# **CONTENTS**

L	ist of Illustrations and Tables	page xiii
$P_i$	reface	xix
1	INTRODUCTION	I
	A Note on Monuments and Previous Scholarship	2
	How to Use this Book	2
	The Nature of Roman Concrete	3
	Concrete Vaulting during the Republic	3
	Structural Behavior of Concrete Vaults	6
	Roman Mathematical and Analytical Background	10
	Materials, Transport, and Production	12
	The Building Industry in Rome	18
	The Innovations	21
2	CENTERING AND FORMWORK	22
	Assembling the Centering	22
	Removing the Centering and Formwork	26
	The Use of Brick Linings on the Intrados of Vaults	29
	Evidence for Centering Arrangements	32
	Barrel Vaults, 32 • Cross Vaults, 34 • Domes and Semidomes, 40	-
	Conclusions	48
3	INGREDIENTS: MORTAR AND CAEMENTA	51
	Mortar	ŞI
	Lime, 53 • Pozzolana, 54 • Coccionesto, 58	31

## CONTENTS

	Caementa	59
	Provenance of Caementa, 64	
	Conclusions	65
4	AMPHORAS IN VAULTS	68
	Types of Amphoras Used	69
	Early Examples of Amphoras in Vaults	69
	Examples of Amphoras in Late Antique Vaults	75
	Conclusions	81
5	VAULTING RIBS	86
	Early Development of Vaulting Ribs and Relieving Arches	86
	The Vaulting Ribs at the Colosseum	88
	The Use of Solid Brick (Bipedalis) Ribbing	91
	Ladder and Lattice Ribs in Barrel Vaults	98
	Ladder and Lattice Ribs in Cross Vaults	106
	Ribbing in Domes	108
	Conclusions	III
6	METAL CLAMPS AND TIE BARS	113
	The Earliest Use of Tie Bars	115
	Tie Bars in the Imperial Thermae	116
	Tie Bars at the Forum of Trajan	118
	Spacing of Tie Bars	125
	The Use of Tie Bars with Lightweight Caementa	126
	Iron Architrave Bars and Impost Blocks at Hadrian's Villa	126
	Conclusions	127
7	VAULT BEHAVIOR AND BUTTRESSING	130
	Arches and Barrel Vaults	132
	Cross Vaults	134
	Domes and Semidomes	138
	Conclusions	146
8	STRUCTURAL ANALYSIS: HISTORY AND CASE STUDIES	149
	Historical Development	149
	Basilica Ulpia	156
	"Temple of Mercury" at Baiae	156
	Pantheon	158

### CONTENTS

"Temple of Minerva Medica"	161
Conclusions	164
9 INNOVATIONS IN CONTEXT	166
Accumulated Knowledge	166
Evident Need	168
Economic Ability	170
Social/Cultural/Political Acceptability	172
APPENDIX I. CATALOGUE OF MAJOR MONUMENTS	183
APPENDIX 2. CATALOGUES OF BUILDING TECHNIQUES	205
A. Formwork Imprints on Barrel Vaults	205
B. Formwork Imprints on Domes	206
C. Formwork Imprints on Semidomes	206
D. Brick Linings on the Intrados of Vaults	207
E. Uses of Cocciopesto to Protect the Extrados of Vaults	211
F. Lightweight Caementa	213
G. Amphoras in Vaults	215
H. Vaulting Ribs	216
I. Blocks with Tie Bar Cuttings	221
APPENDIX 3. SCORIA ANALYSIS	222
APPENDIX 4. THRUST LINE ANALYSIS	225
Notes	231
Glossary	245
Works Cited	251
Index	265

Frontispiece. "Temple of Minerva Medica" in the Horti Liciniani.

### **FIGURES**

1. Sanctuary of Jupiter Anxur. Terracina.	page 5
2. Diagram of principal parts of an arch.	6
3. Diagram of stress patterns in a beam.	7
4. Section D at Baths of Trajan. Rome.	8
5. Diagram of deformation of vault due to creep.	9
6. Sanctuary of Fortuna Primigenia. Palestrina.	9
7. Sketches of the Sanctuary of Fortuna Primigenia. Palestrina.	11
8. Reconstruction of wooden centering for concrete barrel vault.	23
9. Wooden trusses at San Pietro and San Paolo Fuori le Mura. Rome.	23
10. Marble panel with depiction of wooden amphitheater.	24
11. Detail of plaster cast from Trajan's Column. Italica, Spain.	24
12. Scarf joints.	25
13. Frame saws.	26
14. Wooden centering. Olympia, Greece.	27
15. Detail of Blackfriar's Bridge. G. B. Piranesi.	28
<ol><li>Diagram of method of lowering the centering of vaults.</li></ol>	29
17. Reconstruction of centering using brick linings.	29
18. Detail of vault built using brick linings. Case a giardino, Ostia.	30
19. Heliocaminus Baths at Hadrian's Villa. Tivoli.	31
20. Pons Fabricius. Rome.	32
21. Pons Cestius. Rome.	33
22. Engravings of Pons Cestius. G. B. Piranesi.	33
23. Reconstruction of centering frames at Pont du Gard. A. Leger.	34
24. Barrel vaulted room under San Clemente. Rome.	35
25. Common deformation pattern for centering frames.	36
26. Basilica of Maxentius. Rome.	36
27. Basilica of Maxentius. Rome.	37
8. Reconstructions of formwork for a pavilion vault and a cross vault.	28

29.	Detail of cross vault from the Colosseum. Rome.	38
30.	Reconstruction of the centering scheme for the Aula at Trajan's	
	Markets. Rome.	39
31.	Comparison of centering schemes (same scale) for cross vaults at Trajan's	
	Markets and the Baths of Caracalla. Rome.	39
32.	Diagram of domes showing formwork layouts.	40
33.	Reconstruction of the centering at the "Temple of Mercury." Baiae.	41
34.	Formwork impressions on the octagonal dome at the Domus Aurea. Rome.	42
35.	Geometry of centering for the octagonal dome at the Domus Aurea. Rome.	43
36.	Pantheon section. Rome.	44
37.	Reconstruction of Pantheon centering. M. Viollet-le-Duc.	45
38.	Reconstruction of formwork for segmental domes.	47
	Excavation photo of the Serapeum at Hadrian's Villa. Tivoli.	47
40.	Diagram showing the cycle of chemical changes in lime mortar production.	53
41.	Quicklime at the Casa del Sacello Iliaco. Pompeii.	54
	Section of Mausoleum of Helena. Rome.	57
	Detail of vault covering from the Basilica Argentaria. Rome.	59
	Reconstruction of horti pensiles at the Domus Tiberiana. Rome.	60
	Vesuvian scoria at the Forum of Caesar. Rome.	61
	Section of the Pantheon showing distribution of materials. Rome.	62
	Mausoleum of Helena with amphoras in dome. Rome.	69
	Amphora types found in vaults in Rome.	70
	Cross vault with amphoras. Magazzini "Traianei," Ostia.	72
	Plan of the Villa alla Vignaccia. Rome.	72
	Villa alla Vignaccia with amphoras in walls and vaults. Rome.	73
	Fallen vault from the Casa de la Exedra. Italica, Spain.	73
	Diagrams showing uses of amphoras for land reclamation projects.	74
	Wall containing amphoras. Pompeii.	75
	Balcony vault of the "Casa di Via Giulio Romano" with amphoras. Rome.	76
	Circus at the Villa of Maxentius with amphoras in vaults. Rome.	77
	Sketch of dome of the "Temple of Minerva Medica." Rome.	78
	Octagonal Hall at the "Villa of the Gordians." Rome.	79
	Semidome at Santa Maura with amphoras. Rome.	83
	Plan and section of St. Jerome. Cologne, Germany.	84
	Acropolis gate at Alatri, Italy.	87
	Porta Rosa in city walls of Velia, Italy.	87
	Theater of Marcellus. Rome.	88
•	Sanctuary of Hercules Victor. Tivoli.	89
	Drawing of the Theater of Marcellus. Rome.	89
	Section through the Theater of Marcellus. Rome.	90
	Four types of vaulting ribs at the Colosseum. Rome.	90
	Drawing of travertine ribs at the Colosseum. Rome.	91
	Section and partial plan of the Colosseum showing location of ribs. Rome.	92
	Sketch section at bay 34 of the Colosseum. Rome.	93
	Detail of Flavian ladder rib at the Colosseum. Rome.	93
	Axon of the Domitianic Vestibule. Rome.	94
73.	Plan of lower level of the Domus Augustana Rome	0.5

74.	Sketch plan of cryptoporticus at the Villa of Domitian. Castelgandolfo.	95
75.	Cryptoporticus at the Villa of Domitian with ribs. Castelgandolfo.	96
76.	Cryptoporticus at the Villa of Domitian with ribs and	90
	coffers. Castelgandolfo.	97
77.	Section E at the Baths of Trajan. Rome.	97
	Drawing of the Trajanic latrine in reconstructed part of the Forum	71
	of Caesar. Rome.	98
79.	Trajanic latrine at the Forum of Caesar with travertine impost	, ,
	blocks. Rome.	99
80.	Drawing of the Pantheon with its ribbing system. Rome.	100
81.	Exterior of the Pantheon. Rome.	101
82.	Plan of the Villa di Sette Bassi. Rome.	102
83.	Ladder rib in the cryptoporticus of the Villa di Sette Bassi. Rome.	102
	Ladder rib at the Villa di Sette Bassi. Rome.	103
85.	Plan of the Severan Baths and the Baths of Maxentius on	Ţ.
	the Palatine. Rome.	103
86.	Lattice ribs at the Severan Baths on the Palatine. Rome.	104
	Nymphaeum Alexandri "Trophies of Marius." Rome.	104
	Detail of rib in outer ambulatory of the Colosseum. Rome.	105
89.	Detail of lattice ribbing at the Baths of Maxentius on the Palatine. Rome.	105
	Detail of nave façade of the Basilica of Maxentius. Rome.	106
	Detail of ladder rib in cross vault at the Villa di Sette Bassi. Rome.	107
92.	Lattice ribs in the cross vaults of the Maxentian substructures on	
	the Palatine. Rome.	107
93.	Dome at the Baths of Agrippa with lattice ribbing. Rome.	108
94.	Plans of domes showing restored rib patterns.	109
95.	Section of "Temple of Minerva Medica." Rome.	III
96.	Architrave block from the Forum of Trajan with remains of iron	
0.5	tie bar. Rome.	114
97.	Reconstructed section of the Horrea Agrippiana. Rome.	115
90.	Cornice block with tie bar cutting from the Horrea Agrippiana. Rome.	116
99. 100	Reconstruction of the portico fronting the Basilica Aemilia. Rome.	117
100.	Measured sketch of <i>bucranium</i> block from the portico fronting the Basilica Aemilia. Rome.	
		117
102	Bucranium block from the portico fronting the Basilica Aemilia. Rome. Section H at Trajan's Baths showing holes for anchor blocks for	118
102.	tie bars. Rome.	
	West palaestra of the Baths of Caracalla. Rome.	119
	East palaestra of the Baths of Diocletian. Rome.	120
	Generic reconstruction of the palaestra portico from an imperial	120
	bath showing tie bar and anchor block.	121
	Cornice blocks from Trajan's Forum. Rome.	121
	Comparison of proposals by C. M. Amici and J. Packer for	121
	reconstruction of the Column Portico at Trajan's Forum. Rome.	122
108.	Comparison of proposals by C. M. Amici and J. Packer for	122
	reconstruction of the Basilica Ulpia. Rome.	122
	Plan of the Basilica Ulpia. Rome.	123
		,

110.	Reconstruction of lintel construction at the Hall of the Doric Pilasters at	
	Hadrian's Villa. Tivoli.	124
ш.	Hall of the Doric Pilasters at Hadrian's Villa. Tivoli.	125
112.	Arcuated lintels at Santa Costanza. Rome.	127
113.	Diagram of two proposed design schemes used at the Pantheon. Rome.	131
	Diagram showing failure patterns of arched structures.	132
	Diagram showing four factors that affect the stability of an arched structure.	133
	Drawing showing vaulting configurations at the Market at Ferentino, the	
	Market at Tivoli, the Domus Aurea, and Trajan's Markets at Rome.	134
117.	Diagram showing the lines of compressive force in a cross vault.	135
118.	View of the Aula at Trajan's Markets. Rome.	130
119.	Gallery overlooking the central hall of the Aula at Trajan's Markets. Rome.	136
	Frigidarium of the Baths of Caracalla. Rome.	137
121.	Aerial view of the Basilica of Maxentius. Rome.	138
122.	Plan and section of the Basilica of Maxentius. Rome.	139
123.	Diagram of construction of dome built of stone voussoirs and diagram of	
	stress patterns in an uncracked concrete dome.	139
124.	Deformation patterns in a cracked dome and a semidome.	140
	Step-rings on the Pantheon dome. Rome.	141
	Large semidome at Trajan's Markets. Rome.	141
	Stairs on dome of the "Temple of Mercury." Baiae.	142
128.	Buttressing walls at the "Temple of Mercury." Baiae.	143
129.	Plan of dome of the "Temple of Mercury." Baiae.	144
130.	Drawing of the buttresses of the octagonal dome at the Domus	
	Aurea. Rome.	144
131.	Drawing of the "Temple of Venus and Cupid" in the Sessorian	
	palace. Rome.	145
132.	Buttress at the "Temple of Venus and Cupid" in the Sessorian	
	palace. Rome.	145
	Diagram demonstrating the concept of the vector.	150
	Diagram demonstrating the concept of moment.	151
	Diagram of stable three-hinge arch and of collapsing four-hinge arch.	151
	Diagram showing the concept of Hooke's hanging line.	152
	Example of a funicular polygon diagram.	153
138.	Thrust line diagrams for three reconstruction proposals of the Basilica	
	Ulpia. Rome.	157
139.	Thrust line through dome of the "Temple of Mercury." Baiae.	158
	Definition of the Rankine safety factor.	159
	Thrust line diagram of the Pantheon dome under different conditions.	159
142.	Thrust line diagram of the "Temple of Minerva Medica" under	1
	different conditions.	162
	Drawing of the "Temple of Minerva Medica." Franz Innocenz Kobell.	163
	Dome of the "Temple of Diana." Baiae.	164
145.	Drawing demonstrating the steps in making a funicular polygon analysis	
	of an arch.	226

#### MAPS

1. Map of Rome and environs locating major monuments discussed in	
the text.	4
2. Map of Italy showing major volcanic districts.	13
3. Geological map of Rome and environs showing locations of major building	
materials used in concrete vaulting.	14
4. Map of Italy showing locations of major sources of timber and limestone.	15
5. Map of the Bay of Naples showing the air fall distribution of the A.D. 79	
eruption and the pre-79 eruption of Mt. Vesuvius.	63
TABLES	
1. Recommended Mortar Mix Proportions	55
2. Amounts of Scoria in Vaults in Rome	67
3. Physical Characteristics of Dressel 20 and Dressel 23 Amphoras	7 I
4. Blocks from Trajan's Forum with Cuttings for Tie Bars	123
5. Proportions of Barrel Vaults	133
6. Proportions of Cross Vaults on Exterior Walls	135
7. Proportions of Freestanding Domes	140
8. Scoria Analysis	223
COLOR PLATES	

#### C

Color plates follow page 154.

- I. Major local building stones used in vaulted structures around Rome.
- II. Detail of opus caementicium vault from the Porticus Aemilia. Rome.
- III. Four types of pozzolana.
- IV. Abandoned pozzolana quarry on via Nesazio. Rome.
- V. Detail of mortar with white pumice from the Colosseum. Rome.
- VI. Plan of the Baths of Trajan. Rome.
- VII. Section H at the Baths of Trajan. Rome.
- VIII. Scoria and tufo giallo della via Tiberina at Section E at the Baths of Trajan. Rome.
- IX. West palaestra at the Baths of Caracalla. Rome.
- X. East palaestra vault from the Baths of Diocletian. Rome.
- XI. Dome at the "Temple of Minerva Medica." Rome.
- XII. Tor de'Schiavi. Detail of painting by Henrik van Lint and reconstruction drawing.
- XIII. Plans of the Baths of Caracalla and the Baths of Diocletian showing vaulting ribs. Rome.