
Table of Contents

Chapter 1	Introduction.....	1
1.1	General Background.....	1
1.2	Protective Planning and Design Philosophy.....	5
1.3	Protection Methodology, Threat, and Risk Assessment.....	8
1.3.1	Threat, Hazard, and Vulnerability Assessments.....	10
1.3.2	Risk Assessment.....	11
1.4	From Threat and Hazard Environment to Load Definition.....	16
1.4.1	Military Threat Assessment.....	19
1.4.1.1	Tactics and Strategy.....	19
1.4.1.2	Weapons Systems.....	21
1.4.1.3	Summary.....	24
1.4.2	Terrorism and Insurgency Threat Assessment.....	24
1.5	Technical Resources and Blast Mitigation Capabilities.....	24
1.5.1	Design Manuals.....	26
1.5.2	Design and Construction Considerations.....	28
1.6	Analysis Requirements and Capabilities.....	30
1.6.1	Computational Analysis.....	30
1.6.2	Experimental Analysis.....	30
1.7	Protective Technology: Current State and Future Needs.....	31
1.7.1	Relationships to R&D.....	33
1.7.2	Policy and Technology Needs.....	35
1.7.3	Development and Implementation of Protective Design Methodology.....	37
1.7.3.1	Basic and Preliminary Applied Research.....	38
1.7.3.2	Applied Research, Advanced Technology Development, and Demonstration and Validation Tests.....	38
1.7.3.3	Demonstration, Validation, and Implementation.....	38
1.8	Summary.....	39
Chapter 2	Explosive Devices and Explosions.....	41
2.1	Introduction.....	41
2.2	Characteristics of Explosive Processes, Devices, and Environments.....	41
2.2.1	Nuclear Weapons.....	41
2.2.2	Conventional Weapons.....	41

	2.2.2.1	Small Arms and Aircraft Cannon Projectiles	42
	2.2.2.2	Direct and Indirect Fire Weapon Projectiles	42
	2.2.2.3	Grenades	44
	2.2.2.4	Bombs	46
	2.2.2.5	Rockets and Missiles	47
	2.2.2.6	Special-Purpose Weapons	48
	2.2.3	Conventional Weapons Summary	49
2.3		Explosives, Explosions, Effects and Their Mitigation.....	50
	2.3.1	Blast Effects and Mitigation	50
	2.3.2	Explosives and Explosions.....	53
	2.3.3	Explosive Types and Properties	58
	2.3.4	Combustion Phenomena and Processes.....	59
	2.3.5	Detonation Process and Shock Waves	60
Chapter 3		Conventional and Nuclear Environments.....	65
3.1		Introduction.....	65
3.2		Airblast.....	68
	3.2.1	HE Devices and Conventional Weapons	68
	3.2.1.1	External Explosions	68
	3.2.1.2	Internal Explosions	75
	3.2.1.3	Leakage Blast Pressure	77
	3.2.2	Nuclear Devices	79
3.3		Penetration	83
	3.3.1	Concrete Penetration	87
	3.3.2	Rock Penetration	92
	3.3.3	Soil and Other Granular Material Penetration	96
	3.3.4	Armor Penetration	98
	3.3.5	Penetration of Other Materials.....	101
	3.3.6	Shaped Charges	103
3.4		HE-Induced Ground Shock, Cratering, and Ejecta.....	106
	3.4.1	HE Charges and Conventional Weapons	106
	3.4.2	Three-Dimensional Stress Wave Propagation.....	106
	3.4.3	One-Dimensional Elastic Wave Propagation.....	110
	3.4.4	Reflection and Transmission of One-Dimensional D-Waves between Two Media	114
	3.4.5	Computational Aspects.....	116
	3.4.6	Shock Waves in One-Dimensional Solids	117
	3.4.7	Stress Wave Propagation in Soils	119
	3.4.7.1	Numerical Evaluation	125
	3.4.8	Application to Protective Design.....	129
	3.4.9	Cratering	135
	3.4.10	Ejecta	137
3.5		Cratering, Ejecta, and Ground Shock from Nuclear Devices	141
	3.5.1	Cratering	141

3.5.2	Ejecta	145
3.5.3	Ground Shock.....	147
3.6	Fragmentation	153
3.6.1	Fragment Penetration	158
3.7	Fire, Chemical, Bacteriological, and Radiological Environments	167

Chapter 4 Conventional and Nuclear Loads on Structures 169

4.1	Conventional Loads on Structures	169
4.1.1	Buried Structures.....	169
4.1.2	Above-Ground Structures	170
4.1.3	Mounded Structures	175
4.1.4	Surface-Flush Structures	175
4.1.5	Blast Fragment Coupling	175
4.2	Nuclear Loads on Structures	177
4.2.1	Above-Ground Structures	177
4.2.2	Buried Structures.....	179
4.2.3	Soil Arching	185
4.3	Step-by-Step Procedures for Deriving Blast Design Loads	187
4.3.1	Constructing Load–Time History on Buried Wall or Roof.....	187
4.3.2	Computing Pressure–Time Curve on Front Wall from External Explosion (Surface Burst).....	187
4.3.3	Computing Pressure–Time Curve on Roof or Sidewall (Span Perpendicular to Shock Front)	190
4.3.4	Computing Pressure–Time Curve on Roof or Sidewall (Span Parallel to Shock Front)	190
4.3.5	Blast Load on Rear Wall.....	191

Chapter 5 Behaviors of Structural Elements 195

5.1	Introduction.....	195
5.2	Government and Non-Government Manuals and Criteria.....	196
5.2.1	Tri-Service Manual TM 5-1300 (Department of the Army, 1990)	196
5.2.2	Army Technical Manuals 5-855-1 (Department of the Army, 1986 and 1998), and UFC 3-340-01 (Department of Defense, June 2002).....	197
5.2.3	ASCE Manual 42 (ASCE, 1985).....	197
5.2.3.1	Design of Blast Resistant Buildings in Petrochemical Facilities (ASCE, 1997).....	197
5.2.3.2	Structural Design for Physical Security (ASCE, 1999).....	197
5.2.4	DoD and GSA Criteria.....	198
5.3	Distances from Explosion and Dynamic Loads	198

5.4	Material Properties of Steel and Concrete.....	198
5.4.1	Steel.....	198
5.4.2	Concrete.....	199
5.4.3	Dynamic Effects.....	202
5.5	Flexural Resistance.....	202
5.6	Shear Resistance.....	205
5.7	Tensile and Compressive Members.....	206
5.8	Principal Reinforcement.....	207
5.9	Cylinders, Arches, and Domes.....	208
5.10	Shear Walls.....	212
5.11	Frames.....	214
5.12	Natural Periods of Vibration.....	215
5.13	Advanced Considerations.....	218
5.13.1	Membrane Behavior.....	218
5.13.1.1	Membrane Application for Analysis and Design.....	225
5.13.2	Direct Shear.....	226
5.13.3	Diagonal Shear Effects.....	228
5.13.4	Size Effects and Combined Size and Rate Effects.....	230
5.13.5	Connections and Support Conditions.....	231
5.14	Application to Structural Design.....	233
5.15	Practical Damage and Response Limits.....	234

Chapter 6 Dynamic Response and Analysis.....237

6.1	Introduction.....	237
6.2	Simple Single Degree of Freedom (SDOF) Analysis.....	240
6.2.1	Theoretical Solution for SDOF Systems: Duhamel's Integral.....	242
6.2.2	Graphical Presentations of Solutions for SDOF Systems.....	247
6.2.3	Numerical Solutions of SDOF Systems.....	247
6.2.4	Advanced SDOF Approaches.....	250
6.3	Multi-Degree-of-Freedom (MDOF) Systems.....	251
6.3.1	Introduction to MDOF.....	251
6.3.2	Numerical Methods for MDOF Transient Responses Analysis.....	255
6.4	Continuous Systems.....	258
6.4.1	General Continuous Systems.....	259
6.5	Intermediate and Advanced Computational Approaches.....	262
6.5.1	Intermediate Approximate Methods.....	263
6.5.2	Advanced Approximate Computational Methods.....	264
6.5.3	Material Models.....	265
6.6	Validation Requirements for Computational Capabilities.....	267

6.7	Practical Computation Support for Protective Analysis and Design Activities.....	272
6.7.1	Equivalent SDOF System Approach.....	274
6.7.2	Applications to Support Analysis and Design.....	276
6.7.3	Approximate Procedure for Multi-Segmental Forcing Functions.....	281
Chapter 7	Connections, Openings, Interfaces, and Internal Shock.....	291
7.1	Connections	291
7.1.1	Introduction	291
7.1.2	Background	292
7.1.3	Studies on Behavior of Structural Concrete Detailing.....	296
7.1.4	Studies on Behavior of Structural Steel Detailing	308
7.1.5	Summary	309
7.2	Openings and Interfaces	310
7.2.1	Entrance Tunnels	310
7.2.2	Blast Doors.....	310
7.2.3	Blast Valves	313
7.2.4	Cable and Conduit Penetrations.....	315
7.2.5	Emergency Exits	317
7.3	Internal Shock and Its Isolation	317
7.4	Internal Pressure	319
7.4.1	Internal Pressure Increases.....	319
7.4.2	Airblast Transmission through Tunnels and Ducts	319
Chapter 8	Pressure-Impulse Diagrams and Their Applications.....	325
8.1	Introduction.....	325
8.2	Background.....	326
8.3	Characteristics of P-I Diagrams	327
8.3.1	Loading Regimes.....	328
8.3.2	Influence of System and Loading Parameters	330
8.4	Analytical Solutions of P-I Diagrams.....	331
8.4.1	Closed-Form Solutions.....	331
8.4.1.1	Response to Rectangular Load Pulse	331
8.4.1.2	Response to Triangular Load Pulse.....	334
8.4.2	Energy Balance Method.....	335
8.4.2.1	Approximating Dynamic Regions	336
8.4.2.2	Continuous Structural Elements	338
8.5	Numerical Approach to P-I Curves.....	339
8.5.1	P-I Curves for Multiple Failure Modes	341
8.5.2	Summary	341
8.6	Dynamic Analysis Approach.....	343
8.6.1	Introduction	343

8.6.2	Dynamic Material and Constitutive Models.....	343
8.6.3	Flexural Behavior.....	344
8.6.3.1	Dynamic Resistance Function	346
8.6.4	Direct Shear Behavior.....	347
8.7	Dynamic Structural Model.....	348
8.7.1	Flexural Response	349
8.7.1.1	Equation of Motion.....	349
8.7.1.2	Transformation Factors	350
8.7.2	Direct Shear Response	351
8.7.2.1	Equation of Motion.....	351
8.7.2.2	Shear Mass.....	351
8.7.2.3	Dynamic Shear Force.....	352
8.7.3	Summary	357
8.8	Application Examples for SDOF and P-I Computational Approaches.....	357
8.8.1	SDOF and P-I Computations for Reinforced Concrete Beams	357
8.8.2	SDOF and P-I Computations for Reinforced Concrete Slabs.....	363
8.8.3	Summary	366
Chapter 9 Progressive Collapse.....		373
9.1	Introduction.....	373
9.1.1	Progressive Collapse Phenomena	373
9.2	Background.....	374
9.2.1	Abnormal Loadings.....	374
9.2.2	Observations	375
9.3	Progressive Collapses of Different Types of Structures	377
9.3.1	Precast Concrete Structures	378
9.3.2	Monolithic Concrete Structures	378
9.3.3	Truss Structures.....	379
9.3.4	Steel Frame Buildings.....	379
9.4	Department of Defense and General Services Administration Guidelines	380
9.4.1	Department of Defense (DoD) Guidelines.....	380
9.4.1.1	Design Requirements for New and Existing Construction.....	380
9.4.1.2	Design Approaches and Strategies	381
9.4.1.3	Damage Limits.....	384
9.4.1.4	Other Topics	384
9.4.2	GSA Guidelines	384
9.4.2.1	Potential for Progressive Collapse Assessment of Existing Facilities.....	385

9.4.2.2	Analysis and Design Guidelines for Mitigating Progressive Collapse in New Facilities.....	385
9.4.2.3	Analysis and Acceptance Criteria.....	387
9.4.2.4	Material Properties and Structural Modeling.....	389
9.4.2.5	Redesigns of Structural Elements.....	389
9.5	Advanced Frame Structure Analysis.....	390
9.5.1	Background	390
9.5.2	Semi-Rigid Connections	392
9.5.3	Computer Code Requirements.....	394
9.5.4	Examples of Progressive Collapse Analysis.....	395
9.5.4.1	Semi-Rigid Connections	395
9.5.4.2	Analyses	397
9.5.4.3	Results	400
9.5.4.4	Conclusions	400
9.6	Summary.....	404

Chapter 10 A Comprehensive Protective Design Approach.....405

10.1	Introduction.....	405
10.2	Background.....	405
10.3	Protection Approaches and Measures	407
10.4	Planning and Design Assumptions.....	410
10.5	Siting, Architectural, and Functional Considerations	411
10.5.1	Perimeter Line.....	413
10.5.2	Access and Approach Control	413
10.5.3	Building Exterior.....	414
10.5.4	Building Interior.....	416
10.5.5	Vital Nonstructural Systems	417
10.5.6	Post-Incident Conditions.....	417
10.6	Load Considerations.....	417
10.7	Structural Behavior and Performance	422
10.8	Structural System Behavior.....	424
10.9	Structural System and Component Selection.....	430
10.10	Multi-Hazard Protective Design.....	433
10.11	Other Safety Considerations.....	434
10.12	Development and Implementation of Effective Protective Technology	434
10.12.1	Recommended Actions.....	435
10.12.1.1	Basic and Preliminary Applied Research.....	435
10.12.1.2	Applied Research, Advanced Technology Development, Demonstrations, and Validation Tests	436
10.12.1.3	Demonstration, Validation, and Implementation	436

10.12.2	Education, Training, and Technology Transfer Needs	437
10.12.3	Recommended Long-Term Research and Development Activities	438
10.13	Summary	441
References		443
Index		459