Cormie, David, Mays, Geoff and Smith, Peter

ISBN 978-0-7277-6147-7

<https://doi.org/10.1680/beob.61477.319>

ICE Publishing: All rights reserved

Index

9/11 attacks 3, 5, 6, 25, 251

accidental actions 222, 247

accidental limit state 9

active vehicle security barriers 264, 267–70

adaptive gridding 82, 84, 84, 87

airblast 3, 34, 206, 278, 280, 282–4

air quality, protected spaces 29, 278–80

Alfred P. Murrah Federal Building (Oklahoma City) 24–5, 25, 223, 227, 227

alternate loadpath methods 25, 221–2, 230, 233–47

ambient/atmospheric pressure 16, 35–6, 38, 40, 44–5, 70, 78, 99

ammonium nitrate–fuel oil (ANFO) 38–9

angle of incidence 45–6, 50

annealed glass 20, 188–92, 197, 218

behaviour 188, 192

dynamic breaking strength 204

in laminated glass *see* laminated glass

anti-ram vehicle barriers 261–2

anti-shatter film (ASF) 191–3

arching behaviour 159, 161–3, 161, 162, 232, 234, 235, 241–2

arrest of collapse 234, 235

Arup 185, 223, 225, 239

automatic access control systems (AACS) 15, 261, 267, 269

vehicle barriers and control points 15, 254–70

Baker–Strehlow method 78

bar connectors 170–6, 179, 181–2

failure modes 14, 170–2, 175

beam–column connections 22, 23, 157, 233, 235, 238

moment capacity 107, 235

in reinforced concrete structures 156–7

in steel structures 124–6

in steel-concrete-steel composite structures 169–76, 179, 181–4

beams/slabs, SDOF properties 102–4, 107, 109, 238, 294–301

bending moment 118, 120

Bishopsgate (London) 45, 223, 226

Bi-Steel *see* steel-concrete-steel composite structures

blast damage

concrete cladding 18, 23, 24, 27

glazed façades 20, 186, 186, 213–14, 219

reinforced concrete buildings 131, 134, 154

steel-framed buildings 114, 116

whole-building damage *see* whole-building response

blast design, partial factors 9

blast engineering, in glazing design 192–3

blast hardening 11, 255, 259

blast links 137–8

blast loading 33, 70

angle of incidence 45–6, 50

blast wave interactions 37

blast wave parameters for loading on structures 39–40

blast wave scaling laws 41–8

blast wavefront parameters in air 37–9

decay 39–40, 48–52, 56, 62, 64–5, 68–70, 75–6

deflagration 33–4, 36, 77–9, 85–7

design of reinforced concrete structures *see* reinforced concrete

design of SCS composite materials *see* steel-concrete-steel composite materials

design of steel structures *see* steel structures

detonation 33–5, 46–7, 51–3, 55, 58, 62, 65, 74–87, 92

dynamic pressure 37, 41, 44, 62, 64–5, 76

external loading of structures 62–6

groundshock 34, 43, 47–52, 53

high explosives 35, 36, 74–5, 77–8, 81–5

human response 99, 100, 101

idealisation 40, 52, 67, 75, 78, 90–1, 93–4

incident impulse 97

incident pressure 37, 39, 52, 58, 99

internal loading of structures 18, 19, 65–70

blowdown time 69–70

gas pressures 65, 68–70

quasi-static pressures 68–70

negative phase 35, 40–3, 47, 54, 65–6

peak overpressure 33, 36–9, 44, 49, 50, 64, 76, 78, 97, 97

positive phase 35, 39–44, 46, 48, 65–6

prediction 73

categorisation of techniques 74

CFD models 74, 79, 81–7

deflagrative events 77–9, 85–7

detonation 74–87

empirical methods 74–8

Euler equations 81, 86

- blast loading (*continued*)
 - first-principle methods 74, 79–87
 - high explosive detonations 74–8, 81–5
 - Navier–Stokes equations 79–81, 86
 - phenomenological methods 74, 78–9
 - reflected impulse 46
 - reflected pressure 18, 37, 39, 53, 75, 207, 212, 314
 - reflection coefficients 44–6, 50, 74, 75–6
 - regular and Mach reflection 45–6, 49
 - reverberation 67–8
 - underwater explosions 52–61
 - vapour cloud explosions 74, 77–9, 81, 85, 87
 - venting 47, 65, 68–70, 68
 - wavefronts 35–42, 45, 48, 65, 76, 84
 - whole-building response 223, 224
- blast resilience
 - building form and façade 12–13
 - building operation 26
 - cladding 11–13, 18, 22, 23, 24, 27
 - design features 12–14, 18–23, 28–9
 - glazing 11–12, 18–21, 188, 191
 - guidelines 11–29
 - internal design 14
 - protected spaces 26–9
 - reinforced concrete 13–14, 19, 22–4, 27–8
 - stand-off distance 12–15, 16, 27
 - steel structures 13, 19, 21–24, 27
 - structural robustness 13, 23–5, 28, 191
 - vehicle-borne threats 255, 258, 261
 - see also* operational resilience
- blast-engineered glass 192–3
- bolt-fixed glass 195
- bollards, vehicle security barriers 9, 15, 262, 264, 266–7, 268, 272
- bomb blast net curtains (BBNCs) 192–3, 216–17
- bomb shelter areas (BSAs) 27–8, 276–7, 281, 288–9
 - evacuation 27–8, 276–7, 281, 288–9
 - life safety support 276–7
 - service continuity 277
- boundary conditions 74–9, 84–5, 101
- breaching 18, 154–5
- breaking strengths 188, 198–204
- brisance 109, 154–5
- brittle failure 13, 23, 247
- bubble loading parameters 58–61
- bubble pulses 53, 54, 55, 59, 61
- buckling 14, 283, 315
 - in reinforced concrete 138, 145, 155
 - in steel-concrete-steel composite materials 169–73, 170, 183
 - in steel structures 119, 121, 124–5
- building design protection criteria 9–10
- building services
 - containment 267, 278, 283, 285–6
 - design for blast loading 5, 275–7, 282, 287
 - fixing/mounting 275, 277, 283–6
 - life safety 276–9
 - protected spaces 26–9, 276–86
 - operational resilience 276, 279, 281–2, 287–9
 - recovery 286–7
- Building Regulations 13, 23–4, 27, 280–1
 - whole-building response 221–6, 229, 231–3, 247
- bunds, vehicle security barriers 264–5
- business continuity 4, 287, 291
- cantilever beams, SDOF properties 298–300
- catenary action
 - glazing design 190, 193
 - mechanism of resistance 232–5, 238, 240–6
- cell size 82, 83, 86
- Centre for the Protection of National Infrastructure (CPNI) 288, 290
- Chamber of Shipping (St Mary Axe, London) 223, 225
- chicanes 260–1, 261
- cladding 84, 111, 194, 224, 263–4
 - blast resilience 11–13, 18, 22–4, 27
- clearing 62, 64, 75–6
- client requirements 11–12, 222, 224–8
- ‘close-in’ blasts 110, 171
- closed-circuit television (CCTV) 254, 265, 273
- collapse, arrest of 222–3, 226, 232, 234, 241, 243, 248
- column loss 231, 234, 236–7, 242, 246
- communications 26, 28, 281, 289–90
- Compound B 38–9
- compression reinforcement 136, 138, 151, 155, 169
- compressive arching action 235
- computational domain 74, 79, 82
- computational efficiency 82, 84, 84, 86
- computational fluid dynamics (CFD) models 74, 79, 81–7
- confining effects 16–17, 17, 76, 77–8
- connections
 - blast resilience 12–13, 22–3, 23, 25, 28
 - connection/joint failure 23, 126, 131, 132
 - flexible connections 285
 - glazing design 215–16
 - in reinforced concrete 156–7
 - in steel-concrete-steel composite materials 169–76, 179, 181–4
 - in steel structures 114, 116, 124–5, 126
 - masonry 160, 162
 - structural response to blast loading 107, 109
 - whole-building response 231–3, 238–40, 245, 247–8
- conservation of energy 80
- conservation of mass 79, 81
- conservation of momentum 79–80, 81
- Construction (Design and Management) (CDM) Regulations (2015) 4–5
- Construction Products Regulation (2011) 5
- contingency planning 288–90
- control (operational resilience) 286
- control volumes 80–1
- conversion factors 38–9, 317
- ConWep 75
- cooling 280

- Corporate Manslaughter and Corporate Homicide Act (2007) 5
- counter-terrorist VSBs 262
- coupling factor 49–52
- cracking
- concrete 110, 137, 141, 143, 155, 239
 - glazing 188, 190–1, 193–202, 204–10, 213–4, 218
 - masonry 161, 163
 - steel-concrete-steel structures 168
- crushing 136–7, 161, 239
- CTSA (counter terrorism security adviser) 29
- curtain walling 12, 19
- damping 91, 110, 239, 241, 245–6
- debris *see* fragments/fragmentation
- decay of blast waves 39–40, 48–52, 56, 62–5, 68–70, 75–6
- deception (vehicle-borne threats) 254
- deflagration–detonation transition (DDT) 87
- deflagrative events 33–4, 36, 77–9, 85–7
- deformation limits 116–17, 134–5, 160, 168, 215–16
- moment capacity 168, 215
 - of reinforced concrete 134–5
 - of steel-concrete-steel composite materials 168
 - of steel structures 116–17
- delivered items 288
- demand/capacity ratios (DCRs) 239
- design
- blast resilience 11, 12–14, 18–23, 28–9
 - glazing 185–220
 - masonry 159–63
 - minimising impact of terrorist attacks 2–6, 9–10
 - operational resilience *see* operational resilience
 - partial factors 9
 - philosophy of 9–10
 - reinforced concrete 129–57
 - steel structures 113–26
 - vehicle security barriers 252–4, 260–2, 264–7, 269–72
 - whole-building response *see* whole-building response
- design flowchart 313–15
- design loads 114–15, 131, 133, 160, 167, 285, 314
- design strengths 115–16, 124, 133–4, 136, 160, 167–8
- detailing
- blast resilience 14, 22–3
 - in reinforced concrete 132, 138, 154–5, 156
 - in steel-concrete-steel composite materials 183–4
 - in steel structures 125–6
 - glazing design 190, 214
 - whole-building response 223, 228, 231, 233
- detonation
- blast loading 33–5, 46–7, 51–3, 55, 58, 62, 65, 74–87, 92
 - high explosive 74–5, 77–8, 81–5, 154, 224
 - ‘in-contact’ 171, 173, 173
 - operational resilience 282
 - in reinforced concrete structures 147, 154
 - in steel-concrete-steel composite materials 171–3
 - vehicle-borne threats 252, 254
- diagonal bars 144–5, 147, 150, 153, 155
- direct design, robustness 6, 228, 247
- displacement at limit of tearing 207
- disproportionate collapse 24, 221–3, 225, 228–31, 237, 239, 247
- double-glazed units 192, 205–6
- drinking water 280
- dry gaskets 194–5
- ductility
- blast resilience 13, 19, 21–3
 - ductility capacity 22, 239–40, 243–4, 245
 - ductility ratio 21, 116, 118–19, 135, 239, 314–15
 - in glazing design 191, 193
 - in reinforced concrete 131, 135, 138, 139, 142, 154, 155
 - in steel-concrete-steel composite materials 167, 169, 183–4
 - in steel structures 114, 116, 118–19, 121, 124, 125
 - structural response to blast loading 107, 109
 - whole-building response 231–3, 238–40, 242–3, 245–8
- duress (vehicle-borne threats) 254
- duty of care 5
- dynamic analysis procedures 21–2, 160–1, 245–7
- dynamic design strengths 115–16, 134, 136, 160
- dynamic equation of motion 90–3, 102, 104, 111, 175, 196
- dynamic increase factor (DIF) 314
- in glazing design 215
 - in reinforced concrete 133–4
 - in steel-concrete-steel composite materials 167, 176
 - in steel structures 115
- dynamic load factor (DLF) 94
- alternate loadpath analysis 234–41, 237
 - linear/nonlinear static analysis 240–1
 - plasticity 238, 240–1
 - SDOF undamped elastic system 237
- dynamic loading
- in glazing design 206, 210
 - in reinforced concrete 141–3, 150–3
 - in steel-concrete-steel composite materials
 - in steel structures 119–24
 - structural response to blast loading 90, 93, 94, 95, 105
 - whole-building response 234–43, 236, 237
- dynamic pressure 37, 41, 44, 62, 64–5, 76
- dynamic reactions 294–301, 315
- in reinforced concrete 147, 153
 - in steel-concrete-steel composite materials 168, 182–3
 - in steel structures 121–2, 124
 - in glazing design 199, 216
 - structural response to blast loading 104–5
- dynamic time history 236, 243, 246

- eardrum damage 101
- earthworks, vehicle security barriers 264–5
- ease of recovery (operational resilience) 286–7
- edge reactions 191–2, 194, 196, 199, 214
- elastic analysis 100–102
- elastic SDOF systems 90–3
- elastomeric gaskets 194–6, 195
- elasto-plastic SDOF systems 106–8, 238, 303–11
- electric shock 278
- element failure 84–5, 85
- emergency access 256, 258, 267, 270
- Emirates Stadium 15
- empirical methods 74–8
- encastré beams, SDOF properties 296
- encroachment (vehicle-borne threats) 254
- end rotations 21, 117, 117, 160, 238, 239
- energy
 - absorption 10, 18–19, 21, 124, 190, 200–201, 242, 266
 - alternate loadpath analysis 25, 221–2, 230, 233–47
 - balance 239, 241–5
 - conservation 80
 - dissipation 43, 48, 53, 86, 239–47
 - heat energy 80
 - impact energy, hostile vehicle mitigation 15, 257, 265, 270–1
 - internal energy 53, 239–44
 - kinetic energy
 - blast waves 37, 80, 86, 94
 - turbulent kinetic energy 86
 - structures 101, 103–4, 139
 - vehicles 270–1
 - whole-building response 241, 243
 - zero kinetic energy criterion 241
 - mechanical energy 80
 - strain energy 19
 - alternate loadpath analysis 239–41
 - laminated glass 190–1, 198–201, 209–10
 - structure 94–5, 101, 103–4, 111, 119, 136, 139, 142
 - work done 142, 197–8
 - alternate loadpath analysis 241–4
 - robustness 241–2
 - structure 94, 101, 103, 111, 119
- equipotential bonding 286
- Ergo 197, 211
- Euler equations 81, 86
- Eurocodes 24, 125, 134, 175, 232
- Europa Hotel (Belfast) 21
- evacuation 3, 5, 6, 225, 254
 - blast resilience 14, 26–8
 - operational resilience 276, 279, 281–2, 287–9
- evacuation time 225
- expansion loops 283, 284
- explosions/explosives, classifications of 33–5
- façade design
 - behaviour when subjected to blast loading 6, 12–13, 18, 20, 37, 75–6, 84, 186
 - edge reactions 191–6, 199, 214
 - framing members 192–4, 196, 199, 214–16
 - framing rebates 194
 - framing systems 193–6
 - stick system 214–15
 - stick-and-cassette system 214
 - unitised system 214–15
- failure
 - façades 12–13, 18, 76–7, 186
 - glazing 12–13, 18, 65, 76–7, 185, 186, 216
 - annealed glass 188, 189, 204
 - heat-strengthened glass 188, 203–4
 - laminated glass 190–1, 193–5, 199–203, 210, 213, 218
 - toughened glass 188, 190
 - masonry 161
 - operational resilience 276–7, 280–3, 285–6
 - reinforced concrete 22–4, 131, 132, 136, 138, 154
 - steel-concrete-steel composite materials 166–7, 169–73, 175, 183
 - steel structures 22–4, 114–15, 119, 121, 125–6
 - whole-building response 222–4, 231–47
- failure mode and effects analysis (FMEA) 282
- failure mode, effects and criticality analysis (FMECA) 282
- failure modes 13, 98, 166, 169–75, 228, 247, 282
- final denial barriers 268, 269
- finite element analysis 199, 214
- fire-fighting systems 281
- first-principle methods 74, 79–87
- flame front 36, 87
- flexural design
 - reinforced concrete 138–43
 - steel-concrete-steel composite materials 175–80
 - steel structures 119–21, 122–3
- flexible connections 285
- float glass *see* annealed glass
- flooding 277–8
- floor slabs 13, 155, 194, 216, 222, 233–4, 280, 283
- form of construction (risk factor) 228
- flow field 74, 79, 82, 85
- fluid flow, governing equations 76–7, 79–85
- fluid–structure interaction 77, 206
- form of construction (risk factor) 228
- Foster + Partners 225
- fragments/fragmentation 3, 4, 35, 85, 99, 117
 - in reinforced concrete 135, 136, 154
 - in steel-concrete-steel composite materials 169, 171–2
- fragment shields 154
- glazing 185–92, 187, 216–19
- vehicle-borne threats 271–2, 277
- Friedlander equation 39, 41, 75
- fuel–air explosions 34, 36, 39, 86
- gas, natural 44–5, 53, 55, 78–9
 - explosions 23, 33–5, 37
 - fuel–air weapons 34, 36, 39, 86
 - leaks 278
 - Ronan Point 23, 223–4, 224

- vapour cloud explosions *see* vapour cloud explosions
- gas pressure 33, 65, 68–70, 77
see also quasi-static pressure
- internal explosions 70
- glass
 - annealed glass *see* annealed glass
 - float *see* annealed glass
 - heat-strengthened glass 188, 192, 203–4
 - laminated glass *see* laminated glass
 - monolithic glass 185, 188, 191–3, 197, 214, 216–18, 219
 - plain *see* annealed glass
 - tempered glass *see* toughened glass
 - toughened glass 20, 188, 190, 191–2, 195, 197, 198, 203–4
- Glasgow Airport 251, 252
- glazing
 - annealed glass 20, 188, 189, 191–2, 197, 198, 201, 204, 207–14, 218
 - blast loading 18–21, 20, 21, 65, 185–6, 194–201, 204, 215–18
 - behaviour under 188–91
 - blast enhancement 191–3
 - resistance function in laminated glass 201, 204
 - blast engineering, in glazing design 192–3
 - blast resilience 11–12, 18–21, 20, 21, 188, 191
 - cracking 188–210, 213–14, 218
 - design 185–6
 - breaching 185–6, 210, 212
 - breaking strengths 188, 198–204
 - connections 215–16
 - deformation limits 215–16
 - edge reactions 191–6, 199, 214
 - fragmentation 185–92, 187, 216–19
 - framing design 214–16
 - framing systems 193–6
 - hazard classification 216–19
 - iso-damage analysis 199, 210, 212–14, 219
 - levels of blast enhancement 191–3
 - notation 185
 - resistance function 196–212
 - SDOF systems 196–8, 210–12
 - tearing 187, 190–6, 198–9, 204–13, 218–19
 - types and behaviour under blast loading 188–91
 - hazard mitigation, in glazing design 185, 192, 210
 - heat-strengthened glass 188, 192, 203–4
 - laminated glass *see* laminated glass
 - palliative measures, in glazing design 192–3
 - toughened glass 20, 188, 190, 191–2, 195, 197, 198, 203–4
- Glazing Hazard Guide 196–7
- ground penetrating radar (GPR) surveys 266
- gravitational loading 126, 222, 233–40, 243, 245–6
- groundshock 19, 34, 43, 47–52, 53, 282
- hazard classification (of glass) 216–19
- hazard mitigation, in glazing design 185, 192, 210
- hazardous substances 278
- Health and Safety at Work Act (1974) 4–5
- heat-affected zone (HAZ) 171, 172
- heat energy 80
- heat-strengthened glass 188, 192, 203–4
- hemispherical explosions 16, 33, 42–3, 45, 46, 47, 48, 55, 74–5, 147, 207, 212
- high explosives 154, 172, 224
 - blast loading 33–5, 36, 42–3, 52–3, 63
 - prediction of 74–5, 77–8, 81–5
 - structural response to 92
- home-made explosive (HME) 35
- Home Office Scientific Development Branch (HOSDB) 185
- Hopkinson-Cranz scaling 41
- hostile vehicle mitigation (HVM) 255–70, 272
- IEDs (improvised explosive devices) 35, 288–9
 - person-borne 15, 192
 - vehicle-borne 251–2, 254–5, 282
- ignition location 36–7, 87
- impact energy 15, 265, 270–1
- impulse
 - incident/side-on impulse 48, 50
 - positive impulse 74–5, 207, 212
 - reflected impulse 46, 147, 207, 212, 314
- impulsive asymptote 95–6, 213
- impulsive design
 - reinforced concrete 139–41, 144–50
 - steel-concrete-steel composite materials 175–6, 180
 - steel structures 121
- impulsive loading 34, 121, 213, 313
 - in reinforced concrete 139–41, 147–50
 - in steel-concrete-steel composite materials 176–82
- incident emergency management 287
- incident/side-on impulse 48, 50
- incident/side-on pressure 37, 45–6, 48–9
- ‘in-contact’ detonation 171, 173, 173
- indirect design 232
- in-plane forces 105, 191, 193–6, 199, 205, 214–15
- insider threats (vehicle-borne threats) 254
- Institution of Structural Engineers 225–7, 231
- interlayer, glazing
 - polyvinyl butyral (pvb) 190–3, 199, 204–7, 209, 214
 - polyurethane 191
- internal energy 53, 239, 241–4
- interlocked barriers 267, 268
- internal blast loading 18, 19, 65, 67, 68
 - blowdown time 69–70
 - gas pressures 33, 65, 68–70, 77
 - quasi-static pressures 68–70
- International Building Code 18
- ‘invacuation’ 26, 28
- inviscid fluid 53, 81, 85
- IRA attacks 2, 223, 225–6
- ISO hazard classification 217, 272

- iso-damage analysis 90, 95–100, 102, 199, 210, 212–14, 219
 - impulsive asymptote 95–6, 213
 - pressure asymptote 94, 212–13
- IWA 14 standard, vehicle security barriers 272
- Kansallis House (Bishopsgate, London) 226
- Kevlar 25
- key element design 13–14, 224, 230–1, 232, 247, 248
- kinetic energy 37, 80, 86, 94, 101, 103–4, 139, 241, 243, 270–1
- L-bars 156–7
- laminated glass 185–6, 187, 188, 190–1
 - blast resilience 21, 21
 - derivation of resistance function 199–207
 - design examples 207–12
 - design for blast loads 196–9
 - framing systems 193–6
 - glazing hazard classification 216, 218–19
 - levels of blast enhancement 191–3
- laps, reinforcement 155
- lateral bracing/restraint 105, 121, 124–5, 315
- lateral-torsional buckling 121
- layered attacks (vehicle-borne threats) 255
- legal obligations 4–5
- legislation 4–5
- lighting, of protected spaces 280
- linear dynamic analysis procedures 245–6
- linear static analysis procedures 240–1
- load–deformation 244
- load–mass transformation factor 104, 120, 139, 143, 160, 198, 210, 294–301, 315
- loading-dependent failure modes 172–3
- local buckling 119, 121, 124–5, 315
- longitudinal shear 169, 170–1, 174–6, 181–2, 199
- Longridge House (Manchester) 22
- loss of reputation 4, 287
- low explosives 34
- lumped mass equivalent SDOF systems 102–5, 111
- lung damage 20, 99–100
- Mach reflection 45–6, 49
- Management of Health and Safety at Work Regulations (1999) 4
- masonry
 - design 159–63
 - arching 159, 161–3, 161, 162
 - behaviour when subjected to blast loading 160–3
 - deformation limits 160
 - design strength 160
 - end rotation 160
 - partial factors 160
 - resistance function 160–2
 - reinforced masonry 159–60
 - unreinforced masonry 159–63
- mass, conservation of 79, 81
- mass transformation factor 90, 104, 139, 160, 198, 210
- material non-linearity 238
- mechanical energy 80
- mechanisms of resistance to progressive collapse
 - catenary action 232–5, 238, 240–6
 - compressive arching 161–2, 232, 234–5, 241–2
 - shear stiffening 174, 179–80, 235, 241
 - tensile membrane action 105, 138, 173
 - Vierendeel action 226, 234–5
- membrane action 105, 125, 138, 155, 173, 232, 234, 240–3, 245–6
- military explosives 35
- modulus of elasticity 115, 140, 160, 175
- modus operandi, terrorism 26, 251–2, 254, 270
- moment capacity 107, 108, 167–8, 177, 215, 294–301
- momentum, conservation of 79–81
- monolithic glass 185, 188, 191–3, 197, 214–9
- motion, equation of 90–1, 93, 102–4, 111, 175
- Murrah Federal Building (Oklahoma City) 24–5, 25, 223, 227
- natural disasters 1, 2
- natural period 18–19, 90, 92–3, 120–1, 142, 314–15
 - see also* positive phase
- Navier–Stokes equations 79–81, 86
- negative phase (of blast wave) 35, 40, 40–1, 43, 43, 47, 54, 65, 66, 206
- net curtains *see* bomb blast net curtains
- new or existing construction (risk factor) 228
- non-linear dynamic analysis procedures 246–7
- non-linear static analysis procedures 240, 241
- non-linear static pushover analysis 241–5, 246
- novel or innovative construction (risk factor) 228
- nuclear explosions 33, 92
- occupancy profile 225, 227
- one-way spanning glass 194–5
- one-way spanning structural systems 105
- operable vehicle security barriers *see* active vehicle security barriers
- operational requirements (vehicle security barrier systems) 253, 272–3
- operational resilience 276, 279, 281–2, 287–9
- out-of-plane forces 169, 183, 191–2, 199, 214
- overpressure *see* pressure
- package bombs 288
- palliative measures, in glazing design 192–3
- ‘pancaking’ of floor slabs 222
- parked vehicles (vehicle-borne threats) 253–4
- partial factors 9, 201
 - masonry 160
 - reinforced concrete
 - compression 133–4, 136–8, 142, 144–5, 151, 154–5
 - flexure 137, 139–43, 148–52
 - partial load factors 131
 - partial material factors 134
 - shear 131, 133–4, 138, 144–7, 149–50, 152–5
 - steel-concrete-steel composite materials 175

- bar connectors 170–4, 176, 179, 181–2
- partial load factors 167
- partial material factors 167
- steel plate 168–9, 173–5
- welds 171–2, 183–4
- steel structures
 - flexure 119–20, 122–3
 - joints/connections 124
 - partial load factors 114
 - partial material factors 116
 - shear 114–16, 119, 121, 123–4
- partial rotational fixity 108–9, 125
- particle velocity 41, 48–50, 51
- partitions 14, 18, 27, 97–8
- PAS 68 standard, vehicle security barriers 271–2
- passive vehicle security barriers 263, 263–5, 268
- porosity/distributed resistance (PDR) method 86
- peak dynamic displacement 243
- peak overpressure 16–17, 33, 36–9, 44, 49, 50, 64, 76, 78, 97, 97
- pedestrian permeability, design of vehicle security barriers 259
- penetrative attacks (vehicle-borne threats) 254
- Pentagon 3, 25
- perimeter security 252, 254, 257–9, 265, 268, 273
- person-borne improvised explosive devices (PBIEDs) 15, 192
- phenomenological methods 74, 78–9
- planning for protection 9–10
- plant and equipment 278
- plastic analysis 102
- plastic strain 19, 238, 240–1, 245, 247
- Poisson effect 48
- polycarbonate 191
- polynomial equations 74–5
- polyurethane 191
- polyvinyl butyral (pvb) 190–3, 199, 204–7, 209, 214
- population (building occupancy) 225
- positive impulse 74–5
- positive phase (of blast waves) 35, 39, 40, 41, 42, 44, 46, 48, 65, 66, 206
- positive pressure 59, 66, 74
- post-crack resistance function 198, 204–6, 208–10
- power supplies 281
- practical site assessment (vehicle-borne threats) 255–7
- pre-crack resistance function 197–205, 207–9
- pre-existing flaws 201–2
- pressure
 - ambient/atmospheric pressure 16, 35–40, 44–5, 70, 78, 99
 - drag pressure *see* dynamic pressure
 - dynamic pressure 37, 41, 44, 62, 64–5, 76
 - gas pressure *see* quasi-static pressure
 - incident/side-on pressure 37, 45–6, 48–9
 - internal pressure 67, 70, 78
 - overpressure
 - blast loading 33, 36–50, 62–8, 74–9, 97–101
 - blast resistance 16–17, 20
 - positive pressure 59, 66, 74
 - pressure energy 35, 37, 53, 57, 80
 - quasi-static pressure 68–70
 - reflected pressure 18, 37, 39, 53, 75, 207, 212, 314
 - stagnation pressure 62
 - static pressure 247
- pressure asymptote 94–6, 212
- pressure energy 35, 37, 53, 57, 80
- pressure–impulse diagrams 84–5, 90, 95–100
- pressure–time function 35, 36, 37, 39, 40, 54, 58, 58, 61, 61, 67, 68, 68–9
- primary explosives 34
- primary injuries 99
- procurement (risk factor) 228
- progressive collapse 4, 23–5, 25, 27, 223, 224, 227, 232, 239, 241
- propped cantilevers, SDOF properties 298–300
- protected spaces 26–9, 276–86
- protection from threats (risk factor) 228
- quasi-static loading 176, 212, 236
 - in reinforced concrete 141–3, 150–3
 - in steel structures 119–24
 - structural response to 90, 92–6, 92, 94, 95, 101–3, 105–6, 110–11
- quasi-static pressure 68–70
- range *see* stand-off distance
- range–charge weight 97, 98–9, 100
- Rankine-Hugoniot relation 37, 44–5
- Rayleigh waves 48
- Rayleigh–Ritz method 100–101
- RDX 34–5, 39
- re-deployable barriers 259
- redundancy 282
- reflections
 - blast waves 67, 75, 77
 - coefficients 44–6, 50, 74–6
 - Mach reflection 45–6, 49
 - regular reflection 45–6, 49
- reflected impulse 46, 147, 207, 212, 314
- reflected pressure 18, 37, 39, 53, 75, 207, 212, 314
- reflection coefficients 44–5, 46, 50, 74, 75–6
- regular reflection 45–6, 49
- reinforced concrete
 - blast resilience 13–14, 19, 22, 23, 24, 24, 27–8
 - comparisons with SCS 166–7, 169–71, 173–5, 182–3
- design 129
 - behaviour when subjected to blast loading 136–8
 - blast loading resistance 138–9
 - breaching *see* spalling and breaching
 - connection 156–7
 - deformation limits 134–5
 - design loads 131, 133
 - design strengths 133–4, 136
 - detailing 154–5, 156
 - ductility ratio 131, 135, 138, 139, 142, 154–5
 - dynamic increase factor 133–4
 - dynamic reactions 147, 153

- reinforced concrete (*continued*)
 - end rotation 155
 - flexural design 138–43
 - impulsive response 139–41, 147–50
 - joint failure 131, 132
 - quasi-static/dynamic response 141–3, 150–3
 - scabbing 154
 - shear design 145, 149–50, 152–3
 - shear reinforcement 144–7
 - spalling and breaching 137–8, 154
 - static increase factor 133
 - stiffness 139
 - wall panel subject to quasi-static/dynamic load 150–3
- structural response to blast loading 109–10
- reinforced masonry 159–60
- reinforcement grade 155
- reinforcement placement 155
- residual pulse 199, 212–13
- resilience *see* blast resilience; operational resilience
- resistance function 242, 304–11
 - in steel-concrete-steel composite materials 175
 - in glazing design 196–212
 - in masonry design 160–2
 - structural response to blast loading 102, 105–9, 111
- resistance–deflection function 119, 314
 - design elements in reinforced concrete 136–42
 - design of steel-concrete-steel composite materials 169–70, 175
 - glazing design 198, 209
 - masonry design 160, 162–3
 - structural response to blast loading 94, 94, 105
- response actions (operational resilience) 288–9
- reverberation 67–8
- risk assessment 9, 225, 239, 253, 290
- risk aversion 2, 8
- risk factors 225–8
- road safety audit 262
- robustness requirements 13, 223
- Ronan Point (London) 23, 223, 224
- rotational ductility 22–3, 124, 233, 239
- rotational fixity 108–9, 125
- sanitation and drainage 280
- scabbing 154, 169, 171–2
- scenario-independent and scenario-dependent modelling 237–8
- single degree of freedom (SDOF) systems
 - advanced methods 107–9
 - beams/slabs 293–301
 - catenary action 232–5, 238, 240–6
 - design elements in reinforced concrete 141, 143, 152
 - design of steel structures 119–20, 123
 - elastic structure 90–2
 - equation of motion 90–1, 93, 102–4, 111, 175
 - equivalent properties for beams and slabs 293–301
 - glazing design 196–98, 210–12
 - limitations of 107
 - lumped mass equivalent systems 102–5, 111
 - maximum deflection and response times 119–20, 123, 141, 143, 303–11
 - whole-building response 236, 237, 238, 243
- seabed interactions 55–6
- seating cleats 126, 126
- secondary explosives 34–5
- secondary effects, steel structures 121, 123–4
- secondary injuries 99
- section type
 - reinforced concrete 169–74, 182
 - type 1 section 136–7, 142, 145–6, 150–2, 313–14
 - type 2 section 137, 140, 144–6, 148, 176, 313–14
- semi-empirical basis 6, 206
- semi-permanent barriers 259
- sensitivity to design assumption (risk factor) 228
- services
 - containment 267, 278, 283, 285–6
 - design for blast loading 5, 275–7, 282, 287
 - fixing/mounting 275, 277, 283–6
 - life safety 276–9
 - protected spaces 26–9, 276–86
 - operational resilience 276, 279, 281–2, 287–9
 - recovery 286–7
- shear and secondary effects 121, 123–4, 276
- shear capacity 13, 107, 119, 121, 138, 145, 247
- shear force 144–6, 152, 155, 174, 176, 180–1, 215
- shear reinforcement 138, 144–6, 154–5
- shear resistance 123, 133, 144–6, 169, 174–6, 181–2
- shear stiffening 174, 179–80, 235, 241
- shelter areas *see* bomb shelter areas
- shielding 76–7, 77, 117, 135, 154, 280
- simply-supported beams, SDOF properties 294–5
- single line of barriers 267, 268
- societal expectations (risk factor) 228
- sound velocity 64
- spalling and breaching 137, 138, 154, 169, 171–2
- special effects of catastrophic loss 8
- spherical explosions 33, 38, 41–3, 43, 44, 45, 48, 55, 74–5, 154
- splices 126
- sprinkler systems 278, 281
- St Mary Axe (Chamber of Shipping, London) 223, 225
- stack joints 215
- stagnation pressure 62
- stand-off distance 147, 173, 228
 - blast loading 65, 75, 97, 98
 - blast resilience 12, 14–15, 16, 27
 - glazing design 192, 196, 207, 211–14
 - vehicle-borne threats 251–5, 257–9, 263, 269, 272
- stagger length, chicanes 261
- static increase factor (SIF) 115, 133, 167–8, 176, 215
- steel-concrete-steel (SCS) composite materials 166

- bar connectors 170–4, 171, 172, 174, 176, 179, 181–2
- behaviour when subject to blast loading 169–73
- Bi-Steel 154, 173, 173–84
- blast loading resistance 175–6
- comparisons with reinforced concrete 166–7, 169–71, 173–5, 182–3
- connections 169–76, 171, 172, 174, 179, 181–4
- deformation limits 168
- design loads 167
- design strengths 167–8
- detailing 183–4
- ductility ratio 167, 169, 183–4
- dynamic increase factor 167, 176
- failure modes 166, 169–75
- flexural design 175–80
- longitudinal shear 169–71, 174–6, 181–2, 199
- resistance function 175
- shear design 170, 174–6, 180–2
- static increase factor 167–8, 176
- stiffness 173–4
- transverse shear 169–71, 174–6, 181
- steel structures
 - blast resilience 13, 19–24, 22, 27
 - design 114
 - behaviour when subjected to blast loading 118–19
 - blast loading resistance 119–21
 - connections 114, 116, 124–5, 126
 - deformation limits 116–17
 - design loads 114–15
 - design strengths 115–16, 124
 - ductility ratio 114–21, 124, 125
 - dynamic increase factor 115
 - dynamic reactions 121–2, 124
 - end rotation 117–18
 - flexural design 119–23
 - impulsive response 121
 - quasi-static/dynamic response 119–21, 122–4
 - shear design 116
 - static increase factor 115
 - stiffness 119, 121, 124–5
 - steelwork detailing 125–6
 - structural response to blast loading 109–10, 110, 111
- stick system 214–15
- stick-and-cassette system 214
- stoichiometry (fuel–air mixture) 36, 86
- strain rate effects 9, 133, 206
- strategic assets 226
- structural response 90, 111
 - advanced SDOF methods 107–9
 - behaviour of structural materials 109–10, 111
 - elastic analysis 100–102
 - energy solutions for specific structural components 100–102
 - iso-damage diagrams 90, 95–100, 102
 - limitations of SDOF methods 107
 - limits of response 93–5
 - lumped mass equivalent SDOF systems 102–5, 111
 - near field 109
 - notation 89–90
 - positive phase 90–3, 98–9
 - pressure–impulse diagrams 90, 95–100
 - quasi-static loading 90, 92–6, 92, 94, 95, 101–3, 105–6, 110–11
 - resistance function 102, 105–9, 111
 - SDOF elastic structure 90–2
 - structural robustness 3, 6–7, 255
 - blast resilience 13, 23–5, 28, 191
 - robustness requirements 13, 223
 - whole-building response 223, 226–8, 230–48
 - structural silicone 192, 194–6, 196, 199, 214–15
 - support rotations 116, 119, 135–7, 139, 145, 154–5, 160, 168, 314
 - support shears 121, 123, 144–6, 150, 153, 294–300
 - surreptitious or forced attacks (vehicle-borne threats) 255
 - system resilience 282–6
- tearing (of glazing) 187, 190–6, 198–9, 204–13, 218–19
- telephoned bomb threats 288
- temporary barriers 259
- tensile membrane action 105, 138, 173
- tensile strength 109, 115, 118, 133, 155, 162, 190, 201
- terrorism
 - glazing design 193, 196
 - minimising impact of attacks 2–6, 9–10
 - modern terrorism 7–8
 - operational resilience 275, 287–90
 - protected spaces 26–9
 - risk 1–2, 8
 - special effects of catastrophic loss 8
 - vehicle-borne threats 251–2, 254, 262, 272
 - whole-building response 222–3, 225–6
- tertiary injuries 99
- Terrestrial Trunked Radio (TETRA) 281
- thermal breaks 194, 215
- threat assessment 287
- tie-force method 230, 231–3
- ties 25, 125, 137, 155–6, 229–33
- TNO multi-energy method 78
- TNT (trinitrotoluene) 34–5, 41–4, 46–8, 57, 60, 74, 97–8, 100, 147, 154, 207, 212
 - TNT equivalence 16, 33, 38–9
- tolerability of risk 1–2, 223–30
- toughened glass 20, 188, 190, 191–2, 195, 197, 198, 203–4
- traffic calming 15, 260–1, 261
- traffic exclusion 258
- traffic exclusion with screening 258–9
- traffic inclusion with HVM 259
- traffic management 253, 258–9, 269, 272–3
- transfer beams 13, 126, 223–4, 227
- transformation factor
 - load 90, 104–5
 - load-mass 104, 139, 160, 198, 210
 - mass 90, 104–5

- transformed sections, flexure 178
- transverse shear 169–71, 174–6, 181
- trees 265
- trial holes, vehicle security barriers 270
- turbulence 85–6
- two-way spanning glass 193
- U-bars 156
- ultimate limit state 9, 21–2, 114, 131
- underwater explosions
 - calculation of blast parameters 55–8
 - calculation of bubble loading parameters 58–61
 - characteristics of 52–5, 56
- unitised system 214–15
- unreinforced masonry 159, 160–3
- unrestrained elements 125–6
- unvented structures 65
- US Army Corps of Engineers 38
- vapour cloud explosions
 - blast loading 33–7, 39
 - prediction of 74, 77–9, 81, 85, 87
- vehicle access control points (VACPs) 254, 256, 258–60, 267, 268, 269–70
- vehicle-as-a-weapon (VAW) attacks 251–2, 257, 262, 272
- vehicle-borne improvised explosive devices (VBIEDs) 251–2, 254–5, 282
- vehicle-borne threats 251–2
 - blast resilience 255, 258, 261
 - mitigation of 252–72
 - practical site assessment 255–7
 - stand-off 251–5, 257–9, 263, 269, 272
 - traffic management 253, 258–9, 269, 272–3
 - types of 253–5
 - VBIEDs 251–2, 254–5
- vehicle access control points 254, 258–60, 267, 268, 269–70
- vehicle dynamics assessment 255, 257, 270
- vehicle security barriers *see* VSBs
- vehicle-as-a-weapon attacks 251–2, 257, 262, 272
- vehicle dynamics assessment (VDA) 255, 257, 270
- vehicle security barriers (VSBs) 15, 15, 251–7, 263, 264, 268
 - active vehicle security barriers 264, 267–70
 - design 252–4, 260–72
 - hostile vehicle mitigation 258–70
 - operational requirements 272–3
- standards and design guidance 271–2
- passive vehicle security barriers 263, 263–5, 268
- temporary barriers 259
- venting 13, 192, 206
 - blast loading 47, 65, 68–70, 68, 74, 77–9
 - operational resilience 277, 279–81, 286
- Vierendeel action 226, 234, 235
- voice-over internet protocol (VOIP) 281
- walls 15, 15
 - blast protection 12, 19, 25, 147–8, 150–1
 - building services 27–8
 - masonry 159–63
 - penetrations 283
- wavefront parameters 16–17, 35, 37–9, 41–2, 45, 48, 65, 76, 84
- web stiffeners 121, 124–5
- welds 110, 124, 126, 154, 171–2, 183–4
- wet or dry glazing, selection of 194
- whole-building response 221–2, 247–8
 - alternate loadpath methods 221–2, 230, 233–47
 - Building Regulations 221–6, 229, 231–3, 247
 - catenary action 232, 234–5, 238–46
 - connections 231–3, 238–40, 245, 247–8
 - disproportionate collapse 221–3, 225, 228–31, 237, 239, 247
 - dynamic load factors 234–43, 236, 237
 - gravitational loading 222, 233–40, 243, 245–6
 - key element design 224, 230–2, 247–8
 - notation 221
 - progressive collapse 222–3, 224, 227, 232, 239, 241
 - reinforced concrete 223, 226, 231, 233
 - SDOF systems 236, 237, 238, 243
 - steel structures 223, 231–3
 - structural robustness 223, 226–8, 230–48
 - tie-force method 230–3
 - tolerability of risk 223–30
- wind loads 11, 114, 131, 160, 167
- World Trade Center (New York City) 3, 5–6, 251
- work done 142, 197–8
 - glazing 241–4
 - robustness 241–2
 - structure 94, 101, 103, 111, 119
- yield strength 102, 115, 133, 167–8, 215
- Young's modulus 101
- zero kinetic energy criterion 241