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Road and Rail Infrastructure III

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IMPROVING THE RESILIENCE OF THE METRO VEHICLE TO BLAST AND FIRE

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Abstract

In the recent years, the occurrences of terrorist attacks in metro systems have increased noticeably, as illustrated for instance by the Tokyo, Paris, Madrid, and London attacks. Indeed, several efforts aim at improving the resilience of the metro coaches in order to Increase the resilience of metro vehicle to terrorist bomb blast, through the selection of vehicle materials and structural design, to speed-up the recovery following an attack, allowing the rail system to return to normal operation quickly and to reduce the attractiveness of metro systems as a target for attack. Such efforts include the European-funded FP7 SECUREMETRO project, which reached its conclusion in June 2013, and gathered 11 partners from United Kingdom, Spain, France and Italy. SECUREMETRO aimed at bringing new solutions in fighting the consequences of damages caused by internal blast in metro vehicles. A first full-size blast test was performed to assess the performance of current rolling stock faced to a blast. The second trial consisted of a series of small-scale blast tests of unitary material samples in order to assess their behaviour and the improvement over existing materials. The final stage of the project then consisted of integrating the new solutions in a demonstrator vehicle, and submitting it to the same blast test as the existing vehicle. The paper presents the results of the SecureMetro projects to improve the resilience of the metro vehicle to protect passengers and staff.

Keywords: metro vehicles, terrorist attacks, blast test, blast-resilient certification

1 Introduction

Considerable effort is being devoted by researchers and stakeholders in order to improve the safety of metro systems with regard to terrorist attacks. The issue has been addressed by many researchers, taking into account the bow-tie model of safety management, in which the node is the terrorist attack, with on one side the causes of the attack (e.g. political issues, technical weaknesses) and on the other side the consequences (e.g. human, organisational, economical) [1], [2].

The common goal is to implement a line of defence to isolate these causes and consequences, in order to prevent the attack from occurring and, should it happen, to mitigate its consequences as much as possible. Several research projects have addressed specific elements, or full sets of integrated solutions implementing technological and organisational measures to increase the effectiveness of this line of defence. An example of such current project is SECUR-ED (http://www.secur-ed.eu) which aims at providing and demonstrating a full, interoperable set of tools. Another example is PROTECTRAIL (http://protectrail.eu) which aims at designing a scalable solution integrating a modular set of sub-mission protection tools for railway security, such as passenger clearance control, electrical or communication systems. A last example is MODSAFE (http://www.modsafe.eu), focused on the establishment of a common European strategy including safety and security measures.

SECUREMETRO [1] aimed at bringing solutions to mitigate the consequences of internal blast in metro vehicles. It adds up to more conventional approaches to reduce the casualties and disruptions related to terrorist attacks, although its findings are also relevant to accidental events.

2 Findings from the analysis of existing attacks

SECUREMETRO concentrated on specific cases chosen for their representativeness and the abundance and relevance of the documentation. These cases are notably the bomb attacks in London (2005) and Madrid (2004), and fires in the Daegu metro (2003) and the Kaprun funicular (2001). Other related situations, such as 9/11 or fires in high buildings and other places from which evacuation is difficult, were also considered. The project found considerable insight in the previous work carried out in these fields. As the databases include all the types of terrorist attacks perpetrated during the period, we disaggregated data according to the aim of the SECUREMETRO project. Considering the target of the attack as the main filter for the selection of relevant cases, we focused on events involving strictly rail-based public transportation assets. The tactic used for perpetration is of particular importance to devise ways to mitigate the effects of the attack. Out of the 833 attacks in the data bases, bombing is used in 73% of the cases. If we consider the weapons [Table 1], bombs are by far the most used way to carry out attacks, not only bombings per se, but also other types of attacks such as sabotage, threat or mixed tactics. These proportions have not significantly evolved over the last decade.
This appears even more clearly in the number of victims [3], [4], with 70% of the fatalities (2,541 out of 3,457) and 77% of the injuries (7,832 out of 10,682, if we don't take into consideration the 5 killed and 5,205 people injured in the sarin gas attack against the Tokyo metro in 1995, which remains the only one of its kind so far) caused by bombing during the considered period, making it the deadliest type of attack.

Table 1 Weapons used to carry out attacks on rail in the last 50 years

Weapon used	Percentage of all attacks, 1960-2010 period
Bomb	73%
Firearm	6%
Firebomb-Molotov	4%
Fire	3%
Landmine	2%
Grenade	1%
Material obstacle	1%
CRBN material	1%
Rocket	1%
Knife	0%
Car-bomb	0%
Other	1%
Unknown	7%

An explosion causes damage through several mechanisms, causing specific types of disruptions and calling for different mitigation measures. The primary effects are the shockwave and the blast, as well as primary fragments from the bomb itself: pieces of its case and artefacts such as nails (Figure 1). These effects are inherent to the bomb and can only be alleviated by shielding or dampening measures to dissipate the blast and to prevent the propagation of fragments. Another effect is the creation of secondary fragments, caused by fragmentation of the inner structures, walls or windows, turned into shrapnel. The last mechanical effect is the loss of structural integrity, causing collapse of overhead equipment or of the roof. Although it

is impossible to design a 100% infallible protection system, it is possible to greatly improve the protection of the passengers from falling debris which is a major cause of head injuries. It was found that non-incendiary bombs do not usually cause a fire, and that the current EN45545 standard is adequate to prevent fire in these conditions.
Although the inner structure of the vehicle was mostly destroyed in the studied cases, the overall structure, wheels, bogies and floor, was mostly intact, allowing access and even towing away. This observation, that holds true even with high explosive loads, motivated us to consider resilience, both from the technical and organisational points of view: if a bombed vehicle has surviving passengers and is still able to operate, even in a very limited manner, it is desirable to add resilience in the design to ease and speed up the rescue and the recovery of the system after the blast.

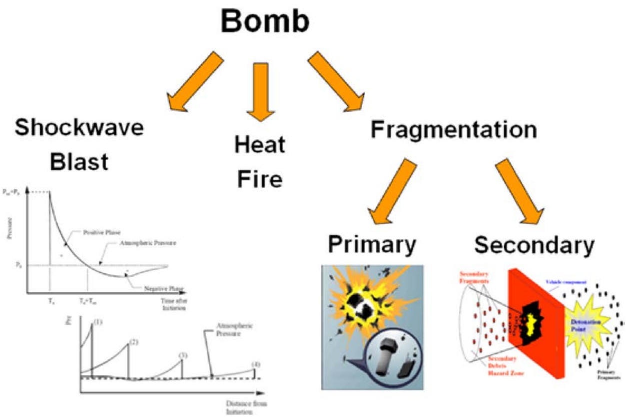

Figure 1 Effects caused by the detonation of a bomb

3 Designs improvements

Particular attention was paid to specific key systems and components of the metro vehicle that must be considered for the safety of the passengers on a bombed train:

- Windows/glazing: should be able to deform plastically, absorbing part of the energy of the blast and minimizing the fragments. High resilience, high plasticity materials should be employed to avoid glass shards. Appropriately supported laminated glass panels have far superior properties that allow them to absorb energy with little or no fragmentation. Another key is the support system: particular attention was paid to the connection between the window and the frame, and between the frame and the carriage structure.
- Walls should be able to deform plastically without fragmenting or breaking into large pieces that could be projected inside by the negative pressure following the blast wave.
- External doors: current rolling stock metro trains have sliding doors, whose mechanism can be severely affected by blast. External doors should not be thrown away.
- Interlocking doors: results from the RAILPROTECT project show that internal walls can contain blast, limiting its effect inside the carriage. Modern trains without interlocking doors can be improved using transparent transversal walls.
- Roof breaks into large pieces under the effect of the blast wave. The roof panels should not fall inside the carriage and injure the passengers. Mechanical systems, like tethered cables, should prevent the panels to be thrown inside.
- Seats: the most important issue is their connection with the vehicle structure, because the blast wave could tear them away from the floor.

- HVAC and other heavy equipment are typically located on the roof of the carriage. As a result they can fall inside the vehicle and hurt the passengers. They would be best placed under the floor, protected by the strong bogies structures.
- Critical systems: since the floor is little affected except at the location of the explosion, all the main supply and critical systems may be protected by placing wires, pipes, etc., inside steel/aluminium cases and ducts placed beneath the floor. A survivable driver's cab could allow driving the train to the closest station, which would dramatically ease rescue and evacuation. All this would increase the weight of the train, so attention should be paid to the mass of the carriage components and to the materials used.

The modifications required to make a metro train blast safe could require a very high investment, which not all could afford. A possible solution is a sort of "blast-resilient certification" for metro lines. Cities where the risk of metro bombings is low may not be interested in a large investment for blast resistant trains. On the contrary medium/high risk cities like London, Paris and Madrid could be interested in being certified as "blast resilient".

4 Experimental assessment

4.1 Test on existing carriage- Metro de Madrid

A full-size blast test was performed to assess the performance of current rolling stock. This test was carried out on a decommissioned Series 5000 carriage given to the SecureMetro project by Metro de Madrid (MdM) [5]. This type of carriage is typical of the rolling stock built in the mid-seventies and still in operation today (Figure 2). The trial consisted of detonating a charge similar to those used in the London attacks, located at the centreline of the carriage. The two doors on both sides of the carriage, at the explosion point became detached and landed 60 meters away. Several other passenger doors were removed from the carriage, while others were buckled and inoperable. All the windows on the right side within the passenger area were shattered, their rubber seals dislodged from their frames.

Figure 2 High-speed image of the trial with an existing MdM carriage

In the driver's cab, all the windows and doors were dislodged, except the access door which remained operable. Damage to the chassis, however, was limited to the rear heat exchanger pack being broken from its mounts, while the central pack was only broken at its rear point. The air reservoir remained intact. Overall, the chassis fared well and the carriage could be towed away, confirming that improved resilience in the passenger area would improve dramatically the security in case of blast. Analysis of the effects, based on this test and the case studies, identified several key areas for improvement, mainly:

· Windows
· Doors
· Interlocking doors
· Components materials
· Joining techniques
· Information and communication systems
· Evacuation system.

Computer simulation was performed to better understand the behaviour of the shock wave inside the carriage, identify the most stressed parts of the internal structure, devise and select structural improvements to improve resilience. This led to a series of small-scale blast tests of unitary samples to assess the improvement over existing materials.

4.2 Test on new demonstrator

The final step then consisted of integrating these solutions in a demonstrator vehicle [Figure 3], and submitting it to the same blast test as the existing vehicle. The improvements brought to the demonstrator consisted notably of:
· Improved resistance of the windows that cleanly separate from the body and do not shatter, thanks to protective film and bonding.
· Improved resistance of the ceiling panels and ceiling-mounted elements using retaining cables to the main vehicle structure: the ceiling does not fall on the passengers, and does not cover the ground with debris which would make walking difficult and hazardous.
· Reinforced lighting using LEDs.
· Reinforced driver's bulkhead.
· Use of flexible backing layer (polyurea) on key elements of the secondary structure to improve flexibility and avoid fragmentation.

In the blast test the driver's bulkhead failed, which the simulation had not predicted. However, the pressure data close to the bulkhead allowed to determine the reasons of the failure, and to propose the necessary reinforcement. The floor was punctured below blast point but did not cause structural failure. Several window bonding solutions were simultaneously tried, and none shattered except the unprotected (reference) window which failed as expected. All the bonded windows stayed in place. The emergency window, protected by film but not bonded to the structure, was ejected in one piece: leaving the frame open but free from glass fragments, allowing safe egress.

Figure 3 High-speed image of the trial with the demonstrator carriage

The seating remained mostly intact, except the seats closest to the charge which were fractured but did not generate secondary fragments. The ceiling panels attached by cables to the main vehicle structure remained attached and did not fall, making walking in the carriage much easier and safer than in the unprotected carriage. Panels attached to secondary elements fell to the floor, showing the importance of tying to the main vehicle structure. The prototype LED lighting worked throughout and after the trial. Overall, these results confirmed the improvement to the resilience of the metro vehicle, passengers and staff. Another achievement of SECUREMETRO is the design of a testing set-up that was an improvement over that used during the first trial.

5 Conclusion

The outcome of the project is expected to yield improvements in the design of metro vehicles to improve blast resilience, and their testing led to the design of measurement methodologies suitable for the specific context of an explosion inside a carriage. It therefore appears that the raised issues, and the solutions found, are both worthy of consideration by the standardization bodies. In addition, adopting low-cost solutions into the design and manufacturing stages will not lead to a marked increase in the cost of rolling stock. For retrofit and future construction, it opens up a new competition in the rail industry supply chain to provide blast-resilient solutions. The results of the work is expected to led to improvements in the design of metro vehicles in the direction of improving their blast resilience, and their testing led to the design of measurement methodologies suitable for the specific context of an explosion inside a carriage. It therefore appears that the issues raised, and the solutions found to these issues in this specific context, are both worthy of consideration by the standardization bodies and insufficiently taken into account by the standards available today, including those pertaining to the related issues of crash worthiness, that take into account some relevant aspects but miss important points related to the pressure wave and its structural effects for instance on doors and windows, and on the environment of the train.

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