impact on passengers or human responses, especially at railway platforms, has not been thoroughly investigated. In this study, we pioneer a novel and innovative development in re-designing and optimising the railway platform layout in order to minimise blast damage to railway passengers. This type of development is highly in significant demand in this modernised but conflicted world.

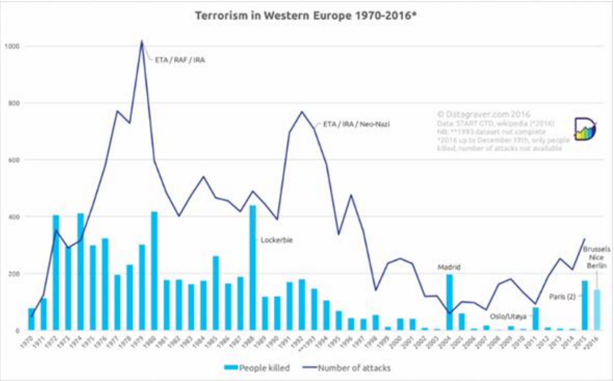


**Fig.1:** Terrorism in Western Europe [1]

**Figure2:** Birmingham Grand Central Station

It is important to note that only high explosives will be considered as a terrorist threat within this research project. The high explosives are often in solid form. TNT is used as a universal reference point for determining a scaled distance from the blast wave source, by converting the charge mass of an explosive into the equivalent mass of TNT. This is done by multiplying the charge mass by a conversion factor derived from the specific energy and charge mass of TNT [8].

An explosion is defined as a sudden release of energy, dissipated as shock waves, projecting missiles and thermal radiation [9]. The detonation of high explosives generates hot gases and high pressures, which rapidly expands, compressing a layer of air and forming a shock wave [10]. As shown in Figure 3, the shock wave instantaneously increases the surrounding pressure above ambient atmospheric pressure, $P_o$, to peak pressure, $P_{so}$. This deteriorates as the shockwaves expand outwards from the epicentre [11]. Once the wave front has passed, after a short period of time, the pressure may drop below the ambient air pressure, producing a partial vacuum. This, together with suction winds, can carry debris for long distances away from the centre of the explosion [11]. Pape et al. [10] also explains that the overpressure, which is any pressure above ambient atmospheric pressure, tapers off and goes below ambient pressure, later returning to equilibrium. It can also be seen in Figure 3 that the area of positive pressure is called the ‘positive phase’ and the area of negative pressure is called the ‘negative phase’. Both the positive and negative phases can contribute to causing damage. The time-pressure curve seen in Figure 3 can usually be approximated using Friendlander’s equation, seen in Eq.1:

$$p(t) = p_s \cdot \left(1 - \frac{t}{t_0}\right) \exp^{\left(-\frac{bt}{t_0}\right)} \qquad (1)$$

There are 3 types of explosion: unconfined explosions, confined explosions and explosions attached to the structure [12]. Unconfined explosions are categorised into two types; an air-burst and a surface-burst, which create shock waves that interact in different ways. Surface-bursts are often the most common type of burst when it comes to terrorist activities, as they usually occur in built-up areas, where devices are placed on or close to the ground surface [12]. Only a surface-burst will be considered for purposes of this study. A surface-burst is when detonation occurs on the near the ground surface, causing initial shockwaves to be immediately reflected and amplified by the ground surface, forming a single wave front, from both the initial and reflected shockwaves [13-14].

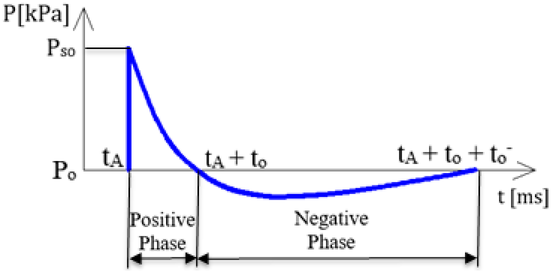


**Fig.3:** Shockwave pressure progression [6]

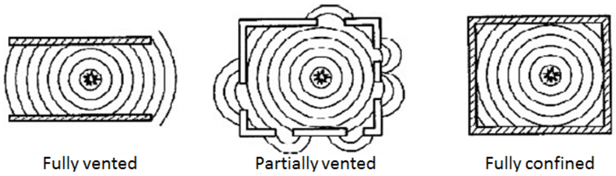


**Fig.4:** Degree of confinement [12]

The effects of an explosion inside a structure will need to be considered, which will depend on the degree of confinement, which in turn depends on the location of a blast. A confined explosion occurs where the initial peak pressures are very high, enhanced by refraction within the structure [13]. Examples of degrees of confinement can be seen below in Figure 4. Other factors that affect the amount of damage inflicted will include ventilation, temperatures, accumulation of gas pressure, blast characteristics, weight of the explosives and location of detonation [15].

## 2 RAILWAY STATION MODELLING

Birmingham Grand Central railway station has been re-developed and opened for multi-purpose uses in September 2015. As illustrated in Figure 5, Grand Central underwent a major overhaul as part of the New Street Station Gateway Plus redevelopment. The mall has been redesigned with a glass atrium roof as centrepiece, and is home to over 60 stores across 500,000 ft2. Many of the shops, restaurants and cafés are creating very vibrant and extremely crowded malls that are fully integrated to one of the UK busiest rail hubs, with 12 train platforms.

In this study, the chosen platform is an island platform with a width of 16m. There are several structural columns situated 12m apart. The columns are 3m high and 1m wide. Fig .6 shows the finite element modelling of the platform. Two types of blast protective barriers have been installed in the simulation at a symmetrical distance in order to measure the comparable impact. The meshing optimization was used to suit the analysis purpose [16-20]. The platform and columns are to be modelled as reinforced concrete. The function CONSTRAINED_LAGRANGE_IN_SOLID is a validated solution to model the rebar within the concrete mesh. The concrete material uses the function MAT_CSCM_CONCRETE. Through which C32/40 concrete properties are imputed. The rebar and steel barriers are both defined to be

MAT_PLASTIC_KINEMATIC. Transverse rebar is 16 millimetres diameter; longitudinal rebar is 10 millimetres diameter. The steel properties of the barrier are shown in Table 1.

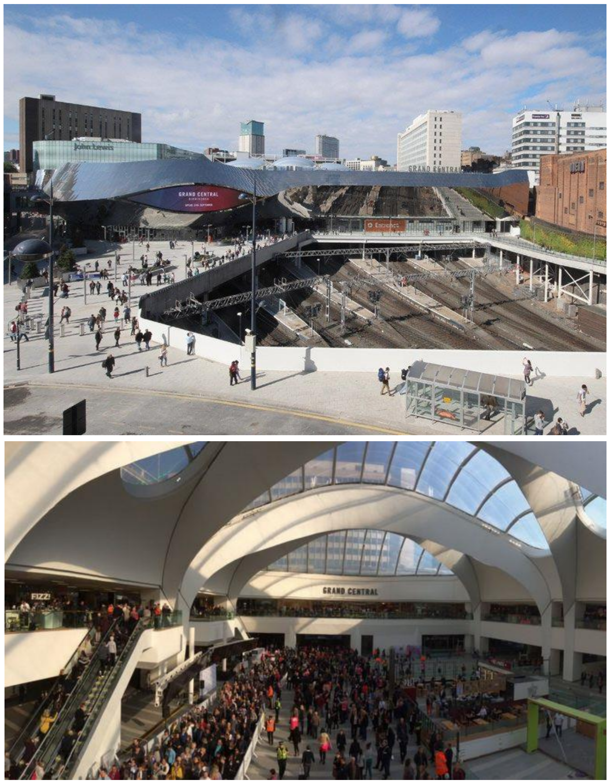


**Figure 5:** Birmingham Grand Central Station

**Table 1:** Steel Properties

| Property | Value | Unit |
|---|---|---|
| Mass Density | 7850 | kg/m$^3$ |
| Young's Modulus | 2.1 x 10$^5$ | MPa |
| Poisson's Ratio | 0.3 | |
| Yield Stress | 400 | MPa |

## 3 EXPLOSIVE BLAST MODELLING

The platform, one scenario of terrorist attacks is simulated, both using 15kg of TNT.

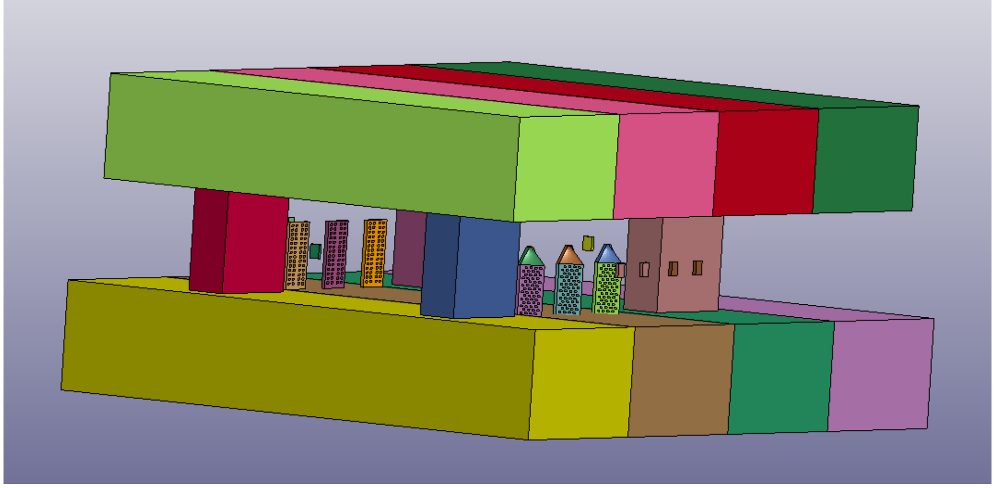
- The bomb is placed in a bag and left on the floor of the platform (0m above G.L).

The barrier design and orientations from the previous study were used [21], as shown in Fig. 6. LS-DYNA software was used to simulate the air blast created from TNT. LS-DYNA has an empirical function LOAD_BLAST_ENHANCED which computes to a high degree of calibration, the pressure exerted on a Lagrangian structure from an air blast. LS-DYNA calculates pressure by measuring the distance from segment to charge, and the angle of incidence from the segments normal. To identify the blast load criticality, the document Unified Facilities Criteria (UFC), Structures to Resist the Effects of Accidental Explosions [5] has been reviewed.

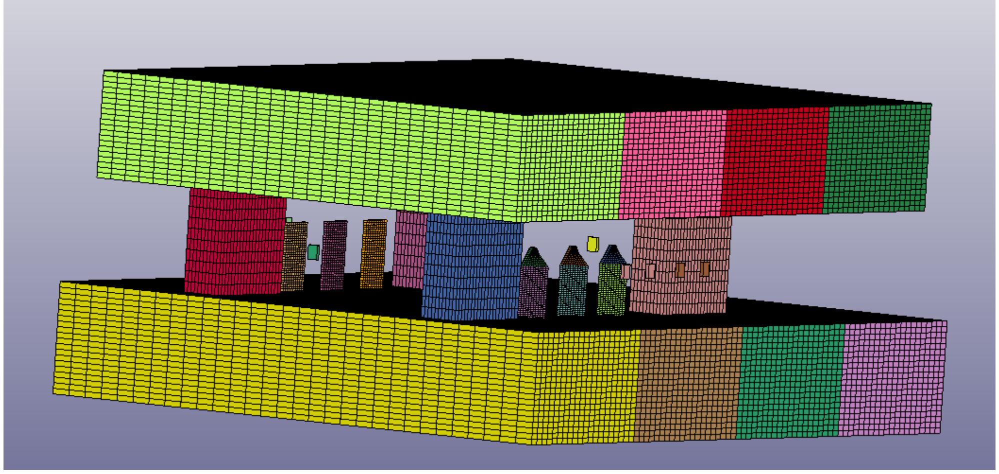
$$Z = \frac{R}{\sqrt[3]{W}} \quad (2)$$

where $R$ is the distance between the point of the detonation and the structure, $W$ is the weight of the charge.

The scaled distance is computed. LOAD_BLAST_ENHANCED uses both of these variables at every cycle to calculate the pressure. The pressure can also be calculated by hand using this formula to validate the pressure computed by LS-DYNA. LOAD_BLAST_ENHANCED enables the blast to be located at any point throughout the model. The function can allows for four different types of blast shape.  This research uses the hemispherical blast with reflected waves, as well as a free air blast with reflective waves. The model was created through LS-DYNA Prepost and is based on Birmingham New Street Station as shown in Figure 6. The floor slab and roof slab were made completely rigid to simulate a blast underground.



a) FEM



b) Mesh

**Fig.6:** Platform modelling with blast protective barriers

The architectural barrier layout arrangements are presented in Figure 7. It can be seen that the different arrangements have been setup to evaluate the hazard risks to the rail passengers measured by sensors (at locations that affect human).

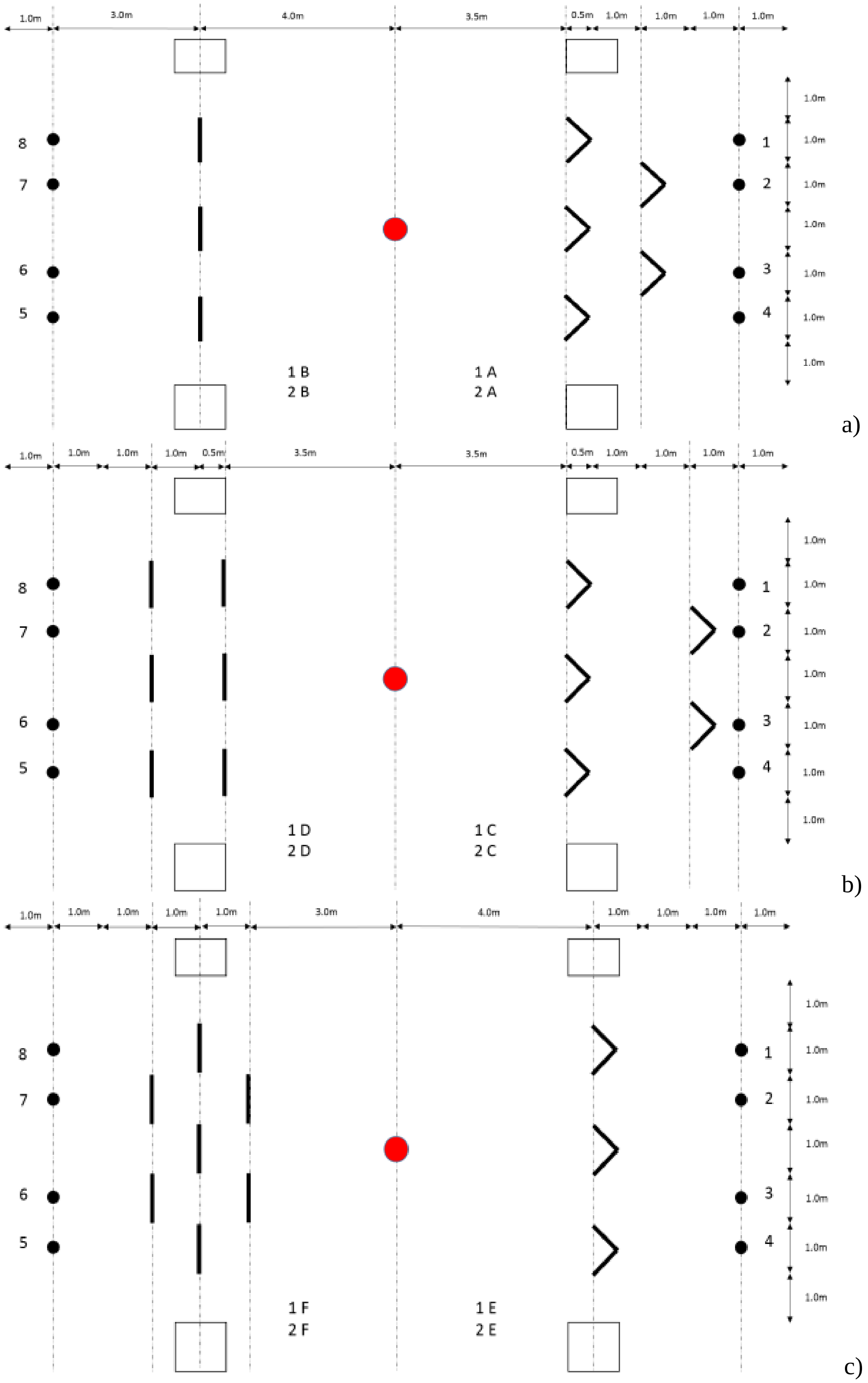


**Figure 7:** Layout optimization of architectural blast protective barriers

## 4 RESULTS AND DISCUSSION

Table 2 shows the pressure on the sensors due to near surface blast. When comparing the control sensor values with arrangements 1B and 1E the two central sensors have an increased pressure. The increased pressure is caused by the blast pressure reflecting and intensifying as it is transmitted through the barriers. It is noted that the flow of a shock wave expands directly after the barrier gap, resulting in the velocity of the wave intensifying [22]. The two external sensors of both arrangements were predicted to act the same due to the findings of recent study [21]. Concluding that the shape of the barriers placed in identical orientation has minimal effect on mitigating the blast wave. It is also concluded that a blast wave travels over a barrier, reforming a reduced pressure wave on the other side.

**Table 2:** Near surface blast pressure (kPa)

| Sensor Number | 1A | 1B | 1C | 1D | 1E | 1F |
|---|---|---|---|---|---|---|
| 1 & 8 | 254 | 289 | 238 | 248 | 289 | 211 |
| 2 & 7 | 279 | 339 | 276 | 315 | 339 | 237 |
| 3 & 6 | 279 | 339 | 276 | 315 | 339 | 237 |
| 4 & 5 | 266 | 305 | 250 | 261 | 305 | 221 |

Arrangement 1A and 1C were created to investigate this conclusion. Arrangement 1C is the same orientation as 1A but the barriers have a greater distance between them. From the results 1C reduced the overall pressure of the blast wave. The two external sensors of 1C both have a decreased pressure of 16 KPa than 1A. As found by [22], the reformed blast wave travels a longer distance until reaching the second row of barriers. Within this distance the wave is dissipating, thus reducing in force. However, the two central sensors show a very minimal decrease in pressure. The cause of both outcomes is as a result of the shape of the transmitted shock wave. As demonstrated in [22] the peak of a transmitted shock wave is created at the centre point between two barriers. The remaining transmitted wave travels in a ‘close to’ hemispherical shape, depending on the angular degree of barrier shape.

1C allows for the transmitted blast wave to dissipate and reduce more, before impacting the external sensors. The peak transmitted blast wave travels identically in both 1A and 1C resulting in minimal reduction at the central sensors. Arrangement 1F insured the two most vulnerable sensors (central) were protected from the peak transmitted blast wave. 1F increased the number and density of the barriers. Comparing the results with the other arrangements, 1F has significantly decreased the pressure over all sensors.

## 5 CONCLUSION

The safety in and within public transport is significantly paramount to every society globally. This study aligns with United Nation’s Sustainable Development by creating novel engineering solutions enabling a safer built environment. The project develops architectural layout design for protective blast barriers to mitigate primary and secondary dangers to train passengers and commuters at a railway platform. Considering recent factual evidences, extreme physical and cyber threats are no longer uncommon and these protective measures could be adopted to prevent damage and improve safety of the public’s daily lives.

Computational multi-physics simulations using LS-Dyna have been used to simulate blast effects from terrorist attacks at a railway platform. Birmingham Grand Central railway station has been selected for case study. A platform layout design as structural wave barriers has been used to illustrate the hazard risk mitigation for train passengers due to explosive blast pressures. The numerical three-dimensional simulations are in excellent agreement with empirical estimates developed by US Army. This study reveals that the layout of blast barriers does have an impact on the reduction of blast pressure. Increasing the amount of barriers between the explosion and target can increase the chance of survival. The results show that layouts 1F and 2F both had very successful effects compared with other layouts. In addition, this study is the first to demonstrate that the shape of the barrier provides minimal effect on the mitigation of blast pressure to rail passengers. The new insight will guide a new platform layout design to minimize damage and hazard risks to rail passengers.

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