
Contents

Preface: Impact and Explosion – Analysis and Design	VII
1 Accident Survey	1
1.1 Introduction	1
1.2 Wind, Hurricane and Tornado Generated Missiles	1
1.2.1 Wind Storm Statistics	2
1.3 Impact and Explosion at Sea	2
1.4 Car Collisions and Explosions	6
1.5 Train Collisions and Impacts	6
1.6 Aircraft and Missile Impacts, Crashes and Explosions	13
1.6.1 Recent Investigations with NTSB Participation	34
1.7 Explosions With and Without Impact	56
1.8 Nuclear Explosions and Loss-of-Coolant Accidents	82
1.9 The Gulf War	84
1.10 Recent Air Crashes: Aircraft Impact at Ground Level	85
1.11 The Dust Explosion Hazard	85
1.11.1 Dust Explosions in the United States, 1900–1956	86
1.11.2 Dust Explosions in the Federal Republic of Germany, 1965–1985	87
1.11.3 Recent Statistics of Grain Dust Explosion in the United States	87
1.12 The Explosion in a Flour Warehouse in Turin on 14 December 1785	92
1.13 Grain Dust Explosions in Norway	92
1.13.1 Wheat Grain Dust, Stavanger Port Silo, June 1970	92
1.13.2 Wheat Grain Dust, New Part of Stavanger Port Silo, October 1988	93
1.13.3 Grain Dust (Barley/Oats), Head House of the Silo Plant at Kambo, June 1976	93
1.13.4 Malted Barley Dust, Oslo Port Silo, July 1976	94
1.13.5 Malted Barley Dust, Oslo Port Silo, June 1987	94

1.14	A Dust Explosion in a Fish Meal Factory in Norway in 1975	94
1.15	Smoldering Gas Explosion in a Silo Plant in Stavanger, Norway, in November 1985	96
1.16	Four Grain Dust Explosions in the United States, 1980–1981	96
1.16.1	Inland Grain Terminal at St. Joseph, Missouri, April 1980	96
1.16.2	River Grain Terminal at St. Paul, Minnesota, 10 June 1980	97
1.17	Two Devastating Aluminum Dust Explosions	98
1.17.1	Mixing Section of Premix Plant of Slurry Explosive Factory at Gullaug, Norway, in 1973	98
1.17.2	Large Export Grain Silo Plant at Corpus Christi, Texas, April 1981	99
1.18	Smoldering Gas Explosions in a Large Storage Facility for Grain and Feedstuffs	100
1.19	Linen Flax Dust Explosion in Harbin Linen Textile Plant ...	101
1.19.1	Explosion Initiation and Development, Scenario 1 ...	101
1.19.2	Explosion Initiation and Development, Scenario 2 ...	103
1.20	Fires and Explosions in Coal Dust Plants	104
1.20.1	Methane Explosion in 17,000 m ³ Coal Silo at Elkford, British Columbia, Canada, in 1982	104
2	Data on Missiles, Impactors, Aircraft and Explosions	105
2.1	Introduction	105
2.2	Types of Conventional Missiles and Impactors	105
2.2.1	Tornado- and Wind-Generated Missiles	106
2.2.2	Plant-Generated Missiles	106
2.2.3	Impact Due to Jet Fluid and Rock Blasting	113
2.2.4	Snow Load as an Impactor	114
2.2.5	Falling or Dropped Weights as Impactors	117
2.2.6	Heavy Lorries, Trucks and Bulldozers as Impactors ..	124
2.2.7	Railway Trains	130
2.3	Military, Air Force and Navy Missiles and Impactors	131
2.3.1	Introduction to Bombs, Rockets and Missiles	131
2.4	Data on Civilian and Military Aircraft, Tanks and Marine Vessels	192
2.4.1	Civilian Aircraft	192
2.4.2	Boeing 737	193
2.4.3	Boeing 767-200ER	199
2.4.4	Boeing 777	200
2.5	Military Aircraft	205
2.5.1	British Aerospace Tornado Interdictor Strike (IDS) and Air Defence Variant (ADV)	205

2.5.2	Northrop F-5E and F-20 Tigershark	206
2.5.3	General Dynamics F-16	206
2.5.4	General Dynamics F-111	211
2.5.5	British Aerospace Jaguar	211
2.5.6	McDonnell Douglas F/A-18 Hornet	213
2.5.7	Soviet Union MIG Aircraft	216
2.5.8	Other Important Fighter/Bomber Aircraft	219
2.6	Lockheed SR-71 Blackbird	231
2.6.1	Introduction	231
2.6.2	Limited Numbers	236
2.7	Northrop Grumman B-2 Spirit	237
2.7.1	Introduction	237
2.8	Grumman F-14 Tomcat	244
2.8.1	Introduction	244
2.9	McDonnell Douglas F-15 Eagle	246
2.9.1	Introduction	246
2.9.2	Multi-Role Fighter	247
2.10	McDonnell Douglas F/-18 Hornet	248
2.10.1	Introduction	248
2.10.2	Fighter Prototypes	249
2.11	Lockheed C-130 Hercules	252
2.11.1	Introduction	252
2.11.2	Design	257
2.11.3	Performance	257
2.11.4	Into service	259
2.12	Mikoyan MIG-23/27 “Flogger”	259
2.12.1	Introduction	259
2.12.2	Fledgling “Floggers”	264
2.13	Sukhoi SU-25 “Frogfoot”	265
2.13.1	Introduction	265
2.13.2	Future “Frogfoots”	269
2.14	Sukhoi Su-27 “Flanker”	270
2.14.1	Introduction	270
2.14.2	Production Variants	270
2.14.3	Long-Range Strike	273
2.14.4	Maritime Role	273
2.14.5	Carrier Trails	273
2.14.6	First Operation Cruise	274
2.14.7	Su-27K Armament Options	274
2.15	Mikoyan MIG-25 “Foxbat”	275
2.15.1	Introduction	275
2.15.2	Mach 3 Spyplane	279
2.15.3	SAM Suppression	279
2.16	Mikoyan MIG-29 “Fulcrum”	280
2.16.1	Introduction	280
2.16.2	Carrierborne “Fulcrum”	280

2.17 Mikoyan–Gurevich MiG-21/Chengdu J-7 “Fishbed”	282
2.17.1 Introduction	282
2.17.2 “Fishbed” Evolution	282
2.17.3 Multi-Variant MiG	283
2.17.4 MiG at War	283
2.18 Mikoyan MiG-31 “Foxhound”	285
2.18.1 Introduction	285
2.18.2 New Design	289
2.18.3 Record Breaker	289
2.18.4 Series Production	291
2.19 EF2000 Fighter Design	293
2.19.1 Introduction	293
2.19.2 Flying Control System	293
2.19.3 No Tailplane Required	294
2.19.4 Direct Voice Input	294
2.20 Saab Viggen (Variants)	294
2.20.1 Introduction	294
2.21 Dassault Mirage F1	296
2.21.1 Introduction	296
2.21.2 Reconnaissance Variant	298
2.21.3 Latest Upgrades	302
2.22 Dassault Mirage 2000	302
2.22.1 Introduction	302
2.22.2 French Operation	306
2.22.3 Weaponry	307
2.22.4 Operators	307
2.22.5 The Future	308
2.22.6 Designing the 2000N	308
2.23 Panavia Tornado	311
2.23.1 Introduction	311
2.23.2 Strike/Attack	312
2.24 Tupolev TU-22 Blinder/TU22M Backfire	313
2.24.1 Introduction	313
2.25 Helicopters	313
2.25.1 Agusta A 101G and Variants	313
2.25.2 McDonnell Douglas AH-64 Apache	325
2.26 Main Battle Tanks (MBTs) as Impactors	349
2.26.1 Marine Vessels	349
2.26.2 Offshore Floating Mobile and Semi-Submersible Structures	355
2.27 Types of Explosion	357
2.27.1 Bombs, Shells and Explosives	357
2.27.2 Gas Explosions	383
2.27.3 Nuclear Explosions	384

2.28	Dust Explosions	393
2.28.1	Introduction	393
2.29	Underwater Explosions	396
3	Basic Structural Dynamics for Impact, Shock and Explosion	399
3.1	General Introduction	399
3.2	Single-Degree-of-Freedom System	399
3.2.1	Unclamped Free Vibrations	399
3.2.2	Solution of the Equation	401
3.2.3	Torsional Vibrations	406
3.2.3	Free Damped Vibrations	423
3.2.4	Undamped Forced Vibrations (Harmonic Disturbing Force)	431
3.2.5	Forced Vibrations with Viscous Damping (Harmonic Force)	441
3.2.6	Single-Degree Undamped Elasto-Plastic System	467
3.3	Two-Degrees-of-Freedom System	468
3.3.1	Undamped Free Vibrations	474
3.3.2	Free Damped Vibration	476
3.3.3	Forced Vibration with Damping	477
3.3.4	Orthogonality Principle	479
3.4	Multi-Degrees-of-Freedom Systems	480
3.4.1	Undamped Free Vibrations	480
3.4.2	Orthogonality Principle	481
3.4.3	Concept of Unit Vectors	482
3.4.4	Undamped Forced Vibrations	483
3.4.5	Non-Linear Response of Multi-Degrees-of- Freedom Systems: Incremental Method	483
3.4.6	Summary of the Wilson- θ Method	488
3.5	Basic Dynamic Analysis of Sonic Booms	490
3.5.1	Introduction	490
3.5.2	Notation for Sonic Boom Analysis	491
3.5.3	Diffraction and Reflection of Sonic Boom Waves: Analytical Method	491
3.5.4	Method of Analysis	493
3.6	Pressure-Time History of a Sonic Boom Wave on Window in a Building	499
3.6.1	Application to a Sonic Boom Wave Incident on a Building	508
3.6.2	Analysis of Results	513

4	Shock and Impact Dynamics	519
4.1	Introduction	519
4.2	The Impactor as a Projectile	519
4.2.1	Direct Impulse/Impact and Momentum	519
4.2.2	Oblique Impact	529
4.3	Aircraft Impact on Structures: Peak Displacement and Frequency	533
4.4	Aircraft Impact: Load–Time Functions	535
4.4.1	Introduction	535
4.4.2	Stevenson’s Direct Head-On Impact Model	535
4.4.3	Riera Model	535
4.4.4	Model of Wolf et al.	538
4.5	Impact Due To Dropped Weights	541
4.5.1	Impact on Piles and Foundations	541
4.5.2	Classical or Rational Pile Formula	545
4.5.3	Impact on Foundations	550
4.5.4	Rock Fall on Structures	552
4.6	Impact on Concrete and Steel	555
4.6.1	General Introduction	555
4.6.2	Available Empirical Formulae	558
4.7	Impact on Soils/Rocks	576
4.7.1	Introduction	576
4.7.2	Empirical Formulations for Earth Penetration	577
4.7.3	Velocity and Deceleration	581
4.7.4	Impact on Rock Masses Due to Jet Fluids	583
4.8	Impact on Water Surfaces and Waves	584
4.8.1	Introduction	584
4.8.2	Impact on Water Surfaces	586
4.8.3	Impact on Ocean Surfaces	592
4.8.4	Wave Impact on Rock Slopes and Beaches	598
4.9	Snow/Ice Impact	602
4.9.1	Introduction	602
4.9.2	Empirical Formulae	604
4.10	Analysis and Modeling of Shock Response of Ceramics	611
4.10.1	Introduction	611
4.10.2	A Comparative Study of Results	613
4.11	Shock Analysis Involving Active Materials	618
4.11.1	Introduction	618
4.11.2	Method of Analysis	618
4.11.3	Input Data	621
4.11.4	Results	621
4.12	Shock Impact Load on the Container	621
4.12.1	Introduction	621
4.12.2	Shock Impact Load Analysis of Rectangular Container	622

4.12.3	Data and Numerical Calculation (a reference is to be made to Tables 4.18 and 4.19)	629
4.12.4	Drop Analysis Using 3D Dynamic Finite Element Analysis	630
4.13	Shock Load Capacity of Anchor in Concrete	633
4.13.1	Introduction	633
4.13.2	Torque Controlled Expansion Anchor	633
4.13.3	Displacement Controlled Expansion Anchors	633
4.13.4	Shock Load Impact Analysis of Expansion Anchors	635
4.14	Concrete Structures Subjected to Fragment Impacts: Dynamic Behaviour and Material Modelling	635
4.14.1	Introduction	635
4.14.2	Modified Crack Softening Law	642
4.14.3	The Modified Strain Rate Law for Concrete in Tension	643
4.15	Impact Resistance of Fibre Concrete Beams	647
4.15.1	Introduction	647
4.15.2	Slow Flexure Tests	652
4.15.3	Impact Tests	655
4.15.4	Impact Analysis of Polypropylene Fibre Reinforced Concrete Beam Using Finite Element	655
4.15.5	Additional Data	655
4.15.6	Results	656
4.16	Bird Impact on Aircraft	657
4.16.1	Introduction	657
4.16.2	Birds, Structures and Bird Impact	658
4.16.3	Aircraft Vulnerable Zones for Bird Impact	659
4.16.4	Material Modelling and Finite Element Analysis and Results	661
4.16.5	LS-Dyna Gap/Contact Elements	665
4.16.6	Bird Striking the Cock-Pit-Finite Element Analysis	668
5	Shock and Explosion Dynamics	671
5.1	Introduction	671
5.2	Fundamental Analyses Related to an Explosion	671
5.2.1	Stress Waves and Blast Waves	671
5.3	Explosions in Air	677
5.3.1	Thickness of the Shock Front	682
5.3.2	Evaluation of Stagnation Pressure, Stagnation and Post-Shock Temperatures	682
5.3.3	Oblique Shock	683
5.4	Shock Reflection	684
5.4.1	Normal Shock Reflection	684
5.4.2	Oblique Reflection	687

5.5	Gas Explosions	687
5.6	Dust Explosions	694
5.6.1	The Schwal and Othmer Method	695
5.6.2	Maisey Method	695
5.6.3	Heinrich Method	697
5.6.4	Palmer's Equation	700
5.6.5	Rust Method	700
5.7	Steel-Concrete Composite Structures	701
5.7.1	Introduction	701
5.7.2	Shear Connection: Full and Partial Interaction	708
5.7.3	Methods of Analysis and Design	709
5.8	Explosions in Soils	724
5.8.1	Explosion Parameters for Soils/Rocks	725
5.8.2	Explosion Cavity	731
5.8.3	Ground Shock Coupling Factor due to Weapon Penetration	735
5.9	Rock Blasting: Construction and Demolition	740
5.9.1	Rock Blasting Using Chemical Explosives of Columnar Shape and a Shot Hole	740
5.9.2	Primary Fragments	742
5.9.3	Blasting: Construction and Demolition	746
5.10	Explosions in Water	751
5.10.1	Introduction	751
5.10.2	Initial Parameters of Shock Waves in Water	752
5.10.3	Major Underwater Shock Theories	757
5.10.4	Penney and Dasgupta Theory	758
5.10.5	A Comparative Study of Underwater Shock Front Theories	759
5.10.6	Shock Wave Based on a Cylindrical Charge Explosion	760
5.10.7	Underwater Contact Explosions	760
5.10.8	Underwater Shock-Wave Reflection	761
5.11	Summary of Primary Effects of Under Water Explosion; Additional Explanatory Notes on Shock Pulse and Waves	762
5.11.1	Detonation Process in Underwater Explosion	762
5.11.2	Compression Loads due to Underwater Explosions	767
6	Dynamic Finite-Element Analysis of Impact and Explosion	769
6.1	Introduction	769
6.2	Finite-Element Equations	769
6.3	Steps for Dynamic Non-Linear Analysis	781
6.3.1	Buckling State and Slip of Layers for Composite Sections	786

6.3.2	Strain Rate Effects Based on the Elastic-Viscoplastic Relationship for Earth Materials Under Impact and Explosion	787
6.3.3	Finite Element of Concrete Modelling	791
6.4	Ice/Snow Impact	798
6.5	Impact due to Missiles, Impactors and Explosions: Contact Problem Solutions	801
6.6	High Explosions	802
6.7	Spectrum Analysis	805
6.8	Solution Procedures	806
6.8.1	Time-Domain Analysis	806
6.8.2	Frequency-Domain Analysis	808
6.8.3	Runge–Kutta Method	809
6.9	Geometrically Non-Linear Problems in the Dynamic Finite Element	809
6.9.1	Introduction	809
6.9.2	Criteria for the Iterative Approach	810
6.9.3	Solution Strategies	811
6.9.4	General Formulation	814
6.9.5	Example: 6.1	816
6.10	Finite Element Analysis of Explosion Using the Method of Explosive Factor	817
6.11	Force or Load–Time Function	819
6.11.1	Introduction	819
6.12	Finite-Element Mesh Schemes	822
A	Steel and Composites	835
A.1	Steel Structures	835
A.1.1	Impact on Steel Beams	835
A.1.2	Impact on Steel Plates	839
A.2	Composite Structures	846
A.2.1	Composite Plates	846
A.3	Impact Analysis of Pipe Rupture	855
A.3.1	Experimental Data	855
A.4	Explosions in Hollow Steel Spherical Cavities and Domes	863
A.4.1	Steel Spherical Cavities	863
A.4.2	Steel Domes	865
A.5	Car Impact and Explosion Analysis	867
A.5.1	General Data	867
A.5.2	Finite-Element Analysis and Results	868

B	Concrete Structures	877
	B.1 Introduction	877
	B.2 Concrete Beams	877
	B.2.1 Reinforced Concrete Beams	877
	B.2.2 Pre-Stressed Concrete Beams	883
	B.2.3 Fibre-Reinforced Concrete Beams	886
	B.3 Reinforced Concrete Slabs and Walls	891
	B.3.1 Introduction	891
	B.3.2 Slabs and Walls Under Impact Loads	892
	B.3.3 Design for Blast Resistance	899
	B.3.4 Steel-Concrete Composite Structures Subject to Blast/Impact Loads	924
	B.3.5 An Office Building: Steel-Concrete Composite Slabs with R.C. Protective Walls Under Blast Loading	931
	B.3.6 Design and Analysis of a Building Against Blast Loading	931
	B.3.7 Impact Resistance of Steel Fibre Reinforced Concrete Panels/Slabs	956
	B.4 Buildings and Structures Subject to Blast Loads	959
	B.4.1 Reinforced Concrete, Single-Storey House	959
	B.4.2 Blast Loads in the Demolition of Buildings and Cooling Towers	965
	B.4.3 Impact and Explosion of Cooling Towers and Chimneys	966
	B.5 Aircraft Crashes on PWR Containment Vessels (Buildings) .	968
C	Brickwork and Blockwork: Impact and Explosion	975
	C.1 General Introduction	975
	C.2 Finite-Element Analysis of Explosion	975
	C.3 Bomb Explosion at a Wall	985
D	Ice/Snow Impact	987
	D.1 Introduction	987
	D.2 Finite-Element Analysis	987
E	Nuclear Reactors	993
	E.1 PWR: Loss-of-Coolant Accident	993
	E.1.1 Introduction to LOCA	993
	E.1.2 Description of the PWR Vessel and Its Materials	993
	E.2 Nuclear Containment Under Hydrogen Detonation	997
	E.3 Impact/Explosion at a Nuclear Power Station: Turbine Hall	1000
	E.4 Jet Impingement Forces on PWR Steel Vessel Components	1010

F	Concrete Nuclear Shelters	1019
	F.1 Introduction	1019
	F.1.1 US Code Ultimate Strength Theory: General Formulae	1019
	F.2 Design of a Concrete Nuclear Shelter Against Explosion and Other Loads Based on the Home Office Manual	1025
	F.2.1 Basic Data (Home Office Code)	1025
	F.2.2 Additional Data for Designs Based on US Codes	1025
	F.3 Design of a Nuclear Shelter Based on the US Codes	1031
	F.3.1 Introduction	1031
	F.3.2 Wall Design	1031
	F.4 Lacing Bars	1035
	F.5 Finite-Element Analysis	1041
	F.5.1 The Swedish Design and Details	1041
G	Sea Environment: Impact and Explosion	1047
	G.1 Multiple Wave Impact on a Beach Front	1047
	G.2 Explosions Around Dams	1052
	G.3 Ship-to-Ship and Ship-to-Platform: Impact Analysis	1055
	G.4 Jacket Platform: Impact and Explosion	1057
	G.4.1 Ship Impact at a Jacket Platform	1057
	G.5 Impact of Dropped Objects on Platforms	1063
	G.5.1 Finite-Element Analysis	1068
	G.5.2 Results	1075
H	Soil/Rock Surface and Buried Structures	1077
	H.1 General Introduction	1077
	H.2 Soil Strata Subject to Missile Impact and Penetration	1077
	H.2.1 Finite-Element Analysis	1078
	H.2.2 Results	1080
	H.2.3 Explosions in Soil Strata	1080
	H.2.4 Craters Resulting from Explosions	1080
	H.2.5 Explosions in Boreholes	1084
	H.2.6 Explosions in an Underground Tunnel	1084
	H.2.7 Rock Fractures Caused by Water Jet Impact	1094
I	Underground and Underwater Explosion and Their Effects	1099
	I.1 Underground Explosion	1099
	I.2 Stress/Shock Waves Propagation: Analytical Investigations	1107
	I.2.1 Introduction	1107
	I.2.2 The Numerical Model	1108
	I.2.3 A Comparative Study of the Finite Element Analysis Results with Cherry and Peterson Results ..	1114

J	Bridges	1129
	J.1 Concrete Bridges Subject to Blast Loads	1129
	J.1.1 Introduction	1129
	J.1.2 Design of the Precast Prestressed M6 Beam for the Overbridge	1132
	J.2 Blast Analysis of Bridges Using Finite Element	1148
	J.2.1 General Information	1148
	J.2.2 Method of Analysis of Girders, Cap Beams and the Deck	1152
	J.2.3 Analysis of Results	1152
	J.3 Barge and Ship Collision with Bridge Piers	1154
	J.3.1 Introduction to Barge and Vessel Collisions	1154
	J.3.2 Current Practice in Different Countries on Ship–Bridge Collision	1155
	J.3.3 Time Integration of Barge/Vessel Equation of Motion	1162
	J.3.4 A Case Study	1163
	J.4 Highway Parapets Under Vehicle Impact	1163
	J.4.1 Introduction	1163
	J.4.2 Post, Bays and Configurations	1165
	J.4.3 Design Loading Values	1167
K	Luggage Container Subject to Internal Explosion	1177
	K.1 Introduction	1177
	K.2 Data On Luggage Container	1177
	K.3 Analysis and Results	1181
L	Blast and Impact on Buildings due to Aircraft Crashes ..	1183
	L.1 Introduction	1183
	L.2 Aircraft Information and Other Tower Data	1185
	L.3 Input Data and Gneral Analysis of WTC-1 and WTC-2 (WORLD TRADE CENTRE)	1185
	L.3.1 Geometrical Data	1185
	L.3.2 Aircraft Impact Areas and Speed	1185
	L.3.3 Connection Details, Structural Sizes and Other Parameters	1193
	L.3.4 Columns, Plates and Spandrels	1193
	L.3.5 Typical Structural Details	1195
	L.3.6 Analysis of Results	1198
	Bibliography	1205
	Appendix 1 Subroutines for Program Isopar and Program F-Bang	1297
	Index	1359