

Contents

1	Introduction to Fracture Mechanics of Concrete	1
1.1	General	1
1.2	Organization of the Book	5
1.3	Closing Remarks	6
	References	7
2	Fracture Mechanics of Concrete – State-of-the-Art Review	9
2.1	Introduction	9
2.2	Linear Elastic Fracture Mechanics	9
2.2.1	Significance of Stress Intensity Factor	11
2.2.2	Concept of R Curve	11
2.3	Elastic–Plastic Fracture Mechanics	13
2.3.1	The CTOD Criterion	13
2.3.2	The J-Integral Approach	13
2.4	Early Research Using LEFM to Concrete	14
2.5	Tensile Behavior of Concrete	17
2.5.1	Strain Localization Effect	17
2.5.2	Fracture Process Zone	19
2.5.3	Nonlinear Behavior of Concrete	20
2.6	Specimen Geometry for Fracture Test of Concrete	21
2.6.1	Dimensions of Test Specimens	22
2.7	Nonlinear Fracture Mechanics for Concrete	24
2.7.1	Cohesive Crack Model (CCM) or Fictitious Crack Model (FCM)	25
2.7.2	Crack Band Model (CBM)	32
2.7.3	Two-Parameter Fracture Model (TPFM)	35
2.7.4	Size-Effect Model (SEM)	36
2.7.5	Effective Crack Model (ECM)	40
2.7.6	Double-K Fracture Model (DKFM)	42
2.7.7	The K_R Curve Associated with Cohesive Stress Distribution in the FPZ	45
2.7.8	Double-G Fracture Model (DGM)	46
2.8	Comparative Study and Size-Effect Behavior	47

2.9	Weight Function Approach	49
2.9.1	Some Existing Weight Functions	50
2.9.2	Universal Weight Function for Edge Cracks in Finite Width Plate	51
2.9.3	Computation of Stress Intensity Factor and Crack Face Displacement	51
2.10	Scope of the Book	52
2.11	Closing Remarks	54
	References	54
3	Fracture Behavior of Concrete using Cohesive Crack and Size-Effect Models	65
3.1	Introduction	65
3.2	Cohesive Crack Model for Three-Point Bending Test	65
3.2.1	Formulation Based on Energy Principle	65
3.2.2	Basic Assumptions	67
3.2.3	Finite Element Discretization	68
3.2.4	Beam Deflection	71
3.2.5	Model Implementation	73
3.3	Softening Function of Concrete	73
3.3.1	Linear Softening Function	74
3.3.2	Bilinear Softening	74
3.3.3	Exponential Softening	76
3.3.4	Nonlinear Softening	76
3.3.5	Quasi-exponential Softening	77
3.4	Numerical Study Using TPBT Specimen	77
3.4.1	Experimental Results and Numerical Computation	77
3.4.2	Comparison with Numerical Results Using Linear Softening	79
3.4.3	Influence of Softening Function on the Global P-CMOD Response	80
3.4.4	Influence of Kink Point in the Bilinear Softening on the Global P-CMOD Response	80
3.4.5	Effect of Finite Element Mesh Size on Bearing Capacity of the Beam	83
3.4.6	Effect of Size Scale on the Type of Failure	85
3.4.7	Size-Scale Deviation From LEFM Concept	87
3.4.8	Influence of Softening Function on Size-Effect Curve	89
3.5	Numerical Study Using Compact Tension (CT) Specimen	90
3.5.1	Global P-COD Response Using Linear Softening Function	91
3.5.2	Influence of Softening Functions on the Global P-COD Response	94
3.5.3	Influence of Softening Functions on the Size-Scale Transition Toward LEFM	95
3.5.4	Influence of Softening Functions on the Size-Effect Curve	97

3.5.5	Evolution of Fracture Zone	97
3.5.6	Influence of Softening Functions on the Development of Fracture Process Zone	100
3.5.7	Influence of Softening Functions on the Load-Carrying Capacity Corresponding to the Fully Developed FPZ	101
3.5.8	Influence of Softening Functions on the Fictitious Crack Length Corresponding to Peak Load	102
3.5.9	Influence of Softening Functions on the CTOD _c	103
3.5.10	Influence of Softening Functions on the Local Stress Distribution at Notch Tip Corresponding to Peak Load	103
3.5.11	Comparison with Experimental Result	105
3.6	Size-Effect Study from Size-Effect Model	106
3.6.1	Size-Effect Law for Size-Effect Model	107
3.6.2	Size Effects and Fracture Load from CCM and SEM	107
3.7	Closing Remarks	110
	References	111
4	Crack Propagation Study Using Double-<i>K</i> and Double-<i>G</i> Fracture Parameters	113
4.1	Introduction	113
4.2	Weight Function Method	113
4.3	Determination of Universal Weight Function for Edge Cracks in Finite Width Plate	115
4.3.1	Four-Term Universal Weight Function	117
4.3.2	Five-Term Universal Weight Function	120
4.4	Linear Asymptotic Superposition Assumption	122
4.5	Determination of Double- <i>K</i> Fracture Parameters	125
4.5.1	Effective Crack Extension for the Analytical Method and Weight Function Approach	125
4.5.2	Effective Crack Extension for Simplified Method	127
4.5.3	Calculation of Double- <i>K</i> Fracture Parameters	128
4.5.4	Determination of SIF due to Cohesive Stress (K^C_I) in FPZ	130
4.6	Determination of Double- <i>G</i> Fracture Parameters	135
4.6.1	Unstable Fracture Energy Release	135
4.6.2	Determination of Critical Cohesive Breaking Energy	136
4.6.3	Determination of Initial Fracture Energy Release	139
4.6.4	Determination of Effective Double- <i>K</i> Fracture Parameters	139
4.7	Application of Weight Function Approach for Double- <i>K</i> Fracture Parameters	139
4.7.1	Comparison with TPBT Geometry	139
4.7.2	Comparison with CT and WST Geometries	145
4.8	Size-Effect Prediction from the Double- <i>K</i> Fracture Model for TPBT	154

4.8.1	Size-Effect Law for Unstable Fracture Toughness K_{IC}^{un}	155
4.8.2	Size-Effect Law for Initiation Fracture Toughness K_{IC}^{ini}	157
4.8.3	Prediction of Size Effects from FCM and DKFM	158
4.9	Numerical Study on Double- K Fracture Parameters	164
4.9.1	Material Properties	164
4.9.2	Comparison Between Methods of Determination for DKFM	166
4.9.3	Influence of Specimen Geometry	170
4.9.4	Influence of Loading Condition	173
4.9.5	Influence of Softening Function	176
4.10	Equivalence Between Double- K and Double- G Fracture Parameters	177
4.10.1	Material Properties	177
4.10.2	Effect of Specimen Geometry on Double- K Fracture Parameters	179
4.10.3	Effect of Specimen Geometry on Double- G Fracture Parameters	181
4.10.4	Equivalence Between Double- K and Double- G Fracture Parameters	183
4.10.5	Influence of Softening Function on the Double- K and Double- G Fracture Parameters	185
4.11	Closing Remarks	188
	References	190
5	Fracture Properties of Concrete Based on the K_R Curve Associated with Cohesive Stress Distribution	193
5.1	Introduction	193
5.2	The K_R -Curve Method	193
5.3	Analytical Method for Evaluation of the K_R Curve	196
5.3.1	Case 1: When $a = a_0$	197
5.3.2	Case 2: When $a_0 \leq a \leq a_c$	197
5.3.3	Case 3: When $a_c \leq a \leq a_{wc}$	198
5.3.4	Case 4: When $a \geq a_{wc}$	198
5.4	Weight Function Approach for Evaluation of the K_R Curve	199
5.4.1	Derivation of Closed-Form Expression for Cohesive Toughness	199
5.4.2	Case 1: When $a = a_0$	201
5.4.3	Case 2: When $a_0 \leq a \leq a_c$	202
5.4.4	Case 3: When $a_c \leq a \leq a_{wc}$	202
5.4.5	Case 4: When $a \geq a_{wc}$	202
5.5	Computation and Validation of the K_R Curve	203
5.5.1	Details of Experimental Results	203
5.5.2	Crack Extension Resistance Curves (K_R Curves) and Stability Criterion	205
5.5.3	Effect of Specimen Size on the K_R Curves	209
5.5.4	The P-CTOD Curves	210

5.5.5	The Relationship Between CTOD and Δa	210
5.5.6	Analysis and Discussion	211
5.6	Numerical Study on the K_R Curve	213
5.6.1	Material Properties and Numerical Computations	213
5.6.2	Crack Extension Resistance Curves (K_R Curves) and Stability Criterion	217
5.6.3	Effect of Specimen Geometry and Size Effect on the K_R Curves	226
5.6.4	Effect of Specimen Geometry and Size Effect on the CTOD Curves	227
5.6.5	Effect of Specimen Geometry and Size Effect on the Process Zone Length	227
5.6.6	Effect of Loading Condition and Size Effect on the K_R Curves	229
5.6.7	Effect of Loading Condition and Size Effect on the CTOD Curves	229
5.6.8	Effect of Loading Condition and Size Effect on the Process Zone Length	232
5.7	Closing Remarks	232
	References	233
6	Comparison of Fracture Parameters of Concrete Using Nonlinear Fracture Models	235
6.1	Introduction	235
6.2	Material Properties and Determination of Fracture Parameters	235
6.3	Size-Effect Analysis Using Various Fracture Models	239
6.3.1	Size Effect of Critical Stress Intensity Factors	239
6.3.2	Effect of Specimen Size on CTOD _{cs} and CTOD _c	242
6.3.3	Effect of Specimen Size on a_e of ECM and a_c of DKFM or DGFM	244
6.3.4	Relation Between c_f of SEM and $a_{cs\infty}$ of TPFM	245
6.4	Closing Remarks	246
	References	247
	Appendix	249
	Index	255