Life cycle assessment of retrofit strategies applied to concrete infrastructure at railway stations exposed to future extreme events

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LIFE CYCLE ASSESSMENT OF RETROFIT STRATEGIES APPLIED TO CONCRETE INFRASTRUCTURE AT RAILWAY STATIONS EXPOSED TO FUTURE EXTREME EVENTS

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Abstract

Critical infrastructures such as railway stations are important assets to society which over time have been shown to be susceptible to multiple hazards that could hinder their ability to function as intended. This study focuses on two unique extreme events, flooding and terror attacks, and the sustainability of the retrofits that are typically prescribed to these facilities to enhance their resilience to these hazards under the influence of uncertainty. A framework that incorporates life cycle assessment was applied during the selection process of the retrofits which allowed each of the solutions to be categorised as either being a "No regret", "Reversible" or "High Safety Margin" option. The sustainability of each retrofit was determined by computing the whole-life costs over a 20-year service life and the net present value as well as by measuring net carbon footprint associated with different processes during this service life.

Keywords: life cycle, assessment, retrofit, railway infrastructure, extreme events

1. INTRODUCTION

Buildings designed to accommodate critical infrastructures should possess a high level of resilience to any events or actions that may threaten its ability to function as intended, and should also remain environmentally sustainable. For the purpose of this study, the resilience of a critical infrastructure has been defined as the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from deliberate attacks, accidents or naturally occurring threats or incidents" [1, 2]. Over time, the resilience and overall performance of a structure will reduce and without adequate maintenance, this will increase its vulnerability to extreme events. Critical infrastructures such as transport systems, which decisively affect a bevy of societal and economic functions, cannot afford to be vulnerable to extreme events because of the adverse impacts that could arise. For instance, the vulnerability of a railway station to extreme events such as flooding and terrorism presents primary impacts which could create a succession of secondary damages and inconveniences that could render it incapable of providing normal levels of service to customers as outlined in Table 1. While railway stations are subject to other hazards, two particular extreme events have been selected for evaluation due to the inherent differences in the ways in which they occur, the time-scales within which they occur and the impacts they present to the building when they do occur.

Table 1: Primary and Secondary impacts of flooding and terror attacks on a railway station

Extreme event	**Causes**	**Likelihood /Timescale**	**Primary impact**	**Secondary impact**
Flood	Storm surges, heavy rainfall	Variable likelihood however, the risk is reoccurring due to natural processes	Water inundation; soil/slope erosion, debris impact, sudden surges of large volumes of water, flood risks to HVAC components, encroachment onto railway track	Site pollution, erosion to landscape such as cuttings which may be susceptible to landslides; disruption to services
Terrorist attack	Political, religious and/or socioeconomic motivations	Occur in short and sudden sequences. Infrequent at the same location	Structural damage, debris impact, death, fatal and non-fatal injuries	Progressive collapse of building, fire, traumatising of people ; disruption to services

Since 2016 there has been a 68% surge of terrorism-linked offences in the UK with most notable terror attacks on railway infrastructure leading to the loss of life and injuries, disruptions to the services and significant damage to the buildings themselves [3, 4]. This is particularly true for the bombings that took place in the Brussels airport and metro station in March of 2016 as well as those in May 2017 in the Manchester Victoria station where 32 and 22 deaths occurred respectively as a direct impact of the explosions and millions worth of pounds of cosmetic and structural damages were incurred according to BBC News [5] and Bardsley [6].

While disparities do exist between both extreme events, when attempting to retrofit an existing critical infrastructure that is susceptible to both hazards, similarities in the constraints can be drawn between them as they both introduce elements of uncertainty into the planning process. There is a great deal of difficulty associated with attempting to predict both the environmental and political/socioeconomic climates of the future; therefore a great deal difficulty associated with prescribing the most appropriate retrofit solution that is not over-engineered yet operates with adequate resilience to prevent future risks. Menassa, et al. [7] argued that in some cases this lack of information & adequate benchmarks associated with the uncertainty can drive reluctant stakeholders and decision-makers to either choose or avoid solutions primarily based on the initial capital investment required. In normal circumstances where there is not a high degree of uncertainty, designers typically prioritise a few parameters such as structural performance, costs, speed of installation and suspension time while sustainability is often considered as an afterthought [8, 9, 10]. However, in this context, the consideration of the environmental impacts of the retrofit to be applied to the critical infrastructure should be regarded as critical component of the decision-making process in order to achieve a sustainable design. Furthermore, a truly sustainable design is only achievable if these impacts of the retrofits are holistically assessed over the entirety of the retrofit's service life; a task which is usually undertaken by using a using decision-support tool by many authors using a life cycle assessment (LCA) [11, 12]. Therefore, this study aims to conduct a life cycle assessment of the retrofit strategies that are introduced to railway stations to enhance resilience against extreme events such as terrorisms under the influence of uncertainty.

2. RETROFIT SOLUTIONS

The approach used in this study evaluated the sustainability of different retrofit solutions that can be introduced to enhance the resilience of a train station that is vulnerable to multiple hazards such as flooding and terror attacks by measuring their economic and environmental impacts over a period of time. Using the framework that was set out by Hallegatte [13], 3 approaches that could be specified to address each extreme event without exact knowledge of the time it will occur or severity of the consequences they could present beforehand were identified in Table 2 on the basis that they could be categorised either as a 'No regret', 'Reversible' or a 'High Safety Margin' option. While the most suitable category has been selected for each solution, it should be noted that some solutions, such as vegetated swales, could be placed in multiple categories (i.e. No regrets).

Table 2: Categorised retrofit solutions to enhance resilience against each extreme event

Solution	Description	Method
1.No Regrets Option	Solutions that can yield secondary benefits even in the absence of the hazard for which they were primarily designed for	**Carbon Fibre Reinforced Polymer (CFRP)** – lightweight material that can be applied to columns to improve resilience against blast loads, as well as deterioration caused by chemical processes propagated by moisture in the air [14].
2.Reversible Option	Solutions which can be easily reversed/removed should the hazard they were designed for not occur or be deemed unlikely to.	**Modified Steel Jacketing (MSJ)** – removable protective coating that can be applied to concrete columns using bolts to improve resilience against blast loads [15].
3.High Safety Margin Option	Solutions for which additional safety measures are provided to significantly reduce the impact	**Ductile CONcrete (DUCON)–** marketed based on basis of the security applications of its ductility, DUCON is a high performance concrete characterised by its high blast and ballistic resistance that allows it to retain 50-100% loading capacity following a contact detonation in comparison to reinforced concrete which could only achieve 4-15% under the same conditions [16].

3. CASE STUDY: BIRMINGHAM INTERNATIONAL RAILWAY STATION

For the purposes of this study, it has been assumed that Birmingham International Railway Station can be categorised amongst the select few railway stations in the United Kingdom that are at a higher risk of suffering from both flooding and terrorism risks. This assumption has been based on the fact the station serves the NEC Genting Arena and Resorts World which generate high volumes of pedestrian traffic each year for concerts, conferences and other large events and the fact that it supports another critical infrastructure; Birmingham International airport, the 3rd largest airport outside of London that saw a record breaking 11.6 million passengers in 2016 [17].

The site to which the retrofit solutions discussed in the previous section have been applied has been illustrated in Figure 1 which depict the plan layout of the entirety of the site that is being considered, the front elevation of the building and a plan view of the ground floor respectively. For the purposes of this study, the corresponding dimensions of the short stay parking lot, taxi ranks and staff parking pavements and the dimensions of the vegetated belts of land which characterise the site boundaries outside the building have been measured using Google Maps to be approximately 1600m^2 and 6710m^2.

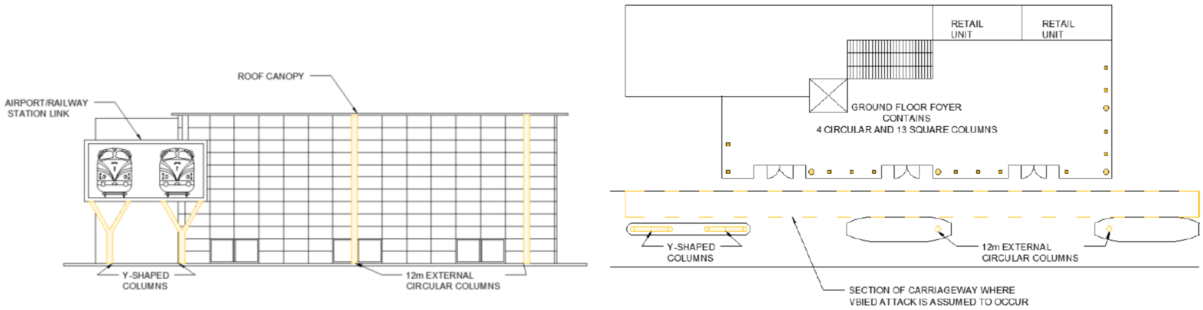

Figure 1: Train station views

4. LIFE CYCLE ANALYSIS

Unlike typical residential and commercial properties, there is an implicit difficulty that can be awarded to the process of assigning a monetary value to a critical infrastructure such as Birmingham International Railway Station and estimating the true costs that would be incurred by either extreme event due to the number of stakeholders (e.g. station managers, rail operators, passengers, staff). The cost of the structural damage experienced will depend on the level of resilience offered by the existing infrastructure and proposed retrofits as well as the magnitude of the event. However, in addition to the structural damage, one must also consider the losses suffered due to a reduced service in the station and the loss of passengers. While it is known that the amount of passengers that exit and enter Birmingham International Railway station annually will be directly affected, currently estimated to be 6.5 million, the ways in which this figure will be affected as a result of either events is beyond the scope of this study. Details of the structural columns within the interior and the exterior of the building have been outlined in Table 3 and have been illustrated in Figure 1.

Although various experiments have been conducted on the materials outlined in this study to observe and determine their blast resilience, there exists limited literature that focuses on their application to columns. Therefore, the thicknesses that have been specified in Table 4 have been adopted from relevant studies and literature where structural columns were retrofitted with CFRP, MSJ and DUCON and they displayed greater residual load capacities following the detonation of an explosive device.

Table 3: Geometrical details of structural columns distributed on ground floor

	Diameter/Width (m)	**Height (m)**	**Area (m^2)**	**Quantity**
Internal square steel columns	0.3	12	0.09	13
Internal circular concrete columns	0.5	12	0.20	4
External circular concrete columns	0.5 0.5	12 (straight columns) 6 (Y-shaped columns)	0.20 0.20	2 2

Table 4: Initial costs and production/extraction carbon emissions of column retrofits solutions

Method	**Thickness (mm)**		**Cost (£/kg)**		**Constituent Materials**	**eCO2 kg/kg**	
		Source		Source			Source
CFRP	2	(Elsanadedy, et al., 2011)	9.66	(Shama Rao, et al., 2017)	Epoxy Resin	2.3300	(Ye & Yue, 2010)
					Polyacrylonitrile (PAN)	31.000	(Das, 2011)
MSJ	8	(Fouche, et al., 2016)	0.59	(S&P Global Platts, 2018)	Iron ore	0.3570	(NSC, 2010)
DUCON	60	(DUCON® Security, 2017)	0.13	(BUILT, 2018)	Quartz sand	0.0026	(Kim, et al., 2015)
					Portland Cement	0.9590	(Norchem, 2011)
					Silica fume	0.0140	(Norchem, 2011)
					Water	0.0002	(Kim, et al., 2015)
					Superplasticiser	1.0643	(Ma, et al., 2016)
			2.65	(UltimateOne, 2018)	Mat Reinforcement (10% of the volume)	2.5000	(Geyer, n.d.)

The capital investment initially required for each material for retrofitting has been computed using the values in Table 4. The equivalent mass of carbon dioxide emissions per kilogram of each constituent material within the retrofit solutions has been specified in order to compute the contribution made to global warming from their individual extraction and production processes. The values associated with each of the retrofit solutions provided in Table 4 have been applied to the appropriate columns within the site and used to determine the financial costs and global warming potential of their application which would aid the determination of their sustainability and feasibility for their purpose. Given the complexity and the number of variables associated with planning for terror attacks, it is often difficult for decision-makers to determine the return on investment that is associated with each retrofit. Several assumptions must be made given that the value of the assets, the number of people in the vicinity of the attack, the true value of the assets to all stakeholders, the magnitude and the extent of the possible damage are all unknown when conducting the calculation of the net present value (NPV) of each solution before the extreme event. The value of the NPV is given by $NPV = \sum[(B_t - C_t)/(1+i)^t]$. where t represents the design life, B_t represents the total monetary benefits in each year between zero and the end of life t, C_t represents the total monetary costs in each year between zero and the end of life *t* and *i* represents discount rate applied for the year under consideration.

Given a scenario where a VBIED attack similar to that of the 1995 Murrah Federal Building bombing occurred in this station with a magnitude sufficient enough to cause the failure of unprotected columns in the absence of protective coatings, but insufficient magnitude to cause the progressive collapse of the building if any of the retrofit solutions that had been applied to the columns, it could be possible to deduce a return on the investment made in a given year. By avoiding the loss of life/fatal injuries to staff and passengers, the value of Bt could be derived by considering it to be a fraction of the monetary value attributed to the life of a single human being. While in most cases this is considered to be an intangible cost, the value can be assumed to be equivalent to 'the cost to society per case of fatal injuries to a single person is equivalent to £1,597,000 [18]. The decision-maker then has the responsibility of crediting a percentage of the benefits to the retrofit initiative based on its15contribution to the prevention of the failure of the structure but must take care to avoid over-valuing the benefits [19]. It has also been assumed that following the explosion; none of the retrofits will remain fit for their intended purpose as a result of the incurred damage and must be replaced and recycled for future use. While it has been assumed for there to be no monetary gain from recycling the remnants of the CFRP and DUCON, any valuable MSJ and mat reinforcement within the DUCON (10% of volume) can be sold for £0.05-0.14 per kg following the VBIED attack [20]. The return of this benefit in each year has been discounted at 3.5% [21].

5. RESULTS AND DISCUSSION

The initial costs of retrofitting the columns within the ground floor of the train station entrance using MSJ, DUCON and CFRP wraps based on the geometric parameters outlined in Table 6 have been calculated and displayed in Figure 2. When considering the option of protecting all of the columns to a height of 6m, MSJs incur the lowest initial capital costs of £14,295; immediately followed by CFRP wraps at an initial cost of £16,896; and lastly DUCON coating costing £30,405. This trend is shown to be consistent between all of the different retrofit combinations that could be made whether only the internal circular columns, only the external columns or whether only the internal square columns are protected. It has been assumed that no steel jacketing would be provided for the internal square steel columns.

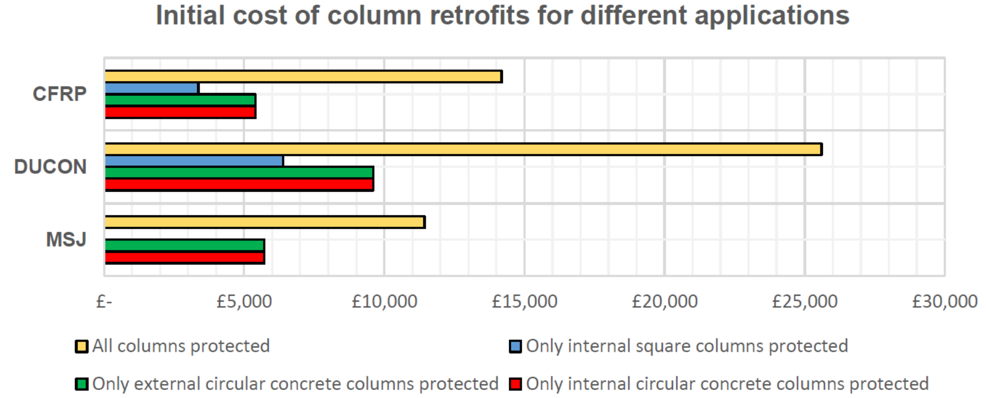

Figure 2: Initial cost of column retrofits for different applications

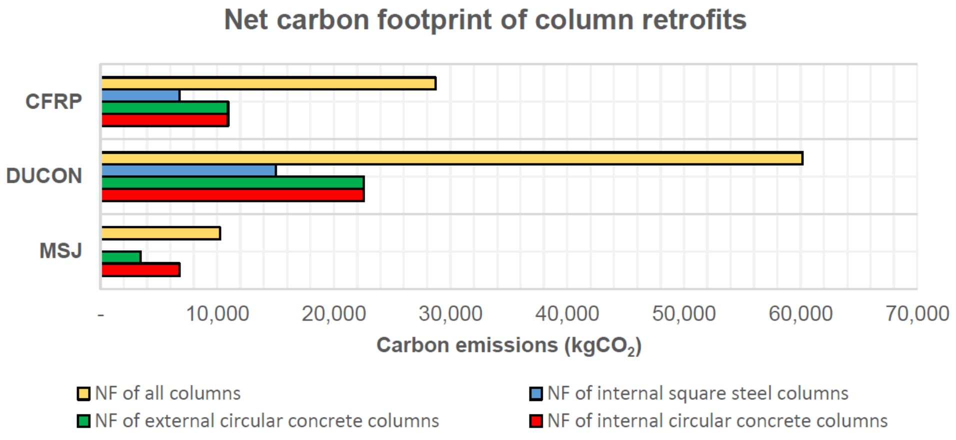

Figure 3: Net carbon footprint of column retrofits

As highlighted in Figures 2 and 3, while the use of DUCON (i.e."High Safety Margin" option) will significantly enhance the robustness and resilience of the columns, it does so at a higher cost to the decision-maker and the environment than the other protective retrofits do. Unlike the porous pavements in Section 4.1, the DUCON retrofits are not multifunctional applications and do not yield additional benefits which would otherwise be used to justify the fact that the net carbon footprint of 6 circular columns is shown to emit 33,862 kgCO2 during production/extraction; nearly 4 times as much 23 MSJs that produce 8,840kgCO2; roughly similar to the emissions from all 23 CFRP wraps of 34,162 kgCO2. In a similar fashion to Philips, et al. [22]'s results which showed that 20% of the resilience frameworks they examined harboured a negative relationship with sustainability, the results of this study with regards to DUCON coating seek to reinforce the notion that the most resilient solutions tend to be the least sustainable.

6. CONCLUSION

This study reviewed various resilience and sustainability frameworks from previous studies relevant to this topic and in doing so highlighted the difficulties and impacts associated with retrofitting for future hazards when there are several unknowns and uncertainties that must be considered. It has shown how LCA's can be practical decision-support tools that could be utilised by decision-makers when planning for future extreme events. By assessing the environmental and economic impacts of different retrofit options that enhance the resilience of a critical infrastructure when faced with uncertainty, this study is able to determine the sustainability of each option. The modified steel jacketing (MSJ) is found to be the most suitable method in terms of both economical and environmental sustainability.

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REFERENCES

[1] Kaewunruen S, Sussman JM, Matsumoto A. Grand challenges in transportation and transit systems. *Front Built Environ* 2016; 2(4).

[2] Homeland Security, *Critical Infrastructure Security and Resilience*. s.l., International Committee on Global Navigation Satellite Systems, 2014.

[3] Travis, A., UK terror arrests rise 68% to record level during year of attacks, 2017. [Online] Available at: https://www.theguardian.com/uk-news/2017/sep/14/uk-terror-arrests-rise-68-record-level-during-year-attacks .

[4] Rennie J, Kaewunruen S, Baniotopoulos C. Blast effects on spatial glass shells for a long-span roof structure, *IASS Symposium 2018*, Massachusetts Institute of Technology (MIT), IASS 2018, Cambridge, United States.

[5] BBC News, Brussels explosions: What we know about airport and metro attacks, 2016. [Online] Available at: http://www.bbc.co.uk/news/world-europe-35869985

[6] Bradsley, S., Cost to line a stripe a parking lot, 2015. [Online] Available at: http://www.fixasphalt.com/blog/cost-to-line-stripe-a-parking-lot

[7] Menassa, C. C., Evaluating sustainable retrofits in existing buildings under uncertainty. *Energy and Buildings*, 43(12), pp. 3576 - 3583. (2011).

[8] Setsobhonkul S, Kaewunruen S and Sussman JM., Lifecycle Assessments of Railway Bridge Transitions Exposed to Extreme Climate Events. *Front. Built Environ*. 3:35. (2017) doi: 10.3389/fbuil.2017.00035

[9] Vitiello, U. et al., Life-cycle assessment of seismic retrofit strategies applied to existing building structures. *Sustainability*, 8(12), 1275. (2016).

[10] Kaewunruen, S., Sussman, J. M., and Einstein, H. H. Strategic framework to achieve carbon-efficient construction and maintenance of railway infrastructure systems. *Front. Environ. Sci.* 3:6. (2015). doi:10.3389/fenvs.2015.00006

[11] Tuler, M.V. and Kaewunruen, S. Life cycle analysis of mitigation methodologies for railway rolling noise and groundbourne vibration. *J. Environ. Manag.* (2017), *191*, 75–82.

[12] Tavares de Freitas, R. and Kaewunruen, S. Life Cycle Cost Evaluation of Noise and Vibration Control Methods at Urban Railway Turnouts. *Environments* (2016), 3, 34.

[13] Hallegatte, S., Strategies to adapt to an uncertain climate change. *Global Environmental Change*, 19(2), pp. 240 -247, (2009).

[14] Burgoyne, C. and Balafas, I., *Why is FRP not a financial success?*. Patras, Greece: s.n. (2007).

[15] Fouche, P., Bruneau, M. and Chiarito, V. P., Modified Steel-Jacketed Columns for Combined Blast and Seismic Retrofit of Exisiting Bridge Columns. *Journal of Bridge Engineering*, 21(7). (2016).

[16] DUCON® Security, *Structural Flexibility and Resilience*, Darmstadt: s.n. (2017).

[17] Birmingham Updates, Birmingham Airport celebrates a record breaking year – 11.6 million passengers in 2016. (2017). [Online] Available at: http://www.birminghamupdates.com/birmingham-airport-celebrates-a-record-breaking-year-11-6-million-passengers-in-2016

[18] Health and Safety Executive, Appraisal values or 'unit costs'. (2015). [Online] Available at: http://www.hse.gov.uk/economics/eauappraisal.htm

[19] Office of Rail and Road, *Estimates of station usage*. London, UK. (2017).

[20] Kaewunruen, S., Wu, L., Goto, K., Najih, Y.M. Vulnerability of Structural Concrete to Extreme Climate Variances. *Climate* 2018, 6, 40 (2018).

[21] HM Treasury, *Green Book*, s.l.: s.n. (2013).

[22] Philips, R., Troup, L., Fannon, D. & Eckelman, M. J., 2017. Do resilient and sustainable design strategies conflict in commercial buildings? A critical analysis of existing resilient building frameworks and their sustainability implications. *Energy and Buildings*, 146, pp. 295-311.