Modeling and application of piezoelectric transducers for structural health monitoring

Sabet Divsholi Bahador

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**NANYANG
TECHNOLOGICAL
UNIVERSITY**

**MODELING AND APPLICATION OF PIEZOELECTRIC
TRANSDUCERS FOR STRUCTURAL HEALTH
MONITORING**

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**SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING
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in partial fulfillment of the requirement for the degree of
Doctor of Philosophy**

2012

To:

My Wife, Arezoo Rahimi and Our Parents

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TABLE OF CONTENTS

ACKNOWLEDGMENTS.....	ii
TABLE OF CONTENTS	iii
SUMMARY	vii
LIST OF TABLES	ix
LIST OF FIGURES.....	x
LIST OF SYMBOLS	xvii
1 CHAPTER 1 INTRODUCTION.....	1
1.1 Background	1
1.2 Objectives.....	3
1.3 Scope of work.....	3
1.4 Research originality and contributions.....	6
1.5 Organization of report	7
2 CHAPTER 2 LITERATURE REVIEW.....	8
2.1 Introduction to piezoelectricity	8
2.1.1 Piezoelectric constitutive relations	9
2.1.2 Piezoelectric materials	11
2.2 Strain transfer model	17
2.2.1 Uniform model with inclusion of shear lag effect	17
2.2.2 Bernoulli-Euler formulation.....	22
2.3 Structural health monitoring (SHM)	24
2.3.1 Electro mechanical impedance (EMI) technique	25
2.3.1.1 Advantages and limitations of EMI technique	28
2.3.2 Wave propagation techniques	29
2.3.3 Wave transmission technique	32
2.4 Need for future research.....	32
2.4.1 Effect of epoxy layer on strain transfer and EMI signature.....	32
2.4.2 Selection of frequency range in EMI method	33
2.4.3 Reusable PZT traducer.....	33

- 2.4.4 Combining EMI, wave propagation and wave transmission techniques for SHM 34

3	CHAPTER 3 STRAIN TRANSFER MODELS FOR ACTUATION AND EMI SENSING	35
3.1	Introduction	35
3.2	Existing strain transfer models and limitations	36
3.3	Two dimensional modeling based on Bernoulli-Euler formulation.....	36
3.4	Modification of Bernoulli-Euler formulation.....	38
3.4.1	Modified Bernoulli-Euler (1-D) model.....	39
3.4.2	Modified Bernoulli-Euler (2-D) model.....	39
3.5	Finite element modeling (FEM) of strain transfer	40
3.6	Validation of analytical and simulation results	42
3.6.1	Experimental test on strain transfer in cantilever beam.....	42
3.6.2	Experimental test on epoxy layer properties.....	43
3.7	Results and discussions	45
3.8	Inclusion of epoxy layer properties in EMI model	48
3.9	Analytical modeling for inclusion of epoxy layer properties in EMI	51
3.10	Parametric study on reduction factor	54
3.11	Finite element modeling.....	57
3.12	Concluding remarks	62
4	CHAPTER 4 APPLICATION OF PZT TRANSDUCERS FOR DETECTION OF DAMAGE SEVERITY AND LOCATION.....	64
4.1	Introduction	64
4.2	Preliminary test on beam-column joint in concrete structures	65
4.2.1	Experimental work.....	65
4.2.2	Results and discussions.....	70
4.2.2.1	Comparison of PZT and MFC transducers.....	70
4.2.2.2	Study on EMI signature	72
4.2.2.3	Structural mechanical impedance	75
4.2.3	Uncertainties and limitations	76
4.3	Preliminary test on variation of RMSD results for various frequency range	76
4.3.1	Experimental setup.....	77
4.3.2	Results and discussions.....	79
4.3.3	Uncertainties and limitations	81

4.4	Study on location and severity of damage in concrete structures	82
4.4.1	Experimental Work.....	82
4.4.2	Results and discussions.....	86
4.4.2.1	Sensing region	86
4.4.2.2	Damage detection	90
4.4.2.3	Comparison of RMSD-S with RMSD	95
4.4.3	Damage identification scheme	98
4.4.4	Concluding remarks	102
4.5	Study on location and severity of damage in steel structures	102
4.5.1	Introduction.....	102
4.5.2	Experimental work.....	103
4.5.3	Results and discussions.....	106
4.5.3.1	RMSD-S results for various damage points	106
4.5.3.2	RMSD-S Results for Three PZTs.....	113
4.5.3.3	Logarithmic Wave Attenuation	118
4.5.4	Concluding remarks	122
5	CHAPTER 5 REUSABLE PZT TRANSDUCER FOR MONITORING INITIAL HYDRATION OF CONCRETE AND STRUCTURAL HEALTH ...	123
5.1	Introduction	123
5.2	Experimental study.....	125
5.2.1	Reusable PZT setup	125
5.2.2	Initial hydration tests.....	126
5.2.3	Structural health monitoring (SHM).....	128
5.3	Results and discussions	130
5.3.1	Repeatability and reliability	130
5.3.2	Monitoring initial hydration of concrete.....	134
5.3.3	Structural health monitoring	139
5.4	Concluding remarks	141
6	CHAPTER 6 EXPERIMENTAL WORK ON EMBEDDED, REUSABLE AND SURFACE-BONDED PZTS BY USING EMI, WAVE PROPAGATION AND PITCH CATCH TECHNIQUES	142
6.1	Introduction	142
6.2	Experimental work	144
6.2.1	Preparation of PZT transducers	144

6.2.2	Beam preparation	145
6.3	Results and discussions	154
6.3.1	Hydration of concrete	154
6.3.1.1	Direct embedding of PZT transducer in concrete.....	155
6.3.1.2	Monitoring hydration with smart aggregates.....	157
6.3.2	Structural health monitoring	162
6.3.2.1	Smart aggregates using the wave transmission technique.....	164
6.3.2.2	Surface-bonded PZTs using wave propagation technique	167
6.3.2.3	Surface-bonded PZTs using EMI technique.....	170
6.3.2.4	Reusable PZT setups for SHM	176
6.3.2.5	Combination of smart aggregates and surface-bonded PZTs	177
6.4	Concluding remarks	179
7	CHAPTER 7 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK.....	180
7.1	Conclusions and contributions	180
7.2	Recommendations for future work.....	185
8	REFERENCES	187
9	APPENDIX: AUTHORS' PUBLICATIONS AND AWARDS	202

SUMMARY

The last few decades have witnessed vast applications of smart materials in structural health monitoring (SHM). Piezoelectric lead zirconate titanate (PZT) transducers are robust, cost effective, sensitive to damage, and ideal for monitoring constructed infrastructures. However PZT is brittle and cannot be installed on the curve surfaces. On the other hand, the newly developed macro fiber composites (MFC) are flexible, durable and damage tolerant. The MFC is good sensor and very strong actuator. However it is less sensitive as sensor for the same level of applied electrical charge compared to PZT.

In this work, one and two dimensional strain transfer models with inclusion of adhesive layer are developed. A finite element model (FEM) using ABAQUS for actuation of a cantilever beam with MFC actuator is performed. An experimental test is carried out and the results are compared with the FEM and analytical results. The developed model is useful for the applications such as vibration control, sensing and actuation where the stiffnesses of the host structure and actuator are comparable. By incorporating the developed strain transfer model, the existing electromechanical impedance (EMI) model for SHM is improved. A reduction factor is derived analytically and parametric study is performed on the reduction factor. A finite element model is developed in ANSYS to numerically investigate and verify the effect of epoxy layer properties on the sensitivity of PZT transducer.

The root mean square deviation (RMSD) method has been used extensively in the EMI technique for SHM. However, study on identification of damage severity and location is still in need. This work proposes a new approach for damage identification by calculating the RMSD values of sub-frequency intervals (RMSD-S) in a large frequency range. The proposed RMSD-S based damage identification method reduces inconsistency and uncertainties in the traditional RMSD method which uses limited high frequency range. Using the observation that the damage close to the PZT changes the RMSD-S at high frequency range significantly and the damage far away from the PZT changes the RMSD-S at low frequency range significantly, the location and severity of damage can be assessed.

To reduce the cost of PZT based SHM, a reusable PZT setup for monitoring initial hydration of concrete and structural health is developed. The results show that the developed transducer is able to effectively monitor the initial hydration of concrete and can be detached from the concrete for future use.

Comparative study on surface-bonded, reusable and embedded PZT transducers using the EMI, wave propagation and wave transmission techniques is conducted. The PZT based EMI technique can only monitor small and local area in concrete structures. The wave propagation technique with high actuation voltage can monitor larger area. However, the results are significantly affected by the surface condition. In addition, the calculation of damage location and severity demands complex modeling of wave propagation. On the other hand, the wave transmission technique using smart aggregates (embedded PZT transducers) can be employed to monitor very large areas with reasonable low actuation signal. The combination of the smart aggregates using the wave transmission technique to study the overall condition of the structure with the surface-bonded PZTs using the EMI or wave propagation techniques to study the local condition of the structure provides an effective way for SHM.

LIST OF TABLES

TABLE 3-1 SUMMERY OF CONDITIONS IN PARAMETRIC STUDY	55
TABLE 4-1 RMSD-S FOR PZT 5.....	91
TABLE 4-2 RMSD-S FOR PZT 4.....	91
TABLE 4-3 RMSD-S FOR PZT 2.....	92
TABLE 4-4 RMSD-S VERSUS DISTANCE FROM PZT	99
TABLE 5-1 SUMMARY OF EXPERIMENTAL WORK	127
TABLE 5-2 CONTINUATION OF HYDRATION BY COMPARING THE SIGNATURES IN VARIOUS HOURS	137
TABLE 5-3 RMSD VALUES OF TWO REUSABLE PZT SETUPS.....	139
TABLE 5-4 RMSD VALUES FOR REUSABLE PZT SETUPS AND SURFACE-BONDED PZTs	140
TABLE 6-1 CONCRETE MIX DESIGN.....	145
TABLE 6-2 RMSD RESULTS FROM EMBEDDED PZT TRANSDUCER	156

LIST OF FIGURES

FIGURE 1-1 SCHEMATIC PRESENTATION OF THIS STUDY	4
FIGURE 2-1 ILLUSTRATION OF DIMENSIONS FOR PZT D_{31} MATERIALS	11
FIGURE 2-2 1-3 COMPOSITE ACTUATORS BY SMART MATERIALS CORP. (SMART-MATERIALS, 2010)	12
FIGURE 2-3 SCHEMATIC CROSS SECTION OF AN AFC ACTUATOR (WILKIE ET AL. 2000)	14
FIGURE 2-4 DIFFERENT LAYERS IN MACRO FIBER COMPOSITE (MFC)	15
FIGURE 2-5 FABRICATION PROCESS OF MFC PIEZO FIBERS (WILKIE ET AL. 2000)	16
FIGURE 2-6 BONDING OF PIEZO FIBERS AND INTERDIGITATED ELECTRODES (WILKIE ET AL. 2000)	16
FIGURE 2-7 BEAM CONFIGURATION	18
FIGURE 2-8 STRESSSS AND STRAIN IN THE STRAIN ACTUATOR AND BEAM	18
FIGURE 2-9 SHEAR CAUSED BEAM EXTENSION AND BENDING	19
FIGURE 2-10 CONDUCTANCE (A), SUSCEPTANCE (B) PLOTS OF PZT BONDED TO CONCRETE STRUCTURE	27
FIGURE 3-1 SIMULATION OF CANTILEVER BEAM AND MFC ACTUATOR WITH ABAQUS	40
FIGURE 3-2 DAMPING CURVE FOR FIRST MODE	41
FIGURE 3-3 DAMPING CURVE FOR SECOND MODE	42
FIGURE 3-4 EXPERIMENTAL SETUP FOR CANTILEVER BEAM	43
FIGURE 3-5 STRAIN GAUGE ON BOTTOM OF BEAM.....	43
FIGURE 3-6 PREPARATION OF UNIFORM EPOXY SHEET	44
FIGURE 3-7 PREPARATION OF EPOXY SPECIMEN	44
FIGURE 3-8 TENSION TEST SETUP	45
FIGURE 3-9 TENSION TEST RESULTS FOR EPOXY.....	45
FIGURE 3-10 ANALYTICAL, NUMERICAL AND EXPERIMENTAL FOR STRAIN IN BOTTOM OF BEAM	46
FIGURE 3-11 EXPERIMENTAL AND FEM RESULTS FOR STRAIN ON TOP SURFACE OF MFC	46
FIGURE 3-12 FEM AND EXPERIMENTAL RESULTS FOR BEAM-TIP DEFLECTION	47
FIGURE 3-13 EFFECT OF THICKNESS OF EPOXY ON BEAM-TIP DEFLECTION	48

FIGURE 3-14 EFFECT OF MODULUS OF EPOXY ON BEAM-TIP DEFLECTION.....	48
FIGURE 3-15 EFFECT OF EPOXY MODULUS OF ELASTICITY ON REDUCTION FACTOR.....	56
FIGURE 3-16 EFFECT OF EPOXY THICKNESS ON REDUCTION FACTOR.....	56
FIGURE 3-17 OVERALL MODEL IN ANSYS	58
FIGURE 3-18 MESH OF THE ELEMENTS	58
FIGURE 3-19 EFFECT OF EPOXY THICKNESS ON EMI SIGNATURE	59
FIGURE 3-20 (A) EFFECT OF EPOXY MODULUS OF ELASTICITY ON EMI SIGNATURE, (B) COMPARISON FOR LIMITED FREQUENCY RANGE	60
FIGURE 4-1 CONFIGURATION OF EXPERIMENTAL SETUP	66
FIGURE 4-2 DETAILING OF SPECIMENS L1 AND L2	67
FIGURE 4-3 DETAILING OF SPECIMENS L3 AND L4	67
FIGURE 4-4 EXPERIMENTAL SETUP DURING THE TEST	68
FIGURE 4-5 PZT AND MFC TRANSDUCERS ON THE BEAM NEAR THE JOINT	68
FIGURE 4-6 FORTH SPECIMEN AFTER FAILURE	69
FIGURE 4-7 POSITION OF PZT TRANSDUCERS AND CRACKS IN FORTH SPECIMEN L4	69
FIGURE 4-8 PZT WITH THICKNESS OF 0.5 MM ON FIRST SPECIMEN	70
FIGURE 4-9 COMPARISON OF EM SIGNATURE FOR THREE TRANSDUCERS ON CONCRETE SPECIMENS	71
FIGURE 4-10 COMPARISON OF PZT AND MFC (SEVEN TIMES SCALED) SIGNATURES FOR SAME VOLTAGE LEVEL	72
FIGURE 4-11 LOAD-DISPLACEMENT AND STRAIN GAUGE READING (SPECIMEN L4).....	72
FIGURE 4-12 SIGNATURES COLLECTED DURING TEST (SPECIMEN L4, PZT 3).....	73
FIGURE 4-13 COMPRESSION OF IMPORTANT SIGNATURES (SPECIMEN L4, PZT 3)	74
FIGURE 4-14 LOAD-DISPLACEMENT AND RMSD RESULTS (SPECIMEN L4, PZT 3).....	74
FIGURE 4-15 COMPARISON OF REAL PART OF SMI FOR DIFFERENT LEVEL OF LOADING.....	75
FIGURE 4-16 COMPARISON OF EMI AND SMI VALUES.....	76
FIGURE 4-17 CONCRETE STRUCTURE	78
FIGURE 4-18 HOLES DRILLED RANDOMLY AROUND PZTs.....	78
FIGURE 4-19 HOLES DRILLED IN CIRCULAR MANNER FROM CERTAIN DISTANCE TO PZT	79
FIGURE 4-20 HOLES DRILLED AT RIGHT HAND SIDE FROM CERTAIN DISTANCE TO PZTs	79

FIGURE 4-21 VARIATIONS IN RMSD VALUE WITH INCREASE IN DAMAGE SEVERITY FOR DIFFERENT SUB-FREQUENCY INTERVALS.....	80
FIGURE 4-22 RMSD FOR PZT AT 50 CM FROM DAMAGE.....	80
FIGURE 4-23 RMSD FOR PZT AT 30 CM FROM DAMAGE.....	80
FIGURE 4-24 RMSD FOR PZT AT 10 CM FROM DAMAGE.....	81
FIGURE 4-25 RMSD FOR PZT AT 5 CM FROM DAMAGE.....	81
FIGURE 4-26 RMSD FOR PZT AT 2 CM FROM DAMAGE.....	81
FIGURE 4-27 EXPERIMENTAL SETUP.....	83
FIGURE 4-28 PZT TRANSDUCERS ON THE CONCRETE STRUCTURE.....	84
FIGURE 4-29 HANDY CUTTER USED TO CREATE THE DAMAGE POINTS	84
FIGURE 4-30 LOCATION AND SEQUENCE OF DAMAGE POINTS ON STRUCTURE	85
FIGURE 4-31 FREE SIGNATURES OF PZT TRANSDUCERS.....	85
FIGURE 4-32 SURFACE WAVE PROPAGATION AT FREQUENCY OF 50 kHz WITH PZT 1 AS ACTUATOR	87
FIGURE 4-33 SURFACE WAVE PROPAGATION AT FREQUENCY OF 120 kHz WITH PZT 1 AS ACTUATOR	87
FIGURE 4-34 TYPICAL EMI SIGNATURE FOR A SMALL METALLIC STRUCTURES, A CONCRETE STRUCTURE AND AN ACTUAL-SIZED METALLIC STRUCTURE	88
FIGURE 4-35 MAXIMUM VOLTAGE RECEIVED FROM PZT 1 TO 4 BY SETTING PZT 5 AS ACTUATOR	90
FIGURE 4-36 LOCATION AND SEQUENCE OF DAMAGE POINTS FOR EMI METHOD	91
FIGURE 4-37 RMSD-S OF DAMAGE D1 TO D7 FOR PZT 5	93
FIGURE 4-38 RMSD-S OF DAMAGE D1 TO D7 FOR PZT 4	93
FIGURE 4-39 RMSD-S FOR PZTs 4 AND 5 FOR SIMILAR DISTANCE TO DAMAGE	94
FIGURE 4-40 RMSD-S FOR CUMULATIVE EFFECT OF DAMAGE FOR PZT 5.....	95
FIGURE 4-41 POSSIBLE ISSUES OF USING RMSD AS SINGLE VALUE INSTEAD OF RMSD- S, (A) DAMAGE OCCURRED FAR AWAY FROM PZT (B) SIMILAR DAMAGE OCCURRED AT TWO DIFFERENT DISTANCES FROM PZT.....	96
FIGURE 4-42 INCONSISTENCY IN EMI RESULT FOR RMSD OF LIMITED FREQUENCY RANGE.....	97
FIGURE 4-43 PZT SIGNATURES IN HEALTHY CONDITION	98
FIGURE 4-44 SURFACE CONDITION NEAR PZTs.....	98
FIGURE 4-45 SELECTED AREA OF CONCRETE WALL.....	99

FIGURE 4-46 PREDICTED LOCATION OF DAMAGE FOR VARIOUS RMSD-S, (A) DAMAGE IN AREA (A) OF REGION Z, (B) DAMAGE IN AREA (E) OR (F) OF REGION Z, (C) DAMAGE IN REGION Y IN AREA (A) OR (B) FOR PZT 2 WHICH OVERLAPS WITH AREA (C) TO (E) FOR PZT 5	101
FIGURE 4-47 OVERVIEW OF STEEL BEAM UNDER MONITORING	104
FIGURE 4-48 REMOVAL OF PAINTING, INSTALLING AND WATERPROOFING OF PZT TRANSDUCER	104
FIGURE 4-49 LOCATION OF PZT TRANSDUCERS INSTALLED ON THE BEAM	105
FIGURE 4-50 DAMAGE POINTS INDUCED NEAR THREE PZTs	105
FIGURE 4-51 LOCATION AND SEQUENCE OF DAMAGE POINTS ON STEEL BEAM	106
FIGURE 4-52 RMSD-S OF PZT 1, 2 AND 3 AFTER DAMAGE D1	107
FIGURE 4-53 RMSD-S OF PZT 1, 2 AND 3 AFTER DAMAGE D2	108
FIGURE 4-54 RMSD-S OF PZT 1, 2 AND 3 AFTER DAMAGE D3	109
FIGURE 4-55 RMSD-S OF PZT 1, 2 AND 3 AFTER DAMAGE D4	109
FIGURE 4-56 RMSD-S OF PZT 1, 2 AND 3 AFTER DAMAGE D5	110
FIGURE 4-57 RMSD-S OF PZT 1, 2 AND 3 AFTER DAMAGE D6	110
FIGURE 4-58 RMSD-S OF PZT 1, 2 AND 3 AFTER DAMAGE D7	111
FIGURE 4-59 RMSD-S OF PZT 1, 2 AND 3 AFTER DAMAGE D8	112
FIGURE 4-60 RMSD-S OF PZT 1, 2 AND 3 AFTER DAMAGE D9	112
FIGURE 4-61 RMSD-S OF PZT 1, 2 AND 3 AFTER DAMAGE D10	113
FIGURE 4-62 RMSD-S OF PZT 1 AFTER VARIOUS DAMAGE POINTS	114
FIGURE 4-63 RMSD-S OF PZT 2 AFTER VARIOUS DAMAGE POINTS	115
FIGURE 4-64 RMSD-S OF PZT 3 AFTER VARIOUS DAMAGE POINTS	115
FIGURE 4-65 SENSING REGION FOR FREQUENCY RANGES (A) TO (F)	116
FIGURE 4-66 EMI SIGNATURE OF PZT 1 BEFORE AND AFTER DAMAGE	117
FIGURE 4-67 RMSD-S OF PZT 1 AFTER DAMAGE POINTS D5 AND D10	118
FIGURE 4-68 RMSD VERSUS DISTANCE FOR THREE PZTs	118
FIGURE 4-69 NORMALIZED RMSD VERSUS WAVE TRAVELING DISTANCE.....	119
FIGURE 4-70 CALCULATED WAVE ATTENUATION.....	120
FIGURE 4-71 RMSD-S OF PZT 1 AFTER DAMAGE POINTS D5, D9 AND D10.....	121
FIGURE 5-1 DEVELOPED REUSABLE PZT SETUPS	126
FIGURE 5-2 MONITORING HYDRATION RATE WITH REUSABLE PZT TRANSDUCERS IN CAST 4	127

FIGURE 5-3 CYCLING LOADING SETUP FOR CAST 7	128
FIGURE 5-4 (A) REUSABLE PZT TRANSDUCER AND SURFACE-BONDED PZT TRANSDUCER, (B) 100 MM CUBE SAMPLE UNDER ON HOLD LOADING	129
FIGURE 5-5 REUSABLE SETUP DETACHED AFTER COMPRESSIVE LOADING	130
FIGURE 5-6 FREE SIGNATURES OBTAINED FROM PZT TRANSDUCERS	131
FIGURE 5-7 REPEATABILITY OF SIGNATURES FOR THREE SETUPS	131
FIGURE 5-8 INITIAL SIGNATURES OBTAINED FROM SETUP 1A AT INITIAL CONDITION AND AFTER REMOVING FROM SAMPLES	132
FIGURE 5-9 INITIAL SIGNATURE OBTAINED FROM SETUP AFTER INSTALLING INSIDE THE CONCRETE	133
FIGURE 5-10 VARIATION OF PZT SIGNATURES AT DIFFERENT HYDRATION TIME	134
FIGURE 5-11 VARIATION OF PZT SIGNATURES IN DIFFERENT CONDITIONS	135
FIGURE 5-12 REPEATABILITY OF RMSD FOR SAME MIX PROPORTION	136
FIGURE 5-13 EFFECT OF RETARDER AND FAULTY RETARDER ON HYDRATION RATE ...	138
FIGURE 5-14 COMPARISON OF RMSD VALUES FOR REUSABLE PZT SETUP AND SURFACE-BONDED PZT	140
FIGURE 6-1 (A) WATERPROOF COATED PZTs AND THE MOLDS, (B) SMART AGGREGATES DURING HYDRATION AND AFTER DEMOLDING	144
FIGURE 6-2 WATERPROOF COATING OF REUSABLE PZT TRANSDUCERS	145
FIGURE 6-3 A REUSABLE PZT TRANSDUCER	145
FIGURE 6-4 INSTALLATION OF STRAIN GAUGE (LEFT) AND STRAIN GAUGE PROTECTION (RIGHT)	146
FIGURE 6-5 INSTALLATION OF SMART AGGREGATE (LEFT), WHOLE FORMWORK (RIGHT)	146
FIGURE 6-6 THREE HOLES CREATED ON ONE SIDE OF FORMWORK FOR INSTALLATION OF REUSABLE PZT SETUP	147
FIGURE 6-7 REUSABLE PZT SETUPS INSTALLED, OUTSIDE VIEW (LEFT), INSIDE VIEW (RIGHT)	147
FIGURE 6-8 MONITORING THE HYDRATION OF CONCRETE	148
FIGURE 6-9 THREE REUSABLE PZT SETUPS ON THE BEAM	148
FIGURE 6-10 FIVE SURFACE BONDED PZTs ON THE BEAM	149
FIGURE 6-11 SCHEMATIC PRESENTATION OF THE BEAM UNDER LOADING	149
FIGURE 6-12 READINGS OF STRAIN GAUGE 1	151

FIGURE 6-13 READINGS OF STRAIN GAUGE 2	151
FIGURE 6-14 READINGS OF STRAIN GAUGE 3	152
FIGURE 6-15 READINGS OF STRAIN GAUGE 4	152
FIGURE 6-16 READINGS OF STRAIN GAUGE 5	153
FIGURE 6-17 STRAIN GAUGE 1 READING AFTER FAILURE	154
FIGURE 6-18 VARIATION OF SIGNATURES FOR EMBEDDED PZT TRANSDUCER	155
FIGURE 6-19 (A) TOTAL RMSD CHANGES, (B) RMSD CHANGES COMPARED TO PREVIOUS READING DIVIDED BY DELTA TIME, (C) TOTAL RMSD CHANGES DIVIDED BY TOTAL TIME	156
FIGURE 6-20 COMPARISON BETWEEN EMBEDDED AND REUSABLE PZT TRANSDUCERS	157
FIGURE 6-21 MAXIMUM VOLTAGE RECEIVED BY SMART AGGREGATE 2 BY SETTING SMART AGGREGATE 1 AS ACTUATOR.....	157
FIGURE 6-22 COMPARISON OF ACTUATION SIGNAL AND ACQUIRED SIGNAL.....	159
FIGURE 6-23 COMPARISON OF THE SIGNAL RECEIVED AFTER 2 HRS AND 72 HRS BY SMART AGGREGATE 2.....	159
FIGURE 6-24 MAXIMUM SIGNAL ACQUIRED BY SMART AGGREGATES 2, 3, AND 4 AT 60, 100, AND 160 CM DISTANCES FROM SMART AGGREGATE 1, RESPECTIVELY	160
FIGURE 6-25 SIGNAL ACQUIRED BY SMART AGGREGATES 2, 3 AND 4.....	161
FIGURE 6-26 VARIATION OF MAXIMUM VOLTAGE ACQUIRED AT DIFFERENT FREQUENCIES	161
FIGURE 6-27 OVERALL EXPERIMENTAL SETUP	162
FIGURE 6-28 CRACKS DEVELOPED BETWEEN SURFACE-BONDED PZTs 1 AND 2.....	163
FIGURE 6-29 ALL CRACKS DEVELOPED ON ONE SIDE OF THE BEAM.....	163
FIGURE 6-30 ACQUIRED SIGNAL UNDER 40 kN FOR THE FIRST LOADING STEP AND UNDER 40 kN AFTER FAILURE.....	164
FIGURE 6-31 COMPARISON OF AUCTION SIGNAL WITH ACQUIRED SIGNAL UNDER 40 kN LOADING	164
FIGURE 6-32 LOCATION OF SMART AGGREGATES AND DEVELOPED CRACKS ON THE BEAM	165
FIGURE 6-33 MAXIMUM AMPLITUDE OF ACQUIRED SIGNAL UNDER LOADING AND RELEASED LOADING	166

FIGURE 6-34 COMPARISON OF REDUCTION IN SIGNAL AMPLITUDE UNDER LOADING BETWEEN SMART AGGREGATES 3 AND 4 AND SMART AGGREGATES 2 AND 4	167
FIGURE 6-35 ACTUATION AND SENSING SIGNALS IN WAVE PROPAGATION TECHNIQUE	168
FIGURE 6-36 NORMALIZED AMPLITUDE OF SENSING SIGNAL FOR CASE 3.....	169
FIGURE 6-37 CRACK DEVELOPMENT BETWEEN SURFACE-BONDED PZTs 2 AND 3.....	169
FIGURE 6-38 NORMALIZED AMPLITUDE OF SENSING SIGNAL FOR CASE 5.....	170
FIGURE 6-39 CRACK DEVELOPMENT BETWEEN SURFACE-BONDED PZTs 4 AND 5.....	170
FIGURE 6-40 REGION CLOSE TO PZTs 1 AND 5.....	171
FIGURE 6-41 RMSD-S OF PZT 5	172
FIGURE 6-42 CRACKS DEVELOPED CLOSE TO PZT 2.....	173
FIGURE 6-43 RMSD-S OF PZT 2	173
FIGURE 6-44 CRACKS DEVELOPED AROUND PZT 3	174
FIGURE 6-45 RMSD-S OF PZT 3	174
FIGURE 6-46 CRACKS DEVELOPED CLOSE TO PZT 4.....	175
FIGURE 6-47 RMSD-S OF PZT 4	175
FIGURE 6-48 CRACKS DEVELOPED AROUND THREE REUSABLE PZTs	176
FIGURE 6-49 COMPARISON OF RESULTS FROM SMART AGGREGATES AND SURFACE- BONDED PZTs.....	177

LIST OF SYMBOLS

A	Area
A_x	Amplitude of signal at distance x
b_c	Width of piezoelectric patch
b_s	Width of epoxy layer
b_b	Width of beam
$b(z)$	Width of uniform equivalent section
$C_{1,2,3}$	Coefficients in Eqns. (2.28) to (2.30)
$\hat{C}_{1,2,3}$	Coefficients in Eqns. (2.28) to (2.30)
$D, D_{1(i)}$	Electrical displacement across the surface normal to 1(i)
$[D]$	Electrical displacement vector
d	Piezoelectric strain coefficient
$\hat{d}$	Piezoelectric strain coefficient, prime indicates transpose
$d_{31(jk)(im)}^{c(d)}$	Piezoelectric strain coefficient of the patch corresponding to axes 3(j)(i) and 1(k)(m), c and d related to converse and direct effect
$E, E_3 (E_j)$	Electrical field along axis 3 (j) of the piezoelectric patch
$[E]$	Electrical field vector
$\bar{E}$	Complex Young's modulus of elasticity at constant electrical field
E_b	Modulus of elasticity of beam
E_c	Modulus of elasticity of actuator
E_s	Modulus of elasticity of epoxy layer
$E(z)$	Modulus of elasticity of uniform equivalent section
f	frequency
F	Force
G_s	Shear modulus of elasticity of epoxy layer
$\bar{I}$	Complex electric current
j	$\sqrt{-1}$
K_b	Stiffness of bonding layer
K_s	Stiffness of structure
l_c	Length of piezoelectric material
l_s	Length of the epoxy layer

l_b	Length of the beam
$M, M_{x,y,\Lambda(m)}$	Bending moment in x (y) direction from actuator (Λ) or external (m)
$P, P_{x,y,\Lambda(m)}$	Force in x (y) direction from actuator (Λ) or external (m)
q	Electrical charge
S^E, S_{km}^E	An element of the elastic compliance matrix at constant electrical field
t_c	Thickness of piezoelectric patch
t_s	Thickness of epoxy layer
t_b	Thickness of beam
u	Displacement
$u_{c(b)}^{s(o)}$	Displacement in actuator (c), beam (b) at surface (s) and neutral axis (o)
V	Voltage
w_c	Width of the piezoelectric material
w_s	Width of the epoxy layer
w_b	Width of the beam
$\bar{Y}$	Complex electro mechanical admittance
$\bar{Y}_A$	Active component of complex admittance
$\bar{Y}_p$	Passive component of complex admittance
$\bar{Z}$	Neutral axis
z	Thickness of section
Z	Complex mechanical impedance of structure
Z_{res}	Modified mechanical impedance of structure
$\bar{\epsilon}_{33(ij)}^T$	Complex permittivity of piezoelectric patch along axis 33(ij) at constant stress
ϵ, ϵ_1	Mechanical strain along axis 1
ϵ_i	Mechanical strain due to inertial force
ϵ_k	Mechanical strain vector
ϵ_s	Mechanical strain due to shear force
ϵ_c	Mechanical strain in actuator
$\epsilon_b^{o(s)}$	Mechanical strain in neutral axis (o), surface (s) of beam
ω	Angular frequency (rad/s)

$\sigma, \sigma_{1(x)}$	Mechanical stress along axis 1(x)
$\sigma_b^{o(s)}$	Mechanical stress in neutral axis (o), surface (s) of beam
σ_c	Mechanical stress in actuator
σ_m	Mechanical stress vector
δ	Dielectric loss factor
ρ	Material density
η	Mechanical loss factor of piezoelectric patch
k	Beam curvature
τ_s	Shear stress
α	Coefficient in Rayleigh damping
β	Coefficient in Rayleigh damping
φ	Reduction factor of mechanical impedance of structure
Γ	Shear lag parameter
ξ_n	Damping ratio in natural frequency n
ν	Poisson's ratio
Λ	Free piezoelectric strain ($=E_3d_{31}$)
ψ	Stiffness ratio
κ	Wave number
γ_s	Shear strain in epoxy (s)
G_i^0, G_i^1	Pre-damage and post-damage raw conductance respectively for i^{th} frequency point.
ADP	Ammoniumdihydrogen-Phosphate
AFC	Active Fiber Composite
ASTM	American society for Testing and Mechanical
BEM	Boundary Element Method
EMI	Electro Mechanical Impedance
FEM	Finite Element Method
FDM	Finite Difference Method
MEMS	Micro-electromechanical System
MFC	Macro Fiber Composites
NASA	National Astronautics and Space Administration
NDE	Non-Destructive Evaluation
NDT	Non-Distractive Testing

PC	Personal computer
PMN	Lead Metaniobate
PVDF	Poly Vinylidene Fluoride
RC	Reinforced Concrete
PZT	Lead Zirconate Titanate
RMSD	Root Mean Square Deviation
RMSD-S	Root Mean Square Deviation of sub frequency intervals
SAFE	Semi Analytical Finite Element method
SDOF	Single Degree of Freedom (System)
SHM	Structural Health Monitoring
SMI	Structural Mechanical Impedance

CHAPTER

1

INTRODUCTION

1.1 Background

The last few decades have witnessed the vast applications of smart materials in structural health monitoring (SHM), non-destructive evaluation (NDE), vibration control, sensing, actuation and energy harvesting. Monitoring of infrastructure, air craft, spaceships, heavy machinery and change in material characteristics, controlling the vibration of car engines, and harvesting the energy for self powered sensors are some of the area of applications of smart materials.

Any structure such as building or bridges, once constructed needs regular assessment of its safety and health condition. In addition to huge economic losses, an unexpected failure could cost many lives. Considering deterioration and damage on the structures over a period of time, as result of excessive loading, environmental effects, earthquakes and degradation of material properties and wide variety of unforeseen conditions, it is very difficult to ensure the safety of the structures over their life span (Naidu, 2004).

SHM technique for in situ online damage detection of structures using Lead Zirconate Titanate (PZT) sensors was initiated at the Center for Intelligent Material Systems and Structures, Virginia Tech (Sun et al., 1995). PZT material is robust, cost effective, sensitive to damage and ideal for constructed infrastructures as sensors. PZT has been used for SHM, vibration control and many other applications over the past few decades (Liang et al., 1994; Qiu and Tani, 1995; Quinn et al., 1999; Sirohi

and Chopra, 2000a; Soh et al., 2000; Park et al., 2000a; 2003a; Naidu, 2004; Yang et al., 2006, Lei and Zongjin, 2008; Meng et al, 2010).

However, extremely brittle nature of the PZT materials requires extra attention during the handling and bonding procedures, and the conformability of PZT actuator to curved surfaces is extremely poor (Williams et al., 2002). Recently developed PZT fiber composite actuators are composed of unidirectional piezoelectric ceramic fibers sandwiched between two integrated electrodes and embedded in a polymer matrix (Sodano et al., 2004). One of the advantages of piezo-composite actuators is to provide low cost and in-situ actuation with high flexibility (Nguyen and Kornmann, 2006). One of such actuators is the macro fiber composite (MFC) developed by NASA Langley Research Center (Sodano et al., 2004). Smart Materials Corp. has commercialized the MFC technology and offers a variety of different design forms of MFC. The MFC can function as good sensor and very strong actuator. High flexibility and maximum operational voltage of 1500 volts DC and 500 volts AC make it very strong actuator. However it is less sensitive as sensor for the same level of applied electrical charge compared to PZT. Many research projects have shown the potential of MFC for vibration and noise control, health monitoring, morphing of structures and energy harvesting (Park et al., 2003b; Schultz and Hyer, 2004; Schönecker et al., 2006; Ro et al., 2007).

The piezoelectric transducers have found a very vast application as sensors, particularly for SHM using the electro mechanical impedance (EMI) technique. In the EMI technique, the structure under monitoring is subjected to high frequency excitation (typically in the range of 30 kHz to 400 kHz), and the resulting vibration response of the structure is acquired. In this technique, the actuation signal generated using piezoelectric transducers propagate in the structure and an impedance analyzer is used to acquire the vibration response of the structure through the same piezoelectric transducers. Piezoelectric transducers are also employed for SHM using the wave propagation and wave transmission techniques. In the wave propagation and wave transmission techniques, a signal generated by piezoelectric transducer propagates/transmits to structure and the resulting signal is acquired by one or more piezoelectric transducers. Damage in the structure can be quantified with the variations in the magnitude and/or shape of the acquired signal.

In sensing and actuation applications of piezoelectric transducers, the models related to the strain transfer inside the transducer and host structure are rather undeveloped. Thus, development of models to simulate the strain transfer is essential. Furthermore, one of the difficulties in application of the EMI method for SHM is the combined effect of damage severity and location. If the frequency range is limited, a small damage close to piezoelectric transducer can change the signature similar to a severe damage far away from piezoelectric transducer. Also, in the existing EMI models, perfect bonding between the piezoelectric transducer and host structure has been assumed, which is not realistic for practical application. Furthermore, surface-bonded or embedded piezoelectric transducers have been used for SHM using the EMI and wave propagation techniques. The study on sensitivity and applicability of each technique and the combination of these techniques for the improvement of SHM efficiency is needed.

1.2 Objectives

The primary goal of this research is to address the above mentioned issues on the modeling and application of piezoelectric transducers for SHM. The objectives of this study include:

- 1) Development of strain transfer model and modified EMI model for piezoelectric transducers;
- 2) Identification of damage severity and location using piezoelectric transducers;
- 3) Development of reusable PZT transducer; and
- 4) Comparative study on the EMI, wave propagation and wave transmission techniques and development of a combined technique for SHM.

1.3 Scope of work

To achieve the objectives, the scope of this study is presented as follows. Figure 1-1 shows the schematic presentation of this scope.

Figure 1-1 Schematic presentation of this study

- Theoretical development of strain transfer model and modified EMI model:** In this work, an existing 1-D Bernoulli-Euler formulation for strain transfer is modified to account for the strain inside of the actuator. The model is then extended to 2-D case, where the thickness and modulus of elasticity of epoxy layer can be considered. A finite element model for actuation of a cantilever beam with MFC actuator is developed using ABAQUS to verify the strain transfer through the epoxy layer to the structure. An experimental test is carried out and the results are compared with the FEM and analytical results. Liang *et al* (1994) developed the EMI model for PZT transducers based on fully bonded assumption. However, it is not the case for real-world application which PZT transducer is bonded to structure with epoxy layer and the epoxy layer properties will affect the sensitivity of PZT for SHM. The developed strain transfer model is used to modify the existing EMI model for the inclusion of epoxy layer properties. A reduction factor is derived analytically to consider the epoxy layer properties. Parametric study is performed on reduction factor. A finite element model is developed in ANSYS to numerically investigate and

verify the effect of epoxy layer properties on the sensitivity of PZT transducer.

- **Identification of damage severity and location with PZT based EMI:** Park *et al* (2003b) recommended a frequency range of 30 kHz to 400 kHz for SHM using the EMI technique. To achieve high sensitivity to damage, high frequency signatures (>200 kHz) have been used to monitor the region close to the PZT location while low frequency signatures (<100 kHz) have been traditionally ignored. However, it has been reported that the use of root mean square deviation (RMSD) as the damage indicator is difficult to specify the damage location and severity due to the inconsistency in the RMSD results. This work proposes to use the large frequency range (30-400 kHz) and calculate the RMSD values of sub-frequency intervals for damage identification. Experiments are carried out on an actual-sized concrete and steel structures subjected to artificial damage. The PZT admittance signatures in a frequency range of 30 to 400 kHz for different structural damage are analyzed and the RMSD values of sub-frequency intervals (RMSD-S) are calculated. A damage identification scheme is proposed to study the damage severity and location using various RMSD-S values.
- **Development of reusable PZT setup:** A reusable PZT setup for monitoring initial hydration of concrete and structural health is designed and fabricated, where a piece of PZT is bonded to a metal/ plastic enclosure with two bolts tightened inside of the holes drilled in the enclosure. During the concrete casting, the bolts and the bottom surface of the enclosure is set to penetrate part of the fresh concrete. Experimental results show that the developed transducer is able to effectively monitor the initial hydration of concrete and can be detached from the concrete for future use.
- **Experimental study on embedded, reusable and surface-bonded PZTs using the EMI, wave propagation and wave transmission techniques:** Due to very high damping of concrete, the EMI technique can only monitor small and local area in concrete structures. By using an impedance analyzer

with interrogation voltage of 2 volts, the sensing region is limited to 30 cm around PZT. The wave propagation technique with high actuation voltage can monitor larger area. However, the results are significantly affected by the surface condition. In addition, the calculation of damage location and severity demands complex modeling of wave propagation especially for concrete structures with rough surfaces and boundaries. On the other hand, the wave transmission technique using smart aggregates (embedded PZT transducer) can be employed to monitor very large areas with reasonable low actuation signal. Analysis of the wave transmission signal provides a convenient way to detect the discontinuities within the structure. The combination of embedded smart aggregates transducers (using the wave transmission technique) with surface-bonded PZTs (using the EMI technique or the wave propagation technique) can provide an effective method to study both the local and overall conditions of the structure. Experiments are carried out on an actual-sized concrete structure to integrate these techniques for SHM.

1.4 Research originality and contributions

Upon the completion of the above scope of work, the originality and contributions of this research can be summarized as follows.

(i) In this work, the existing 1-D Bernoulli-Euler formulation for strain transfer is modified and extended to 2-D case, to account for the effect of thickness and modulus of elasticity of the epoxy layer. The developed model is useful for the applications such as vibration control, energy harvesting and sensing and actuation where the stiffnesses of the host structure and actuator are comparable. The developed strain transfer model is also used to modify the existing EMI model for inclusion of epoxy layer properties. A reduction factor is derived analytically to consider the epoxy layer properties.

(ii) By calculating the RMSD values of sub-frequency intervals in a large frequency range, the proposed RMSD-S based damage identification method reduces inconsistency and uncertainties in the traditional RMSD method which uses limited high frequency range. Using the observation that the damage close to the PZT

changes the RMSD-S at high frequency range significantly and the damage far away from the PZT changes the RMSD-S at low frequency range significantly, the location and severity of damage can be assessed.

(iii) To reduce the cost of PZT based SHM, a reusable PZT setup for monitoring initial hydration of concrete and structural health is developed. The results show that the developed transducer is able to effectively monitor the initial hydration of concrete and can be detached from the concrete for future use. The reusable PZT setup can also be used to monitor the structural health after the curing of concrete. However, it is less sensitive to damage compared to the surface-bonded PZTs and can only pick up the cracks underneath it.

(iv) Comparative study on surface-bonded, reusable and embedded PZT transducers using the EMI, wave propagation and wave transmission techniques is conducted. The combination of the smart aggregates using the wave transmission technique to study the overall condition of the structure with the surface-bonded PZTs using the EMI or wave propagation techniques to study the local condition of the structure provides an effective way for SHM.

1.5 Organization of report

This chapter presented the background, objectives, scope and contributions of this research. Chapter 2 presents the literature review on the piezoelectric transducers and their applications, strain transfer model, and structural health monitoring. Development of a new strain transfer model for strain actuators and modification of the existing EMI model for inclusion of epoxy layer properties including the FEM modeling and experimental validation are presented in Chapter 3. Study on the location and severity of the damage by the RMSD-S based damage identification scheme is conducted in Chapter 4. The development of reusable PZT setup for monitoring of the initial hydration of concrete and structural health is presented in Chapter 5. Chapter 6 presents the comparison and combination of surface-bonded, reusable setup and embedded PZT transducers for monitoring initial hydration of concrete and structural health. Finally, summary of current work and recommendations for future work are presented in Chapter 7.

CHAPTER

2

LITERATURE REVIEW

2.1 Introduction to piezoelectricity

Piezoelectricity is ability of some materials to generate electrical charge in response to applied mechanical stress and to generate mechanical stress in response to applied electrical charge. The word ‘piezo’ is derived from a Greek word meaning pressure and the phenomenon of piezoelectricity was discovered in 1880 by Pierre and Paul-Jacques Curie. In direct piezoelectricity, when a mechanical strain is applied to the material an electric charge generates. In converse piezoelectricity, an electric charge induces a mechanical strain in the material. The converse piezoelectric effect was mathematically proven in 1881 by Lippmann using the fundamental thermodynamic principles (Sodano, 2003).

Beginning the mid 1930’s, there were some advances in the production of materials with higher piezoelectric properties, leading to the development of the crystal ADP (ammoniumdihydrogen-phosphate). ADP possessed the rugged characteristic of the quartz crystal and the strong piezoelectric characteristics of Rochelle salt (Inman and Cudney, 2000). In addition to ADP several other piezoelectric crystals were identified.

The next phase in the development of piezoelectric materials occurred during World War II. In the U.S., Japan and the Soviet Union, research groups were

developing advanced capacitor materials and found that certain ceramics prepared by sintering metallic oxide powders, exhibited dielectric constants up to 100 times greater than those of the commonly cut crystals of the time. Ferroelectric materials were constructed to have similar improvements in piezoelectric properties. The greater research efforts began to produce ceramic materials with better piezoelectric properties, leading to the development of numerous materials, the most important of these being lead metaniobate (PMN) and lead zirconate titanate (PZT). These two materials are still among the most used for piezoelectric applications today. After development of the piezoceramic was the piezoelectric semiconductor film and piezoelectric polymers. The most important of the piezo-polymers is the poly vinylidene fluoride film (PVDF), which is still heavily used (Sodano, 2003).

2.1.1 Piezoelectric constitutive relations

Under small field conditions, the constitutive relations for a piezoelectric material are (ANSI/IEEE, 1987)

$$\varepsilon_k = S_{km}^E \sigma_m + d_{jk}^c E_j \quad (2.1)$$

$$D_i = d_{im}^d \sigma_m + \varepsilon_{ij}^T E_j \quad (2.2)$$

Eqn. (2.1) represents the “direct effect” (stress induced electrical charge) and Eqn. (2.2) represent the “converse effect” (electric field induced mechanical strain). ε_k is the strain vector (6×1) (dimensionless), S_{km}^E is the elastic compliance (6×6) (m^2/N), σ_m is the stress vector (6×1) (N/m^2), d_{jk}^c (6×3), d_{im}^d (3×6) are the piezoelectric dielectric coefficients ($Coulomb/N, m/Volt$), E_j is the applied electric field vector (3×1) ($Volt/m$), D_i (3×1) is the dielectric displacement ($Coulomb/m^2$) and ε_{ij}^T (3×3) is the dielectric permittivity ($Farad/m$). Superscripts c and d related to converse and direct effect respectively. Eqns. (2.1) and (2.2) can be written in matrix form (Sirohi and Chopra, 2000b).

$$\begin{bmatrix} \varepsilon \\ D \end{bmatrix} = \begin{bmatrix} S^E & d \\ d' & e^b \end{bmatrix} \begin{bmatrix} \sigma \\ E \end{bmatrix} \quad (2.3)$$

The superscript E indicates that the quantity is measured at constant electric field. The prime indicates a transpose, which is a consequence of the fact that the direct and converse effects are equal. If static electric field is applied under the free boundary condition, no mechanical stresses will develop. Similarly, if the stress is applied under the short-circuited condition, no electric field (or surface charges) will develop (Bhalla, 2004).

The d_{jk}^C matrix for PZT can be expressed as

$$d = \begin{bmatrix} 0 & 0 & d_{31} \\ 0 & 0 & d_{32} \\ 0 & 0 & d_{33} \\ 0 & d_{25} & 0 \\ d_{15} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad (2.4)$$

where the coefficients d_{31} , d_{32} and d_{33} are the normal strain in the 1, 2 and 3 directions respectively. The coefficients d_{15} and d_{25} are the shear strain in the plane.

The compliance matrix is written as

$$S^E = \begin{bmatrix} S_{11} & S_{12} & S_{13} & 0 & 0 & 0 \\ S_{12} & S_{22} & S_{23} & 0 & 0 & 0 \\ S_{13} & S_{23} & S_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & S_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & S_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & S_{66} \end{bmatrix} \quad (2.5)$$

The permittivity matrix is:

$$\epsilon_{ij}^T = \begin{bmatrix} \epsilon_{11}^T & 0 & 0 \\ 0 & \epsilon_{22}^T & 0 \\ 0 & 0 & \epsilon_{33}^T \end{bmatrix} \quad (2.6)$$

And finally, the electrical displacement D is the generated charge which can be written as follows

$$q = \iint \begin{bmatrix} D_1 & D_2 & D_3 \end{bmatrix} \begin{bmatrix} dA_1 \\ dA_2 \\ dA_3 \end{bmatrix} \quad (2.7)$$

where dA_1 , dA_2 and dA_3 are the components of the electrode area.

2.1.2 Piezoelectric materials

The most commonly used piezoelectric materials are solid solution of lead zirconate and lead titanate, called lead zirconate titanates (PZTs). These ceramics are manufactured by mixing proportional amount of these materials and heating the matrix to around 800-1000°C. During the cooling process, the material undergoes a paraelectric to ferroelectric phase transition and the cubic unit cell becomes tetragonal and becomes elongate in one direction and has permanent dipole moment (Sirohi and Chopra, 2000b). With application of a high electrical field, most of the cell units will align parallel to applied field.

PZT called d_{31} element, means the electrical field in the third dimension will result in deflection in the first dimension which is demonstrated in Figure 2-1.

Figure 2-1 Illustration of dimensions for PZT d_{31} materials

PZT transducer exhibits most of the characteristics of the ceramic, including a high modulus of elasticity, brittleness and low tensile strength (Sirohi and Chopra, 2000b). Extremely brittle nature of the PZT transducer requires extra attention during the handling and bonding procedures, and the conformability of PZT actuator to curved surfaces is extremely poor (Sodano et al., 2004).

These limitations have motivated researchers to develop alternative piezoceramic materials for the growing applications. To overcome the brittleness of PZTs for many applications, the idea of using a composite material consisting of an active piezoceramic fibers embedded in a polymeric matrix phase was proposed (Sodano et al., 2004). The polymer matrix increases the flexibility of piezoceramic fibers and increases conformability to curved surfaces and provides a protective layer around the piezoelectric material. This polymer layer allows the piezo fibers to withstand impacts and harsh environments. Several piezo fiber technologies are commercially available, namely the 1-3 composites developed by Smart Materials Corp. (Smart-Materials, 2010), active fiber composite (AFC) actuators developed by MIT (Bent, 1999; Bent and Pizzochero, 2000), and macro fiber composite (MFC) actuators constructed at NASA Langley Research Center (Wilkie et al., 2000).

1-3 Composites

The 1-3 composite material from Smart Material Corp. (Smart-Materials, 2010) consists of piezoelectric rods embedded in a polymer matrix. The piezoelectric ceramic material is aligned through the longitudinal direction inside the polymer phase. These actuators are constructed using a soft mold process. This process consists of copying a reusable soft mold from a positive form of the final structure then filling the mold with the piezoceramic material. Once the mold is filled with the piezoelectric material it is fired to sinter the piezoceramic. Using this process the active pixels can be constructed in either round (70 micron diameter with 50-micron spaces) or rectangular (80 microns with 120 micron spaces) as shown in Figure 2-2.

Figure 2-2 1-3 composite actuators by Smart Materials Corp. (Smart-Materials, 2010)

The soft molding process have many advantages over the die and fill, injection molding or dicing techniques due to the molds being reusable, allowing thousands similar actuators to be made. Furthermore, the fabrication is relatively easy and cost effective because of the simplicity of the mold construction in comparison to the other methods for fiber construction. Once the brittle fibers are formed a polymer matrix is added to the remaining spaces to protect the fibers from breakage (Sodano et al., 2004).

Due to lower acoustic impedance, higher coupling coefficients, reduced lateral coupling due to isolated fibers, higher flexibility through the polymer matrix and higher bandwidths up to 10 MHz, this material is better than PZTs. The advantages have made the 1-3 composite actuators a popular choice for ultrasound applications, including medical ultrasound, flow control, sonar, nondestructive testing and broadband transceivers. In addition to these applications, the 1-3 composite is used for attenuation of acoustic waves in smart composite panels. When this arrangement is attached to a structure such as an aircraft fuselage it can be used to attenuate noise levels, function as pressure sensors or reduce the broadband vibration levels inside the fuselage of an aircraft by 20 dB (Sodano et al., 2004).

Active Fiber Composites

The active fiber composite (AFC) actuator was developed at MIT's Active Materials and Structures Lab. It has seen much attention due to its wide range of potential applications. This actuator is constructed of unidirectional aligned piezoceramic fibers surrounded by a polymer matrix. The AFC can also be adapted such that inactive glass fibers are inserted into the polymer matrix to add additional structural strength. The piezoceramic fibers are produced through injection molding process (Gentilman et al., 2003). The procedure combines either PZT or PMN powder with a wax based binder, and then the material is granulated as feedstock for the injection molding process. Once this is completed the feedstock is heated to the specified viscosity and rapidly injected at high pressure into a cooled mold. The homogeneous density of the material produces uniform microstructures, dimensions and electromechanical properties after firing.

After the production of the piezoceramic fibers an electrode layer is placed on top and bottom of the fibers. The AFC uses interdigitated electrodes that allow the electrical potential to form along the length of the fiber; therefore higher d_{33} piezoelectric coupling coefficient can be achieved. A schematic to visualize the electric field developed along the fibers is shown in Figure 2-3.

One of the major areas for application of this material is to embed the fibers into the rotor blades of a helicopter. The helicopter blades experience large aerodynamic loads and in turn induce large vibration and noise issues. With the active fiber embedded inside the rotor blade the vibration and noise levels inside the helicopter could be significantly reduced providing increased comfort to the pilot and passengers of the aircraft (Sodano et al., 2004).

Figure 2-3 Schematic cross section of an AFC actuator (Wilkie et al. 2000)

Macro Fiber Composites

The third type of piezoceramic fiber actuator is the macro fiber composite (MFC) actuator which was developed at the NASA Langley Research Center (Wilkie et al., 2000). Similar to the AFC, the MFC consists of active piezoceramic fibers aligned in

a unidirectional manner, interdigitated electrodes, and an adhesive polymer matrix. The layers of the MFC are shown in Figure 2-4.

Figure 2-4 Different layers in macro fiber composite (MFC)

The MFC has rectangular fibers which greatly affects the manufacturing process and the performance. The fibers of the MFC have a rectangular cross section due to the method used to form the fibers. Instead of forming them through an injection molding process as done in fabrication of the AFC, they are machined from low cost piezoceramic wafers and a computer controlled dicing saw. This process is shown in Figure 2-5.

After the piezoceramic wafer has been cut, it is then transferred and fixed to the bottom electrode film using a thermosetting epoxy adhesive that functions as the polymer matrix material. The sheet is then slightly heated to allow the epoxy to secure the piezoceramic fibers and ensure they are properly aligned. Once the fibers are secured the polymer carrier sheet is removed and a layer of thermosetting epoxy is added to the top before applying the top electrode sheet. This process is shown in Figure 2-6.

NASA Langley Research Center / ARL Vehicle Technology Directorate

Figure 2-5 Fabrication process of MFC piezo fibers (Wilkie et al. 2000)

Figure 2-6 Bonding of piezo fibers and interdigitated electrodes (Wilkie et al. 2000)

After all layers of the MFC are stacked together the entire assembly is placed inside of a vacuum press where heat and pressure are applied to avoid the formation and growth of voids in the epoxy matrix. Similar to AFC, the MFC is extremely

flexible, durable and has the advantage of higher electromechanical coupling coefficients due to interdigitated electrodes. However, the manufacturing processes discussed in the previous paragraphs allow the MFC to be produced at a much lower cost. MFC has found many applications in actuation and vibration control in recent years (Schultz and Hyer, 2004; Schönecker et al., 2006; Ro et al., 2007).

MFC can be manufactured in d_{33} (also called d_{11}) and d_{31} types. For the d_{33} type, the electrical potential flow in the length of MFC instead of the thickness of the MFC. The MFC- d_{33} is good sensor and very strong actuator. High flexibility and maximum operational voltage of 1500 volts DC and 500 volts AC makes it very strong actuator. Despite all the improvement in MFC compared to PZT, MFC is less sensitive compared to PZT for SHM for the same level of applied electrical field.

2.2 Strain transfer model

For the applications of SHM, vibration control and actuation, it becomes necessary to formulate the interaction between PZT/MFC and the structure (Park et al., 1996). Several one dimensional models have been reported in literature. However development of fiber composites and huge increase in actuation capacity of piezoelectric materials increased the need to further study the strain transfer phenomena. The derivation of the existing models is presented in the following section. Modifications and development of new models and study on their limitations and applications are presented in Chapter 3.

2.2.1 Uniform model with inclusion of shear lag effect

Crawley and De Luis (1985) developed a uniform strain model of the beam with strain actuator bonded on the top surface. As shown in Figure 2-7, the model is based on a beam with a strain actuator bonded to its surface with finite thickness of epoxy.

Figure 2-7 Beam configuration

The governing equations are developed through the force and moment equilibrium of the elemental section shown in Figure 2-8. The actuator is assumed to induce the linear strain only in its major axis direction. The strain is assumed to be uniform through the actuator thickness and linear through the beam and adhesive thickness.

Figure 2-8 Stresss and strain in the strain actuator and beam

The shear transferred by adhesive layer will cause the beam extension and the beam bending as shown in Figure 2-9.

Figure 2-9 Shear caused beam extension and bending

The equilibrium equations for the differential element of a straight rectangular isotropic beam are

$$-\sigma_x b_c t_c + \left(\sigma_x + \frac{\partial \sigma_x}{\partial x} \right) b_c t_c - \tau_s b_c = 0 \Rightarrow \frac{\partial \sigma_x}{\partial x} - \frac{\tau_s}{t_c} = 0 \quad (2.8)$$

$$-\sigma_b^o b_b t_b + \tau_s b_c + \left(\sigma_b^o + \frac{\partial \sigma_b^o}{\partial x} \right) b_b t_b = 0 \Rightarrow \frac{\partial \sigma_b^o}{\partial x} + \frac{b_c}{b_b t_b} \tau_s = 0 \quad (2.9)$$

$$\begin{aligned} & \tau_s b_c t_b + \left(\sigma_b^o + \frac{\partial \sigma_b^o}{\partial x} \right) b_b t_b \frac{t_b}{2} - \sigma_b^o b_b t_b \frac{t_b}{2} + \frac{1}{2} \left(\sigma_2 + \frac{\partial \sigma_2}{\partial x} \right) b_b \frac{t_b}{2} \times \frac{5}{6} t_b - \\ & \frac{1}{2} (\sigma_2) b_b \frac{t_b}{2} \times \frac{5}{6} t_b - \frac{1}{2} \left(\sigma_2 + \frac{\partial \sigma_2}{\partial x} \right) b_b \frac{t_b}{2} \times \frac{1}{6} t_b + \frac{1}{2} (\sigma_2) b_b \frac{t_b}{2} \times \frac{1}{6} t_b \Rightarrow \frac{3b_c}{b_b t_b} \tau_s + \frac{\partial \sigma_b^s}{\partial x} - \\ & \frac{\partial \sigma_b^o}{\partial x} = 0 \end{aligned} \quad (2.10)$$

where $\sigma_b^o = \sigma_1$ (The stress in the neutral axis of the beam) and $\sigma_b^s = \sigma_1 + \sigma_2$ (on surface of the beam)

For one dimensional system the strain and displacement are related as follows

$$\varepsilon_c = \frac{\partial u_c}{\partial x} \text{ (actuator strain)} \quad (2.11)$$

$$\varepsilon_b^s = \frac{\partial u_b^s}{\partial x} \quad (2.12)$$

$$\varepsilon_b^o = \frac{\partial u_b^o}{\partial x} \quad (2.13)$$

$$\gamma_s = \frac{u_c - u_b^s}{t_s} \quad (2.14)$$

The stress in the actuator is related to the difference between the apparent and induced strain

$$\sigma_c = E_c(\varepsilon_c - \Lambda) \quad (2.15)$$

where Λ is the induced strain.

Other stress-strain relations are as follows

$$\sigma_b^s = E_b \varepsilon_b^s \quad (2.16)$$

$$\sigma_b^o = E_b \varepsilon_b^o \quad (2.17)$$

$$\tau_s = G_s \gamma_s \quad (2.18)$$

Substituting Eqns. (2.11) through (2.18) into Eqns. (2.8) to (2.10) and differentiating with respect to x produce three governing differential equations.

$$\frac{\partial^2 \varepsilon_c}{\partial x^2} - \frac{G_s}{E_c t_c t_s} (\varepsilon_c - \varepsilon_b^s) = 0 \quad (2.19)$$

$$\frac{\partial^2 \varepsilon_b^s}{\partial x^2} - \frac{\partial^2 \varepsilon_b^o}{\partial x^2} + \frac{3b_c G_s}{(E_b t_b b_b) t_s} (\varepsilon_c - \varepsilon_b^s) = 0 \quad (2.20)$$

$$\frac{\partial^2 \varepsilon_b^o}{\partial x^2} + \frac{b_c G_s}{(E_b t_b b_b) t_s} (\varepsilon_c - \varepsilon_b^s) = 0 \quad (2.21)$$

Combining the governing equations and non-dimensionalizing with respect to actuator length reduce the system equations to a single second order differential equation.

$$\frac{\partial^2 \zeta}{\partial \bar{x}^2} - \Gamma^2 \zeta = 0 \quad (2.22)$$

$$\zeta = \varepsilon_c - \varepsilon_b^s \quad (2.23)$$

The non-dimensional shear lag (Γ), stiffness ratio (ψ) and length are defined as

$$\Gamma^2 = \frac{\psi_s}{\bar{t}_s^2} \left(1 + \frac{4}{\psi_b} \right), \psi_b = \frac{E_b t_b b_b}{E_c t_c b_c}, \psi_s = \frac{G_s t_s b_s}{E_c t_c b_c}, \bar{t}_s = \frac{t_s}{l_{c/2}}, \bar{x}_s = \frac{x_s}{l_{c/2}}$$

The solution to the equation is

$$\zeta(\bar{x}) = A \cosh(\Gamma \bar{x}) + B \sinh(\Gamma \bar{x}) \quad (2.24)$$

Substituting Eqn. (2.24) into Eqns. (2.19) to (2.21) gives

$$\frac{\partial^2 \varepsilon_c}{\partial \bar{x}^2} = \frac{\psi_s}{\bar{t}_s^2} (A \cosh(\Gamma \bar{x}) + B \sinh(\Gamma \bar{x})) \quad (2.25)$$

$$\frac{\partial^2 \varepsilon_b^s}{\partial \bar{x}^2} = -\frac{4\psi_s}{\psi_b \bar{t}_s^2} (A \cosh(\Gamma \bar{x}) + B \sinh(\Gamma \bar{x})) \quad (2.26)$$

$$\frac{\partial^2 \varepsilon_b^o}{\partial \bar{x}^2} = -\frac{\psi_s}{\psi_b \bar{t}_s^2} (A \cosh(\Gamma \bar{x}) + B \sinh(\Gamma \bar{x})) \quad (2.27)$$

The solutions are:

$$\varepsilon_c(\bar{x}) = C_1 + \hat{C}_1 \bar{x} + \frac{\psi_s}{\bar{t}_s^2 \Gamma^2} (A \cosh(\Gamma \bar{x}) + B \sinh(\Gamma \bar{x})) \quad (2.28)$$

$$\varepsilon_b^s(\bar{x}) = C_2 + \hat{C}_2 \bar{x} - \frac{4\psi_s}{\psi_b \bar{t}_s^2 \Gamma^2} (A \cosh(\Gamma \bar{x}) + B \sinh(\Gamma \bar{x})) \quad (2.29)$$

$$\varepsilon_b^o(\bar{x}) = C_3 + \hat{C}_3 \bar{x} - \frac{\psi_s}{\psi_b \bar{t}_s^2 \Gamma^2} (A \cosh(\Gamma \bar{x}) + B \sinh(\Gamma \bar{x})) \quad (2.30)$$

By subtracting Eqn. (2.30) from Eqn. (2.29) and equating to Eqn. (2.24) through Eqn. (2.23), we obtain

$$C_1 = C_2, \hat{C}_1 = \hat{C}_2$$

The coefficients are obtained through the stress free boundary conditions as follows

$$\varepsilon_c(\pm 1) = \Lambda \quad (2.31)$$

$$\varepsilon_b^s(\pm 1) = 0 \quad (2.32)$$

$$\varepsilon_b^o(\pm 1) = 0 \quad (2.33)$$

$$A = \frac{\Lambda}{\cosh(\Gamma)}, B = \dot{C}_i = 0, C_1 = C_2 = \Lambda \frac{4}{\psi_b+4}, C_3 = \Lambda \frac{1}{\psi_b+4}$$

Then the final solution for the actuator and beam strain will be

$$\frac{\varepsilon_c(\bar{x})}{\Lambda} = \frac{4}{\psi_b+4} + \frac{\psi_b}{(\psi_b+4)\cosh(\Gamma)} \cosh(\Gamma\bar{x}) \quad (2.34)$$

$$\frac{\varepsilon_b^s(\bar{x})}{\Lambda} = \frac{4}{\psi_b+4} - \frac{4}{(\psi_b+4)\cosh(\Gamma)} \cosh(\Gamma\bar{x}) \quad (2.35)$$

$$\frac{\varepsilon_b^o(\bar{x})}{\Lambda} = \frac{1}{\psi_b+4} - \frac{1}{(\psi_b+4)\cosh(\Gamma)} \cosh(\Gamma\bar{x}) \quad (2.36)$$

$$\frac{\varepsilon_b^b(\bar{x})}{\Lambda} = -\frac{2}{\psi_b+4} + \frac{2}{(\psi_b+4)\cosh(\Gamma)} \cosh(\Gamma\bar{x}) \quad (2.37)$$

For large value of Γ , the strain is constant over the span of the actuator and reduces to perfectly bonded condition where

$$\frac{\varepsilon_c(\bar{x})}{\Lambda} = \frac{\varepsilon_b^s(\bar{x})}{\Lambda} = \frac{4}{\psi_b+4} \quad (2.38)$$

$$\frac{\varepsilon_b^o(\bar{x})}{\Lambda} = \frac{1}{\psi_b+4} \quad (2.39)$$

$$\frac{\varepsilon_b^b(\bar{x})}{\Lambda} = -\frac{2}{\psi_b+4} \quad (2.40)$$

$$\frac{\partial^2 w}{\partial x^2} = -\kappa = -\frac{2}{t_b} (\varepsilon_b^s - \varepsilon_b^o) \rightarrow \frac{\kappa t_b}{2\Lambda} = \left(\frac{3}{\psi_b+4}\right) \quad (2.41)$$

2.2.2 Bernoulli-Euler formulation

The 1-D Bernoulli-Euler model proposed by Crawley and Anderson (1989) does not simplify the adhesive to shear layer and the strain is linear and consistent throughout the entire cross section. The strain in any location of the beam is

$$\mathcal{E}(z) = \mathcal{E}_0 - z\kappa \quad (2.42)$$

This formulation allows a linear variation of the strain through the actuator and does not simplify the adhesive to a shear layer. Force and moment equilibrium obtained by integrating over the cross section provide the governing equations as follows

$$\begin{bmatrix} EA & ES \\ ES & EI \end{bmatrix} \begin{bmatrix} \varepsilon \\ -k \end{bmatrix} = \begin{bmatrix} P_\Lambda \pm P_m \\ M_\Lambda \pm M_m \end{bmatrix} \quad (2.43)$$

in which

$$EA = \int_z E(z)b(z)dz \quad (2.44)$$

$$ES = \int_z E(z)b(z)zdz \quad (2.45)$$

$$EI = \int_z E(z)b(z)z^2dz \quad (2.46)$$

$$P_m = \int_z \sigma(z)dz \quad (2.47)$$

$$M_m = \int_z \sigma(z)zdz \quad (2.48)$$

$$P_\Lambda = \int_z E(z)\Lambda(z)b(z)dz \quad (2.49)$$

$$M_\Lambda = \int_z E(z)\Lambda(z)b(z)zdz \quad (2.50)$$

For isotropic rectangular beam with a surface-bonded actuator, the cross sectional properties with respect to the neutral axis can be calculated as follows

$$\bar{z} = \frac{E_b b_b t_b (\frac{t_b}{2}) + E_s b_s t_s (t_b + \frac{t_s}{2}) + E_c b_c t_c (t_b + t_s + \frac{t_c}{2})}{E_b b_b t_b + E_s b_s t_s + E_c b_c t_c} \quad (2.51)$$

The induced forces and moments are

$$P_\Lambda = E_c b_c t_c \Lambda \quad (2.52)$$

$$M_{\Lambda} = E_c b_c t_c (t_b + t_s + \frac{t_c}{2} - \bar{z}) \Lambda \quad (2.53)$$

where $EA = E_b b_b t_b + E_s b_s t_s + E_c b_c t_c$ and

$$EI = \frac{1}{12} E_b b_b t_b^3 + E_b b_b t_b (\frac{t_b}{2} - \bar{z})^2 + \frac{1}{12} E_s b_s t_s^3 + E_s b_s t_s (t_b + \frac{t_s}{2} - \bar{z})^2 + \frac{1}{12} E_c b_c t_c^3 + E_c b_c t_c (t_b + t_s + \frac{t_c}{2} - \bar{z})^2$$

If no external force or moment is present, ϵ_0 and κ can be calculated as follows

$$\begin{bmatrix} EA & 0 \\ 0 & EI \end{bmatrix} \begin{bmatrix} \epsilon_0 \\ -\kappa \end{bmatrix} = \begin{bmatrix} P_{\Lambda} \\ M_{\Lambda} \end{bmatrix} \quad (2.54)$$

Then by using Eqn. (2.42), the strain at any location of the beam can be calculated. Comparison of these models, their limitations and applications are discussed in Chapter 3.

2.3 Structural health monitoring (SHM)

The SHM techniques can be classified into global techniques which depend on global structural response and local techniques which employ localized structural interrogation. The global techniques can be divided into dynamic and static ones.

In the global dynamic technique, the structure is subjected to low frequency excitation and the resulting vibration response will be recorded at specific locations along the structure. The recording will be processed to extract the first few mode shapes of the structure (Stubbs and Kim, 1996; Kim et al, 2004; Bhalla, 2004;). However, first few mode shapes are not sensitive enough to be altered by localized damage (Pandey and Biswas, 1994; Farrar and Jauregul, 1998). Furthermore, the technique is very expensive (Lynch et al., 2003) and due to low frequency, interference could cause by the ambient noise.

The methods based on the global static techniques such as strain measurement techniques (Sanayei and Saletnik, 1996) and displacement response techniques (Banan and Hjelmstad, 1994) are not feasible for actual-sized structures, since huge amount of force needed to develop a recordable strain or displacement in actual-sized structures.

Local SHM techniques include the ultrasonic techniques, acoustic emission, eddy current, impact echo testing, magnetic field analysis and X-ray analysis. The ultrasonic method uses high frequency waves and has been used by many researchers (Popovics et al., 2000; Shah et al., 2000). However, the complex processing which needs the availability of both surfaces of the structure and the inadequacy in detection of transverse cracks are the main limitations (Giurgiutiu and Rogers, 1997). Other methods like acoustic emission, eddy current, impact echo testing, magnetic field analysis and X-ray analysis have their own limitations (Park et al., 2000a; Bhalla, 2004).

The piezoelectric transducers have found a very vast application as sensors, particularly for SHM using the electro mechanical impedance (EMI) technique which is reviewed in the following section.

2.3.1 Electro mechanical impedance (EMI) technique

In the EMI technique, the structure under monitoring is subjected to high frequency excitation (typically in the range of 30 kHz to 400 kHz), and the resulting vibration response of the structure will be acquired. In this method, the piezoelectric transducers are bonded to or embedded into the structure and an impedance analyzer is used to acquire the vibration response of the structure which called “signature” or “signature of the structure”. Higher frequency ranges were also used for health monitoring in some research works (Kim et al, 2005; 2006).

For health monitoring of actual-sized structures, it is acceptable to assume that the vibrating patch i.e. PZT is infinitesimally small and poses negligible mass and stiffness compared to the host structure (Bhalla, 2004). The bonding is assumed to be

uniform for entire bonding area and vibration patch has zero displacement at mid point. Finally the structure has mechanical impedance defined by Z .

Under above assumptions the constitutive relations for d_{31} piezoelectric material can be simplified as follows (Ikeda, 1990).

$$D_3 = \bar{\epsilon}_{33}^T E_3 + d_{31} \sigma_1 \quad (2.55)$$

$$\epsilon_1 = \frac{\sigma_1}{\bar{E}} + d_{31} E_3 \quad (2.56)$$

where $\bar{E} = E(1 + \eta j)$ is the complex modulus of elasticity and $\bar{\epsilon}_{33}^T = \epsilon_{33}^T(1 - \delta j)$ is the complex electric permittivity at constant stress and $j = \sqrt{-1}$, η and δ are the mechanical loss factor and dielectric loss factor, respectively.

By assuming prefect bonding between the vibrating patch and the structure, one dimensional model to calculate the electromechanical admittance (inverse of electro mechanical impedance) was developed by Liang *et al* (1994).

$$\bar{Y} = (\omega j) \frac{b_c l_c}{t_c} [(\bar{\epsilon}_{33}^T - d_{31}^2 \bar{E}) + (\frac{Z_a}{Z + Z_a}) d_{31}^2 \bar{E} (\frac{\tan \kappa l}{\kappa l})] \quad (2.57)$$

where κ is the wave number, related to the angular frequency of excitation ω , the density ρ and the complex modulus of elasticity of vibrating patch as follows

$$\kappa = \omega \sqrt{\frac{\rho}{\bar{E}}} \quad (2.58)$$

b_c , l_c and t_c are the width, length and thickness of PZT transducer, respectively. Z_a is the short-circuit mechanical impedance of vibrating patch, given by

$$Z_a = \frac{\kappa b_c t_c \bar{E}}{(j\omega) \tan \kappa l} \quad (2.59)$$

The electromechanical admittance consists of the real (conductance) and imaginary (susceptance) parts. A plot of conductance and susceptance signatures for the concrete structure in author's experimental work is presented in Figure 2-10.

The peaks in the conductance signature represent the natural frequencies of the structure. If the health status of the structure does not change with time, the same signature should be obtained at different time. The prominent effect of damage on the signature is the lateral or vertical movement or appearance of new peaks in the signature. Traditionally, it is believed that the susceptance has weak interaction with the structure (Sun et al., 1995) and the conductance has been used for monitoring in most of the research work.

(a)

(b)

Figure 2-10 Conductance (a), susceptance (b) plots of PZT bonded to concrete structure

After Liang *et al* (1994) developed the one dimensional model for the EMI technique; numerous work have been done on the development or modification of the model to explore the application of the technique for various engineering aspects. Application of the EMI technique for health monitoring of civil structures was pioneered by Park *et al* (2000a; 2003a; 2003b), Soh *et al* (2000), Inman *et al* (2001), Peairs *et al* (2002; 2004), followed by many other researchers. Combination of the EMI with the wave propagation technique has been studied by Park *et al* (2000b), Giurgiutiu and Zagari (2002) and Bhalla *et al* (2005). Two dimensional and three dimensional EMI models and structural impedance (extracted from admittance by eliminating the PZT impedance from signature) method have been reported in the literature (Bhalla and Soh, 2004a, 2004b, 2004c; Yang *et al*, 2005; Annamdas and Soh, 2008). Effect of temperature on EMI signature was studied by Sun *et al* (1995), De Vera and Guemes (1998), Park *et al* (1999), Bhalla and Soh (2004d) and Kim *et al* (2005). Further studies on multiplexing of PZT, sensitivity of PZT for damage detection, damage severity and location and effect of external vibration source on signature have also been reported in the literature (Sabet and Yang, 2008; Yang *et al.*, 2008a; Yang *et al.*, 2008b; Yang and Miao, 2008).

2.3.1.1 Advantages and limitations of EMI technique

The EMI technique shows higher damage sensitivity compared to the conventional methods (Park *et al.*, 2003a). It does not need expensive equipment and does not need to be moved around the structures. The vibrating patches demand low power consumption and possess negligible mass. And various types of piezoelectric materials are commercially available with low cost. The method can be used for existing structures and inaccessible areas can be monitored without disassembling the structure. The mechanical noise does not affect the results. Furthermore, considering the limited sensing region of piezoelectric transducers, it is suitable for localized damage detection in the specific locations like the joints.

Several limitations and difficulties for modeling and application of the EMI technique have been reported in the literature. The sensing region of piezoelectric transducers is relatively small and for monitoring of actual-sized structures, a huge number of these transducers are needed. The length of wire can affect the acquired

signature. Researchers proposed to use the same length of wire for various piezoelectric transducers to eliminate the problem. However if the length of wire exceeds few ten meters, no peaks in the signature will be acquired. The wireless technology for impedance analysis is improving and this problem would be eliminated in the near future.

Due to localized nature of the acquired signatures and highly indeterminate nature of civil structures, judgment on overall safety and stability of the structure is very difficult. Even failure of few structural elements may not reduce the overall stability significantly but will result in huge variation of the signatures in the failure zones. Application of multiplex PZTs and analyzing the signatures by considering all the signatures may solve the problem. However for complex structures no general solution exists.

The acquired signature found to be sensitive to the temperature change (Sun et al., 1995; Park et al., 1999). Sun *et al* (1995) reported that the variation of temperature will result in horizontal movement of the baseline for the small frequency range. Bhalla (2001) developed a simple compensation method to linearly eliminate the effect of temperature by acquisition of baseline signature at two different temperatures. However in many parts of the world the variation of temperature could be very huge and a linear compensation over two point may not be very accurate. Furthermore the temperature has greater effect on the properties of the epoxy layer used to bond the piezoelectric material to the structure and controlling the thickness of epoxy layer in practical applications is very difficult.

2.3.2 Wave propagation techniques

There are two approaches to study structural health through the wave propagation technique, pulse-echo and surface wave propagation. In the pulse-echo technique, after exciting structure with narrow bandwidth signal through PZT, a response signal reflected back from boundaries and damage will be acquired through the same PZT. A health signature is required to filter out the effect of boundaries. In the surface wave propagation technique, one PZT acts as an actuator and sends the signal through the structure and another PZT will receive the signal as a sensor. Through studying the

pattern of arriving signal, the arrival time, with given boundaries and speed of wave in structure, the location of damage could be studied (Raghavan and Cesnik, 2007).

Theoretical studies of wave propagation can be traced when Lord Rayleigh (1885) studied surface acoustic waves. After that, waves in isotropic plates, waves at solid-solid and solid-liquid interface were studied by Lamb (1917), Stoneley (1924), and Scholte (1942) respectively. In later research, these types of waves are generally referred to as Rayleigh-Lamb type waves that their displacement is in a plane consisting of the wave propagation and thickness direction. Another type of wave is called a shear horizontal wave, whose displacement is perpendicular to the actuator plane. Love (1911) studied the shear horizontal waves in a layer on half space, which was later called a Love wave. Beyond these classic wave types, waves in other fundamental geometries, such as rods and hollow cylinders, were also studied. They can be found in following books (Victorov, 1967; Achenbach, 1973; Graff, 1973; Auld, 1990; Rose, 1990).

Wave propagation in isotropic media can be studied using the Helmholtz decomposition or a partial wave theory. However, analytical solutions of wave propagation in an anisotropic media can only be studied using the partial wave technique. Besides the analytical models, a semi analytical finite element method (SAFE) is also used to simulate wave propagation. The SAFE method was used for the first time to study propagating wave modes in an arbitrary but uniform cross section by Lagasse (1973). In the SAFE method, the cross section of the wave is meshed with finite elements and an analytical solution is assumed in the wave propagation direction. After applying boundary conditions, dispersion curves describing wave propagation mode possibilities can be obtained. The SAFE method was used by Gavric(1995), Hayashi *et al* (2003) and Lee (2006) to study the wave propagation in rods, rails, and pipes.

Analytical methods for solving wave excitation problems generally falls into two categories. One is an integral transform technique and the other is a normal mode expansion technique. The integral transform technique is discussed by Rose (1990), for shear horizontal guided wave excitation in an isotropic plate. The integral transform technique is studied by transforming the excitation source into frequency

and wave number domain. After a harmonic system of equations with source terms is solved, the results are transformed back into time and spatial domain. Giurgiutiu (2005) used the integral transform technique to study the Lamb wave excitation in an aluminum plate. The frequency tuning effect of wave excitation was also investigated. Ajay and Carlos (2005) extended the integral transform technique into a three dimensional analysis of wave excitation in isotropic plates. Although the integral transform technique can be used to analyze wave excitation from localized sources, the inverse process of the integral transform is usually very difficult. In addition, the formulation of the integral transform technique is usually very tedious.

The normal mode expansion technique is based on a reciprocity relation in dynamics. The basic idea is to express the actual wave field as a superposition of orthogonal wave mode solutions. The general theory of normal mode expansion in an elastic and piezoelectric plate was described by Auld (1990). Ditre and Rose (1992; 1994) used the normal mode expansion technique for wave excitation in isotropic plates and pipes. These analyses were later used as a basis for guided wave natural focusing and phased array focusing in pipes. The normal mode expansion technique is closely related to the wave propagation mode analysis. Compared with the integral transform method, a direct physical insight can be obtained from the process of normal mode expansion.

In the past two decades, more and more research on wave excitation and scattering have been carried out using numerical methods such as the finite difference method (FDM), the boundary element method (BEM), and the finite element method (FEM). Commercial finite element software packages, such as ABAQUS and ANSYS, are also used in the simulation of waves in many structures (Su and Ye, 2004; Yang et al., 2006). Although these finite element methods can be used to calculate the wave field in composites, these methods are computationally expensive and usually difficult to handle large structures.

2.3.3 Wave transmission technique

Song *et al* (2008b) developed smart aggregate which can monitor larger sensing area using the wave transmission signal. Several research groups followed their work and investigated the potential of smart aggregates for structural health monitoring (Yan *et al.*, 2009; Meng *et al.*, 2010). In the wave transmission technique, a signal generated by PZT transducer transmits to structure and the resulting signal is acquired by one or more PZT transducers. Damage in the structure can be quantified with the reduction in the amplitude of the acquired signal. Song *et al* (2008b) reported larger sensing region for smart aggregate using this technique in comparison to monitoring the signal acquired by surface-bonded PZTs using the wave propagation technique.

2.4 Need for future research

Despite that numerous research work have been done on the EMI, surface wave propagation and wave transmission techniques, still some aspects are not clearly determined. Some of these problems are discussed as follows.

2.4.1 Effect of epoxy layer on strain transfer and EMI signature

The force transmission between the piezoelectric transducer and the structure is through an epoxy layer. However the effect of epoxy properties and thickness on strain transfer and EMI signature has not been clearly determined. Strain transfer problem was addressed earlier in Section 2.2. Xu and Liu (2002) proposed a modified impedance model and the bonding layer was assumed as a single degree of freedom (SDOF) system. The reduction factor in the EMI model was introduced but no close form solution was offered. Ong *et al* (2003) integrated the shear lag into impedance using effective length assumption. However the length was determined by considering the sensor effect only and it can only be used for beam element. For these models, the main difficulty for determining close form solution arises from the need to calculate the ratio of stiffness of the piezoelectric transducer and epoxy layer in comparison to the host structure. However for actual-sized structures, the effect of epoxy thickness or properties must be independent from the size of the structure as they suppose to pose negligible amount of mass and stiffness compared to the structure.

Bhalla *et al* (2005) further developed a model by solving the problem separately for shear force and inertial force. However no close form solution was offered and the outcome of the FEM analysis through ANSYS software used to study the effect of epoxy layer. Furthermore, in order to clearly determine the effect of bonding layer, Bhalla (2004) recommended solving the partial differential equations by considering both effects simultaneously.

2.4.2 Selection of frequency range in EMI method

One of the difficulties in SHM using EMI is the combined effect of damage severity and location. If the frequency range is limited, a small damage very near to PZT can change the signature similar to a severe damage far away from PZT. Park *et al* (2003b) recommended a frequency range of 30 kHz to 400 kHz for the EMI technique. To achieve high sensitivity to damage, high frequency signatures (>200 kHz) have been used to monitor the region close to the PZT location while low frequency signatures (<100 kHz) have been traditionally ignored. However, it has been reported that the use of RMSD as the damage indicator is difficult to specify the damage location and severity due to the inconsistency in the RMSD results. Thus, this research will propose a sub-frequency RMSD method to tackle this problem, which will be presented in Chapter 4.

2.4.3 Reusable PZT traducer

Surface-bonded PZT transducers have been commonly used for monitoring hydration of concrete or structural health monitoring. A few researchers have studied the applicability of PZT transducers embedded in concrete structures (Chen *et al.*, 2006; Song *et al.*, 2008b; Lei and Zongjin, 2008; Annamdas and Rizzo, 2010; Meng *et al.*, 2010). PZT transducers are relatively cheap compare to other sensors available for SHM. However, they seem still expensive for some of applications involve repetitive use such as monitoring the hydration of concrete in precast plants. Furthermore, smart aggregates (prefabricated embedded PZT transducers) are not sensitive when using EMI to monitor concrete hydration and direct embedding of brittle PZTs in concrete is not feasible for commercial concrete casting plants. Thus,

development of reusable PZT transducers which can be detached from structure for future use seems interesting and valuable.

2.4.4 Combining EMI, wave propagation and wave transmission techniques for SHM

In the early work that attempted to combine the wave propagation with EMI, extensive numerical modeling based on the surface wave propagation theory was performed to identify the sensing region of the impedance-based method (Esteban, 1996). The combination of the EMI and the pulse echo approaches was investigated by Giurgiutiu and Zagrai (2002) and Giurgiutiu et al. (2003). A simple geometry was used to analyze the pulse-echo technique and changes in wave phase and velocity were used to identify the location of damage. They concluded that, the EMI approach is more suitable for near-field damage detection, and the wave propagation approach is more applicable for far-field damage detection. In a network of sensors, each individual PZT patch was activated as an actuator in turn, and the rest of the PZTs acted as sensors scanning a large area. They also provided a conceptual design and suggestions for a health monitoring system for aging aircraft structures using both the EMI and wave propagation techniques. However, these ideas were not studied extensively for actual-sized civil structures. Song *et al* (2008a) recently investigated the feasibility of wave propagation on the surface of concrete structures. However, sensitivity of this technique for damage detection and the combination of the EMI, surface wave propagation and wave transmission techniques for SHM needs further study. As mentioned earlier in Section 2.3.1.1, one of the limitations of EMI is the limited sensing region which requires huge number of transducers for health monitoring of actual-sized structures. Smart aggregates developed by Song *et al* (2008b) promises much larger sensing region using the wave transmission technique. Combining the surface-bonded PZT transducers using the EMI technique or wave propagation technique for monitoring important locations such as joints with smart aggregates using the wave transmission technique for larger sensing region can provide a better health monitoring system for large infrastructures.

CHAPTER

3

STRAIN TRANSFER MODELS FOR ACTUATION AND EMI SENSING

3.1 Introduction

In sensing and actuation applications of piezoelectric transducers, the models related to the strain transfer inside of host structure are rather undeveloped. Thus, development of models to simulate the strain transfer is essential. In this chapter, an existing 1-D Bernoulli-Euler formulation for strain transfer is modified to account for the strain inside of the actuator. The model is then extended to 2-D case. To validate the analytical model, FEM simulation for actuation of the cantilever beam with MFC actuator is conducted using ABAQUS. An experimental test is also carried out and the results are compared with the FEM results and analytical results. The developed strain transfer model is useful for the applications such as vibration control, energy harvesting and actuation where the stiffnesses of the host structure and actuator are comparable.

Liang *et al* (1994) developed the one dimensional EMI model for the PZT transducers based on the fully bonded assumption. However, it is not realistic since the properties of epoxy layer between the PZT and structure will affect the sensitivity of PZT for health monitoring application. To account for the effect of epoxy layer on the EMI signature, the developed strain transfer model is used to modify the existing EMI model. A reduction factor is derived analytically to consider the epoxy layer

properties. Parametric study is then performed on the reduction factor. FEM simulation based on ANSYS is carried out to numerically investigate the effect of epoxy layer properties on the sensitivity of PZT transducer. Both the parametric studies on the reduction factor and the FEM results show a significant effect of epoxy layer on the sensitivity of PZT for SHM using the EMI technique.

3.2 Existing strain transfer models and limitations

The development of the uniform strain transfer model by Crawley and De Luis (1985) and the one-dimensional Bernoulli Euler formulation (Crawley and Anderson, 1989) is presented in Chapter 2. The uniform strain transfer model is based on assumption of finite thickness of epoxy layer. However for the applications such as vibration control and actuation, the host structure is small and the above assumption may not truly describe the strain transfer phenomena.

The Bernoulli Euler formulation on the other hand considered the thickness of epoxy layer, which is appropriate when the stiffnesses of the host structure, epoxy layer and actuator are comparable. For large host structures, the assumption of the equivalent section is not appropriate because due to high stiffness of host structure and piezoelectric actuator, the epoxy layer plays a role of soft intermediate layer, thus the assumption of uniform strain transfer is not valid. In the existing Bernoulli Euler formulation, the strain inside the actuator was not considered which can cause error in the result. In this Chapter, the existing one dimensional Bernoulli Euler formulation is extended to two dimensional case and modified to account for the strain inside of actuator.

3.3 Two dimensional modeling based on Bernoulli-Euler formulation

In this section, the existing 1-D strain transfer model is extended to 2-D by considering the strain distribution in the MFC actuator. The MFC type d_{33} and d_{31} are used but the developed models are not limited to these transducers. Besides the dimensions, free induced strain in each direction is needed in modeling. The detailed characteristics of MFC actuators can be found in Smart Materials Co. (Smart-Materials, 2010). In type d_{31} the electrical potential follows in the thickness direction

of the MFC actuator, while in type d_{33} it follows in the length direction. The free induced strain of MFC actuators can be calculated as follows

$$\Lambda = \varepsilon^E = d \frac{\Delta V}{\Delta Z} \quad (3.1)$$

where d is piezoelectric constant; ΔV is the applied voltage; and ΔZ is the thickness of MFC in type d_{31} and the electrode spacing for type d_{33} . For MFC- d_{33} and MFC- d_{31} , the free strains per volt are around 0.75 and 1.1 ppm in low electrical field ($|E| < 1000 \text{ V mm}^{-1}$) and 0.9 and 1.3 ppm in high electrical field ($|E| > 1000 \text{ V mm}^{-1}$), respectively.

For the 2-D Bernoulli-Euler model, as the modulus of elasticity and the Poisson's ratio of the MFC is different in the X and Y directions (directions as shown in Figure 2-7), the equivalent characteristic of MFC needs to be calculated for both directions. The average Poisson's ratio for both directions can be calculated by using the rule of mixture (Williams et al, 2004). The induced force and moment can be calculated by using Eqns (3.2) to (3.5) in the X and Y directions.

$$P_{\Lambda x} = E_{cx} b_c t_c \Lambda_x \quad (3.2)$$

$$P_{\Lambda y} = -E_{cy} l_c t_c \Lambda_y \quad (3.3)$$

$$M_{\Lambda x} = E_{cx} l_c t_c (t_b + t_s + \frac{t_c}{2} - \bar{z}) \Lambda_x \quad (3.4)$$

$$M_{\Lambda y} = -E_{cy} b_c t_c (t_b + t_s + \frac{t_c}{2} - \bar{z}) \Lambda_y \quad (3.5)$$

These force and moment cause the internal force and moment in the beam. By using the generalized Hook's law, the internal force and moment in the beam can be obtained easily.

$$P_x = \frac{E_x A}{(1-v_{21}^2)} (\varepsilon_x^0 + v_{21} \varepsilon_y^0) \quad (3.6)$$

$$P_y = \frac{E_y A}{(1-v_{12}^2)} (\varepsilon_y^0 + v_{12} \varepsilon_x^0) \quad (3.7)$$

$$M_x = -\frac{E_x I}{(1-v_{21}^2)} (\kappa_x + v_{21} \kappa_y) \quad (3.8)$$

$$M_y = -\frac{E_y I}{(1-\nu_{12}^2)}(\kappa_y + \nu_{12}\kappa_x) \quad (3.9)$$

Solving Eqns. (3.2) to (3.9) and considering the property of MFC of $\Lambda_{cy} = m\Lambda_{cx}$, where $m = -170/400$ for type d_{33} and $m=1$ for type d_{31} (Smart-Materials, 2010), the strain and the curvature can be calculated as follows

$$\frac{\epsilon_{0x}}{\Lambda_x} = \frac{E_{cx}b_c t_c - (m)E_{cy}l_c t_c \left(\frac{\nu_{21}(1-\nu_{12}^2)E_x A}{(1-\nu_{21}^2)E_y A} \right)}{E_x A \left(\frac{1-\nu_{21}\nu_{12}}{1-\nu_{21}^2} \right)} \quad (3.10)$$

$$\frac{\kappa_x}{\Lambda_x} = -\frac{E_{cx}b_c t_c H - (m)E_{cy}l_c t_c H \left(\frac{\nu_{21}(1-\nu_{12}^2)E_x I}{(1-\nu_{21}^2)E_y I} \right)}{E_x I \left(\frac{1-\nu_{21}\nu_{12}}{1-\nu_{21}^2} \right)} \quad (3.11)$$

where $H = (t_b + t_s + t_c / 2 - \bar{z})$. Then by using Eqn. (2.42) and values of ϵ_{0x} and κ_x obtained from the above equations, the strain at any location of the beam in the X direction can be calculated. Following the similar procedure, the strain in the Y direction can be obtained.

3.4 Modification of Bernoulli-Euler formulation

The induced force in the Bernoulli-Euler formulation is related to the induced strain. However the stress in the actuator is related to difference between the apparent and induced strain.

$$\sigma_c = E_c(\epsilon_c - \Lambda) \quad (3.12)$$

where E_c is the modulus of elasticity of actuator; and ϵ_c is the apparent strain.

The original Bernoulli-Euler formulation proposed by Crawley and Anderson (1989) did not consider this reduction in the modeling. As result, the predicted strain is higher than the actual one. In the following derivations, the existing one

dimensional model and the two dimensional model developed in the above section will be modified to account for this strain reduction.

3.4.1 Modified Bernoulli-Euler (1-D) model

Eqns. (2.52) to (2.54) can be modified to

$$E_c b_c t_c (\Lambda - \varepsilon_c) = E_x A \varepsilon_0 \quad (3.13)$$

$$E_c b_c t_c (\Lambda - \varepsilon_c) \left(t_b + t_s + \frac{t_c}{2} - \bar{z} \right) = -E_x I k \quad (3.14)$$

$$\varepsilon_c = \varepsilon_0 - K \left(t_b + t_s + \frac{t_c}{2} - \bar{z} \right) \quad (3.15)$$

Therefore, by considering this equation, the existing 1-D Bernoulli-Euler model can be modified as follows

$$\frac{\varepsilon_0}{\Lambda} = \frac{E_c b_c t_c - \frac{(E_c b_c t_c H)^2}{(EI + E_c b_c t_c H^2)}}{EA + E_c b_c t_c - \frac{(E_c b_c t_c H)^2}{(EI + E_c b_c t_c H^2)}} \quad (3.16)$$

$$\frac{\kappa}{\Lambda} = \frac{(EA + E_c b_c t_c) \frac{\varepsilon_0}{\Lambda} - E_c b_c t_c}{E_c b_c t_c H} \quad (3.17)$$

3.4.2 Modified Bernoulli-Euler (2-D) model

The induced strain can be calculated by the following equations

$$P_{\Lambda x} = E_{cx} b_c t_c (\Lambda_x - \varepsilon_{cx}) \quad (3.18)$$

$$P_{\Lambda y} = -E_{cy} l_c t_c (\Lambda_y - \varepsilon_{cy}) \quad (3.19)$$

$$M_{\Lambda x} = E_{cx} b_c t_c \left(t_b + t_s + \frac{t_c}{2} - \bar{z} \right) (\Lambda_x - \varepsilon_{cx}) \quad (3.20)$$

$$M_{\Lambda y} = -E_{cy} l_c t_c \left(t_b + t_s + \frac{t_c}{2} - \bar{z} \right) (\Lambda_y - \varepsilon_{cy}) \quad (3.21)$$

Also by using Eqns. (3.6) through (3.9) and by considering the property of MFC of $\Lambda_{cy} = m\Lambda_{cx}$, the strain and the curvature can be calculated.

$$\begin{bmatrix} \frac{EA}{1-\nu_{12}^2} + E_{cx}b_c t_c & \frac{\nu_{21}EA}{1-\nu_{21}^2} & -E_{cx}b_c t_c H & 0 \\ \frac{\nu_{12}EA}{1-\nu_{21}^2} & \frac{E_y A}{1-\nu_{12}^2} - E_{cy} l_c t_c & 0 & E_{cy} l_c t_c H \\ E_{cx}b_c t_c H & 0 & -(\frac{EA}{1-\nu_{12}^2} + E_{cx}b_c t_c H^2) & -\frac{\nu_{21}E_x I}{1-\nu_{21}^2} \\ 0 & -E_{cy} l_c t_c H & \frac{\nu_{12}E_y A}{1-\nu_{12}^2} & -(\frac{E_y I}{1-\nu_{12}^2} + E_{cy} l_c t_c H^2) \end{bmatrix} \begin{bmatrix} \frac{\epsilon_{0x}}{\Lambda_x} \\ \frac{\epsilon_{0y}}{\Lambda_x} \\ \frac{\kappa_x}{\Lambda_x} \\ \frac{\kappa_y}{\Lambda_x} \end{bmatrix} = \begin{bmatrix} E_{cx}b_c t_c \\ mE_{cy} l_c t_c \\ E_{cx}b_c t_c H \\ mE_{cy} l_c t_c H \end{bmatrix} \quad (3.22)$$

By solving the above matrix the strain and curvature can be obtained. And by using Eqn. (2.42) the strain in the X and Y directions at any location of the beam can be calculated.

3.5 Finite element modeling (FEM) of strain transfer

To verify the analytical models, an FEM model is developed using ABAQUS to simulate the actuation of MFC under both quasi-static and near natural frequency excitations. The piezoelectric element in ABAQUS is used to simulate the d_{31} transducers. The dielectric parameters presented in Eqn. (2.4) need to be changed to simulate the d_{33} materials. Figure 3-1 shows the FEM simulation of a cantilever beam with an MFC actuator.

Figure 3-1 Simulation of cantilever beam and MFC actuator with ABAQUS

In the dynamic simulation of MFC actuation, resonance will occur at natural frequencies, where the damping ratio plays a crucial role in determining the magnitude of peak deflections at these frequencies. To determine the damping ratio,

an experiment is carried out for the first and second modes. Figures 3-2 and 3-3 show the experimental damping curves for the first and second modes.

By using the logarithmic decrement method, the damping ratio can be obtained as (Silve, 2006).

$$\xi = \frac{1}{2\pi \cdot n} \ln \frac{A_1}{A_{n+1}} \quad (3.23)$$

where A_1 is the peak strain; and A_{n+1} is the strain of the $(n+1)^{\text{th}}$ reading after the 1st peak. By using Eqn. (3.23), the damping ratios for the 1st and 2nd natural frequencies are $\xi_1 = 0.0086$, $\xi_2 = 0.0092$ respectively. The natural frequencies are $f_1 = 13.65$ Hz and $f_2 = 84.6$ Hz.

Figure 3-2 Damping curve for first mode

Figure 3-3 Damping curve for second mode

For the dynamic analysis in ABAQUS, the Rayleigh damping is used (ABAQUS, 2005). The coefficients α and β of the Rayleigh damping can be calculated by using the following equation.

$$\xi_i = \frac{1}{2} \left(\frac{\alpha}{2\pi f_i} + 2\pi f_i \beta \right) \quad (3.24)$$

where f_i is the natural frequency for mode $i=1,2$. Using the values of ξ_1 and ξ_2 obtained above, α and β are calculated as 1.2467 and 3.0 E-5, respectively. These two values are used as input data in ABAQUS for FEM simulation. The strains at top of MFC and at the bottom of the beam can be directly obtained from FEM simulation and compared with the analytical and experimental results.

3.6 Validation of analytical and simulation results

Experimental work is necessary to validate the analytical and FEM results. The experimental work is divided to two parts, the experimental test on a cantilever beam and study on properties of the epoxy layer to be used in the simulation.

3.6.1 Experimental test on strain transfer in cantilever beam

As shown in Figures 3-4 and 3-5, an MFC actuator is bonded on the top surface of an aluminum beam. One strain gauge is bonded on the top of MFC and the other one

on the bottom of the beam at the center location of MFC. A function generator and an amplifier are used for voltage input to the MFC and a dynamic strain meter is used to measure the strain on the top of the MFC and the bottom of the beam. Three similar beams and MFC- d_{33} actuators with dimensions of $31 \times 31 \times 1.5$ mm and $28 \times 14 \times 0.3$ mm with different thickness of epoxy layer are used in the experiment and simulation. The average thickness of epoxy measured from the three beams is 0.2, 0.3 and 0.7 mm, respectively. For all the three beams, the MFC is bonded 13 mm away from the cantilever end. The strains on the top of MFC actuator and at the bottom of the beam are measured.

Figure 3-4 Experimental setup for cantilever beam

Figure 3-5 Strain gauge on bottom of beam

3.6.2 Experimental test on epoxy layer properties

The epoxy layer thickness and modulus of elasticity can have significant effect on strain transfer, thus affecting the beam-tip deflection. To measure the modulus of

elasticity of the epoxy layer, a tension test based on ASTM D638-03 is performed. Figures 3-6, 3-7 and 3-8 show the preparation of uniform epoxy sheet, preparation of tension test samples and the tension test equipment, respectively. As recommended by Smart Materials Corp, a two-component adhesive, 3M's DP 460 Epoxy was used in this study. Figure 3-9 shows the results of the tension test for various specimens cut from one single epoxy sheet. It is observed that even for the single sheet of epoxy which was properly prepared, the results show significant inconsistency. Thus it is necessary to study the effect of modulus of epoxy on the actuation capacity of the MFC. From the results, the average modulus of elasticity is obtained as 0.1 GPa which is used in the FEM simulation process.

Figure 3-6 Preparation of uniform epoxy sheet

Figure 3-7 Preparation of epoxy specimen

Figure 3-8 Tension test setup

Figure 3-9 Tension test results for epoxy

3.7 Results and discussions

Figure 3-10 shows the experimental, analytical, and FEM simulation results for the strain on the bottom of the beam under quasi-static excitation (epoxy thickness equal to 0.1 mm). It can be observed that the 2-D Bernoulli-Euler model has better prediction ability compared to its 1-D counterpart, and the modified models help to improve the accuracy of prediction. The uniform strain model shows a good fit to the experimental data with finite thickness of epoxy, but the prediction accuracy decreases with the increase in thickness of epoxy. The FEM result shows a very good agreement with the experimental results.

Figure 3-11 shows the comparison between the experimental and FEM simulation results of the strain on the top surface of MFC for various frequencies under 500 AC

voltages. As shown in Figure 3-11, by considering the damping effect, the FEM model can predict the strain in MFC near the natural frequencies with good accuracy. Except near natural frequencies, the strain inside of MFC actuator is almost constant for various frequencies and it shows the applicability of the analytical models with quasi-static excitation.

Figure 3-10 Analytical, numerical and experimental for strain in bottom of beam

Figure 3-11 Experimental and FEM results for strain on top surface of MFC

The good actuation capacity of MFC actuators can be realized near the natural frequencies. Figure 3-12 shows the beam-tip deflection obtained from FEM simulation and experimental testing near natural frequencies. Again, good agreement is observed between the simulation and experimental results. To show the effect of the epoxy layer modulus of elasticity, Figure 3-13 depicts the analytical models, FEM simulation, and experimental results of the beam-tip deflection at the first natural frequency. It is obvious that increases in the thickness of the epoxy layer will decrease the tip deflection. The modified (2-D) model shows better prediction of the beam-tip deflection. As shown in Figure 3-14, increasing the modulus of elasticity of the epoxy layer can significantly increase the actuation capacity of the MFC. Therefore, a thin epoxy layer with high modulus of elasticity is recommended for efficient actuation using MFC actuators.

Figure 3-12 FEM and experimental results for beam-tip deflection

Figure 3-13 Effect of thickness of epoxy on beam-tip deflection

Figure 3-14 Effect of modulus of epoxy on beam-tip deflection

3.8 Inclusion of epoxy layer properties in EMI model

The force transmission between the piezoelectric material and the structure is through an epoxy layer. However the effect of epoxy's modulus of elasticity and thickness on the EMI signature has not been clearly determined. Liang *et al* (1994) developed the EMI model for a PZT transducer based on fully bonded assumption as follows

$$\bar{Y} = (\omega j) \frac{b_c l_c}{t_c} [(\bar{\epsilon}_{33}^T - d_{31}^2 \bar{E}) + \left(\frac{Z_a}{Z + Z_a} \right) d_{31}^2 \bar{E} \left(\frac{\tan \kappa l}{\kappa l} \right)] \quad (3.25)$$

where t_c , b_c and l_c are the thickness, width and length of PZT patch, respectively; d_{31} is the dielectric factor in the length of PZT as result of electrical field along the thickness; $\bar{E} = E(1 + \eta j)$ is the complex modulus of elasticity; $\bar{\epsilon}_{33}^T = \epsilon_{33}^T(1 - \xi j)$ is the complex electric permittivity at constant stress and $j = \sqrt{-1}$; η and ξ are the mechanical loss factor and dielectric loss factor, respectively; κ is the wave number, related to angular frequency of excitation ω , the density ρ and the complex modulus of elasticity of vibrating patch calculated as follows

$$\kappa = \omega \sqrt{\frac{\rho}{\bar{E}}} \quad (3.26)$$

Z_a is the short-circuit mechanical impedance of vibrating patch, given by

$$Z_a = \frac{\kappa b_c t_c \bar{E}}{(j\omega) \tan \kappa l} \quad (3.27)$$

Xu and Liu (2002) proposed a modified impedance model. The bonding layer was assumed as single degree of freedom (SDOF) system.

$$Z_{res} = \frac{K_b}{K_b + K_s} Z = \phi Z \quad (3.28)$$

where K_b is the dynamic stiffness of the bonding layer and K_s is the dynamic stiffness of the structure. The reduction factor in the EMI model was introduced but no close form solution was offered.

$$\bar{Y} = (\omega j) \frac{b_c l_c}{t_c} [(\epsilon_{33}^T - d_{31}^2 \bar{E}) + \left(\frac{Z_a}{\phi Z + Z_a} \right) d_{31}^2 \bar{E} \left(\frac{\tan \kappa l}{\kappa l} \right)] \quad (3.29)$$

In above equations, ϕ should vary from 0 to 1 for free PZT transducer to fully bonded PZT transducer. However, by using Eqn. (3.28), it can vary from 0 to 0.5 only. If the bonding layer is very soft compared to the structure, i.e. $K_s \gg K_b$, from Eqn. (3.28), ϕ would be around zero. Therefore, as expected, Eqn. (3.29) will represent the EMI of free PZT. If the bonding layer is as strong as the structure which should represent no bonding layer, then from Eqn. (3.28), $\phi = 0.5$. However ϕ should

be equal to 1. From Eqn. (3.28), it is not possible to obtain $\phi = 1$. Thus, the above model has its limitation in representing the effect of epoxy.

Ong *et al* (2003) integrated the shear lag into the impedance model using the effective length assumption. The shear lag reduction constant α_1 can be calculated as follows

$$\alpha_1 l_c = \int_{-0.5l_c}^{+0.5l_c} \frac{\varepsilon_1}{\varepsilon_t} dz \quad (3.30)$$

where ε_1 is strain inside actuator and ε_t is the strain transferred to the surface of the beam through shear lag. However the effective length was determined by considering the sensor effect only and the model is limited to beam element.

Bhalla and Soh (2004d) further developed a model by solving the problem for shear force and inertial force separately and defining an equivalent impedance. However no close form solution was offered and the FEM analysis outcome through ANSYS software was used to study the effect of epoxy layer.

For these models, the main difficulty in determining the close form solution arises from the need to calculate the stiffness ratio of the PZT and epoxy layer in comparison to the host structure. However the simplified constitutive relations for d_{31} PZT were derived by assuming PZT is infinitesimal and possesses negligible mass and stiffness compared to the host structure. It means that the mechanical and dynamic properties of structure are not affected by PZT vibration. Therefore, the effect of epoxy thickness or modulus of elasticity must be independent from the size or geometry of host structure.

To overcome the limitation of the existing models, an analytical EMI model for inclusion of epoxy layer properties through shear lag theory is developed in the next section. Parametric study on the developed model is carried out. Numerical simulation is also conducted to verify the analytical model. The new analytical model quantifies the effect of epoxy layer properties in EMI molding.

3.9 Analytical modeling for inclusion of epoxy layer properties in EMI

As presented earlier, the constitutive relations for d_{31} piezoelectric materials can be described as follows (Ikeda, 1990).

$$D_3 = \bar{\epsilon}_{33}^T E_3 + d_{31} \sigma_1 \quad (3.31)$$

$$\varepsilon_1 = \frac{\sigma_1}{E} + d_{31} E_3 \quad (3.32)$$

Eqn. (3.31) represents the “direct effect” which mechanical strain induces electrical charge and Eqn. (3.32) represents the “converse effect” which electrical field induces mechanical strain. Force generated by piezoelectric transducers causes shear elongation in epoxy layer, which is neglected in the Liang EMI model. To consider this effect, the term σ_1 in both Eqns. (3.31) and (3.32) is modified to account for the free elongation. In addition, strain due to shear force is considered in Eqn. (3.32). Thus, ε_1 is considered to have two components, i.e., ε_c free elongation of PZT due to shear force and ε_i due to inertial force.

$$\varepsilon_1 = \varepsilon_c + \varepsilon_i \quad (3.33)$$

The total strain inside PZT by considering the shear lag formulation was formulated by Park *et al* (1996) as presented in Chapter 2 Section 2.2.1 as follows

$$\frac{\varepsilon_c(\bar{x})}{\Lambda} = \frac{4}{\psi_b + 4} + \frac{\psi_b}{(\psi_b + 4) \cosh(\Gamma)} \cosh(\Gamma \bar{x}) \quad (3.34)$$

For fully bonded assumption which is governed by the inertial force only, this equation will be reduced to

$$\frac{\varepsilon_c(\bar{x})}{E_3 d_{31}} = \frac{4}{\psi_b + 4} \quad (3.35)$$

This elongation was not considered in the Liang EMI model. However, it was assumed that the PZT is infinitesimal compared to the host structure. ψ_b is the stiffness of the structure over the stiffness of PZT. Therefore, for $\psi_b \rightarrow \infty$ in fully bonded condition, Eqn. (3.35) tends to zero and causes no effect in the EMI model developed by Liang. Strain related to shear, ε_c , can be calculated as follows

$$\varepsilon_c = \frac{(E_3 d_{31}) \psi_b}{(\psi_b + 4) \cosh(\Gamma)} \cosh \left(\sqrt{\frac{\psi_s}{t_s^2}} \left(1 + \frac{4}{\psi_b}\right) \bar{x} \right) \quad -1 < \bar{x} < 1 \quad (3.36)$$

The term $\bar{x}$ is to consider variation of the apparent strain near the free edges of PZT. Similarly, For $\psi_b \rightarrow \infty$, $\frac{\psi_b}{\psi_b + 4} \cong 1$, and the above equation is simplified to

$$\varepsilon_c = \frac{E_3 d_{31}}{\cosh(\Gamma)} \cosh \left(\sqrt{\frac{\psi_s}{t_s^2}} \bar{x} \right) \quad -1 < \bar{x} < 1 \quad (3.37)$$

Eqn. (3.37) is independent from the size or geometry of the host structure. Eqn. (3.36) could give a better estimate for smaller host structures with simplified geometry as the host structure properties can be included in the modeling. For simplicity of presentation, ε_c is expressed as multiple of $E_3 d_{31}$ (induced strain).

$$\varepsilon_c = \Psi E_3 d_{31} \quad (3.38)$$

In which $\Psi = \frac{\cosh \left(\sqrt{\frac{\psi_s}{t_s^2}} \bar{x} \right)}{\cosh(\Gamma)}$ is a known factor.

By using Eqns. (3.32) and (3.33), the stress in PZT is equal to

$$\sigma_1 = \bar{E}(\varepsilon_1 - d_{31} E_3) = \bar{E}(\varepsilon_c + \varepsilon_i - d_{31} E_3) \quad (3.39)$$

Based on the dynamic equilibrium of PZT

$$\bar{E} \frac{\partial^2 u}{\partial x^2} = \rho \frac{\partial^2 u}{\partial t^2} \quad (3.40)$$

where u is the displacement in the x (length) direction at any point of the PZT patch. By method of separation of variables it can be calculated as follows

$$u = (A \sin \kappa x + B \cos \kappa x) e^{j\omega t} \quad (3.41)$$

where κ is the wave number defined in Eqn. (3.26)

Strain and velocity due to inertial force can be calculated as follows

$$\varepsilon_i = \frac{\partial u}{\partial x} = A \kappa \cos \kappa x \quad (3.42)$$

$$\dot{u}(x) = \frac{\partial u}{\partial t} = Aj\omega e^{j\omega x} \sin \kappa x \quad (3.43)$$

The relation of the structural mechanical impedance Z and force inside of PZT can be presented as follows

$$F_{(x=l)} = b_c t_c \sigma_1 = -Z \dot{u}_{(x=l)} \quad (3.44)$$

The negative sign indicates that a positive displacement causes compression force in the PZT patch (Liang et al, 1994). Substituting Eqns. (3.33), (3.39), (3.42) and (3.43) into (3.44) results

$$b_c t_c \bar{E}(\varepsilon_s + Ae^{j\omega t} \kappa \cos \kappa l - d_{31} E_3) = -Z(Aj\omega e^{j\omega x} \sin \kappa l) \quad (3.45)$$

where coefficient “A” can be calculated as follows

$$A = \frac{Z_a}{(Z + Z_a)} \frac{d_{31} E_3 - \varepsilon_s}{\kappa \cos \kappa l e^{j\omega x}} \quad (3.46)$$

where Z_a is the short-circuit mechanical impedance of PZT patch, given in Eqn. (3.27). The electric current, which is the time rate of change in charge, can be calculated from

$$\bar{I} = \iint_A \dot{D}_3 dx dy = j\omega \iint_A D_3 dx dy \quad (3.47)$$

For one dimensional actuation in length of PZT, Eqn. (3.47) is reduced to

$$\bar{I} = j\omega \iint_A D_3 dx dy = (j\omega) b_c \int_0^{lc} D_3 dx \quad (3.48)$$

Substituting Eqn. (3.31) into the above equation gives

$$\bar{I} = (j\omega) b_c \int_0^{lc} D_3 dx = (j\omega) b_c \int_0^{lc} (\bar{\varepsilon}_{33}^T E_3 + d_{31} \sigma_1) dx \quad (3.49)$$

Substituting σ_1 form Eqn. (3.39) gives

$$\bar{I} = (j\omega) b_c \int_0^{lc} D_3 dx = (j\omega) b_c \int_0^{lc} (\bar{\varepsilon}_{33}^T E_3 + d_{31} (\bar{E}(\varepsilon_c + \varepsilon_i - d_{31} E_3))) dx \quad (3.50)$$

Substituting values of ε_c and ε_i from Eqns. (3.38) and (3.42) and performing integration will result in

$$\bar{I} = (j\omega)b_cl_cE_3[(\bar{\varepsilon}_{33}^T - (1 - \Psi)d_{31}^2\bar{E}) + (1 - \Psi)\left(\frac{Z_a}{Z+Z_a}\right)d_{31}^2\bar{E}\left(\frac{\tan \kappa l}{\kappa l}\right)] \quad (3.51)$$

Thus, the modified electromechanical admittance (inverse of resistance) with inclusion of epoxy effect for both actuation and sensing can be obtained as follows

$$\bar{Y} = (\omega j)\frac{b_cl_c}{t_c}[(\bar{\varepsilon}_{33}^T - (1 - \Psi)d_{31}^2\bar{E}) + (1 - \Psi)\left(\frac{Z_a}{Z+Z_a}\right)d_{31}^2\bar{E}\left(\frac{\tan \kappa l}{\kappa l}\right)] \quad (3.52)$$

The first term in above equation i.e. $(\bar{\varepsilon}_{33}^T - (1 - \Psi)d_{31}^2\bar{E})$ is not relevant to the mechanical properties of host structure. However it will affect the baseline and sensitivity of signature. The second term is affected by properties of host structure (through structural impedance Z) and the reduction term of $(1 - \Psi)$ will determine the magnitude of peaks in the EMI signature. In comparison to the models developed by Ong *et al* (2003), Xu and Liu (2002) and Bhalla and Soh (2004d), this new model considers the effect of epoxy thickness and modulus of elasticity on both actuation and sensing and is applicable to any size of structure. In addition, the model is applicable to both sensing and actuation of the PZT transducers. More importantly, the model offers a close form solution which allows one to study the influence of epoxy layer in an explicit manner.

3.10 Parametric study on reduction factor

As mentioned above, the main advantage of newly developed model is to study the effect of epoxy thickness and modulus of elasticity explicitly. By considering Eqn.

$$(3.37), \text{ the reduction term in Eqn. (3.52) is } \left(1 - \frac{\cosh\left(\sqrt{\frac{\psi_s}{t_s^2}}\bar{x}\right)}{\cosh\left(\sqrt{\frac{\psi_s}{t_s^2}}\right)}\right), -1 < \bar{x} < 1. \text{ Using}$$

this expression, a parametric study can be performed to investigate the effect of epoxy thickness and modulus of elasticity on the reduction factor.

In the experimental work presented in Section 3.6.2, the modulus of elasticity of a two-component adhesive, 3M's DP 460 Epoxy was measured around 100 MPa.

However the results were varied from 70 MPa to 150 MPa even for single epoxy sheet as presented earlier in Figure 3-9. Table 3-1 shows the summery of the conditions in this parametric study. Case 1 is to study the effect of epoxy modulus of elasticity, and case 2 is to study the effect of epoxy thickness and the size of host structure.

To ease the comparison, a beam element is used in the analytical and FEM models. Figure 3-15 shows the effect of epoxy modulus of elasticity on the reduction factor in Eqn. (3.52). Figure 3-16 shows the effect of epoxy thickness on the reduction factor.

Table 3-1 Summery of conditions in parametric study

Property	Structure		Epoxy		PZT
	Case 1	Case 2	Case 1	Case 2	
Thickness (mm)	10	$\left\{ \begin{array}{l} \textit{neglecting the size} \\ 10,100,250 \\ 10,200,500 \\ 10,500,500 \end{array} \right\}$	0.1	$\left\{ \begin{array}{l} 0.1 \\ 0.15 \\ 0.2 \\ 0.3 \end{array} \right\}$	0.5
Width (mm)	100		20	20	20
length (mm)	250		20	20	20
E, modulus of elasticity (Gpa)	70		$\left\{ \begin{array}{l} 0.05 \\ 0.07 \\ 0.1 \\ 0.15 \end{array} \right\}$	0.1	66
v (Poisson ratio)	0.35		0.38		0.31

Figure 3-15 Effect of epoxy modulus of elasticity on reduction factor

Figure 3-16 Effect of epoxy thickness on reduction factor

From the above two figures, it is obvious that the epoxy thickness and modulus of elasticity can significantly affect the sensitivity of PZT for EMI application. Increasing the modulus of elasticity and decreasing the thickness of epoxy can increase the sensitivity of PZT significantly. For multiplexing application in the EMI method where a number of PZTs are used to monitor a large area, variations in the thickness and modulus of elasticity of epoxy can significantly affect the results. Generally, a PZT far away from cracks should show smaller change in RMSD values

compared to a PZT nearer to cracks. However, if the PZT far away has a better bonding condition, i.e. higher modulus of elasticity and smaller thickness of epoxy, then its sensitivity is higher and the change in RMSD value could be equal or even larger than the PZT nearer to crack. This will cause the difficulty in determining the location and severity of damage in structures. As observed in Figure 3-16, neglecting the size of host structure will result in minor error if the structure is considerably larger than the PZT and epoxy layer.

3.11 Finite element modeling

The above derivation for inclusion of epoxy modulus of elasticity and thickness in the EMI model was based on two assumptions. First, the dynamic behavior of structure is not affected by the epoxy layer and second, the dynamic behavior of epoxy layer does not affect the PZT signature near resonance peaks. In order to verify the validity of these two assumptions, an FEM analysis using ANSYS is conducted to study the effect of epoxy layer with various excitation frequencies. Figures 3-17 and 3-18 show the overall model and mesh of the elements.

SOLID186 element is employed to simulate the beam and epoxy layer. Possible piezoelectric analysis types in ANSYS are static, modal, prestressed modal, harmonic, prestressed harmonic and transient (ANSYS, 2005). In this work, SOLID 226 element is used to simulate the piezoelectric transducer. SOLID226 has twenty nodes with up to five degrees of freedom per node. Before applying the electrical load and boundaries, a short circuit modal analysis is conducted to calculate the frequencies corresponding to natural modes of the structure. Then, 1 volt load assigned to top surface of the piezoelectric element and harmonic analysis is conducted. In order to increase the accuracy, 4 points are considered in the range of 0.999 to 1.001 of the corresponding frequency of each natural mode.

As shown in Figure 3-17, the beam is divided into three regions in planner directions. Denser mesh is assigned to middle section of the beam. Total of 375 elements are used in planner direction of the beam. The beam height, H is divided to three elements of $1/6 H$, $1/6 H$ and $2/3 H$ from top surface of the beam. Therefore, total number of elements for the beam with size of $250 \times 100 \times 10$ mm is 1125

elements. The piezoelectric transducer is divided to 5 elements in length and width and 8 elements in height. One element in height for epoxy thickness equal to 0.1 and 0.15 mm, and 2 and 3 elements for epoxy heights of 0.2 and 0.3 mm are considered.

Figure 3-17 Overall model in ANSYS

Figure 3-18 Mesh of the elements

Figures 3-19 and 3-20 show the effects of thickness and modulus of elasticity of epoxy on the EMI signature, respectively.

Figure 3-19 Effect of epoxy thickness on EMI signature

Figure 3-20 (a) Effect of epoxy modulus of elasticity on EMI signature, (b) comparison for limited frequency range

Increasing the epoxy thickness increased the number of resonance frequencies from 140 modes for 0.1 mm to 156 modes for 0.3 mm in the frequency range of 90 kHz to 120 kHz. However the resulting new peaks are minor peaks and could not be detected in Figure 3-19. As shown in Figure 3-20(b), positions of major peaks are changed but the changes are very small which shows the adequacy of the two assumptions in analytical modeling. The size of host structure was limited to $100 \times 250 \times 10$ mm to make the analysis possible with personal computer. The change in location of major peaks should be even smaller for actual-sized structures. Therefore, the two assumptions of first, the dynamic behavior of structure is not affected by the epoxy layer and second, the dynamic behavior of epoxy layer does not affect the PZT signature near resonance peaks are valid.

As shown in Figure 3-20 (a), FEM results show changes in both the baseline of signature and magnitude of peaks, which is in line with the analytical model developed in this work. The first reduction factor in Eqn. (3.51) affects the baseline of

the signature, while the second reduction factor affects the amplitude of the peaks in the EM signature. Figures 3-21 and 3-22 show comparisons of the analytical model and the FEM model for the effects of epoxy thickness and modulus of elasticity, respectively. As shown, both the FEM and the analytical model predict significant reductions in EMI sensitivity with increases in the epoxy thickness or decreases in the epoxy modulus of elasticity.

Figure 3-21 Effect of epoxy thickness on sensitivity of EMI signature

Figure 3-22 Effect of epoxy modulus of elasticity on sensitivity of EMI signature

3.12 Concluding remarks

In this Chapter, the existing 1-D Bernoulli-Euler formulation of strain transfer between actuator and structure is extended to 2-D. Then both the 1-D and 2-D strain transfer models are modified to account for the apparent strain inside the actuator. Analytical, numerical and experimental studies are carried out to investigate the strain transfer phenomenon during actuation. The experimental results validate the analytical model and FEM simulation. For quasi-static excitation, the 2-D Bernoulli-Euler model has better prediction ability compared to its 1-D counterpart, and the modified models help to improve the accuracy of prediction. Increase in the modulus of elasticity of epoxy layer improves the efficiency of MFC actuator and increase in epoxy thickness reduces the beam-tip deflection and thus the actuation efficiency of MFC. The results of FEM simulation for both quasi-static and near natural frequency excitation are in good agreement with the experimental ones, showing its potential in modeling of the MFC actuation.

The analytical model developed for inclusion of epoxy properties in the EMI signature offers a close form solution which is applicable to any size of host structures. The results show that the properties of epoxy layer affect both the baseline and magnitude of peaks in the EMI signature. Both the analytical model and FEM simulation show considerable influence of modulus of elasticity and thickness of epoxy on the sensitivity of PZT for EMI application. Inconsistence properties of two-component epoxies can significantly affect the monitoring results, especially in multiplexing PZT applications. Since the epoxy thickness has significant effect on the sensitivity of PZTs, it should be carefully controlled to achieve repeatable results for structural health monitoring application.

As discussed, it is difficult to control the modulus of elasticity and the thickness of the epoxy layer. The problem of considering the epoxy layer properties may be resolved by examining the proposed hypothesis called “post-calibration process”. For instance, PZT A on structure one is used for calibration of the damage severity and location. A standard non-destructive impact will be applied on the surface of structure

one in healthy condition at one or more distances from the location of PZT A and the response of PZT A will be recorded. Various damage will then be introduced on the surface of structure one and the damage severity and location will be studied. The sensing region for sub-frequency intervals and critical thresholds for damage detection are determined. Thereafter, for repetitive application on the second structure, the same standard impact will be applied on the surface of the structure and the responses of PZTs are recorded. These PZT responses can be compared with PZT A to compensate the possible variation in epoxy thickness and modulus of elasticity. The post calibration process in particular can be used for the multiplexing of PZTs, with several PZTs attached to various parts of a structure. A systematic and extensive experimental work is required to investigate the hypothesis. The same hypothesis can be utilized to study and compensate the response due to the effect of temperature, in which the response of the PZT to a standard impact will be acquired at various temperatures.

CHAPTER

4

APPLICATION OF PZT TRANSDUCERS FOR DETECTION OF DAMAGE SEVERITY AND LOCATION

4.1 Introduction

With increasing number of collapses in major infrastructures, health monitoring of structures becomes significantly important. Structures must satisfy strength and serviceability criteria throughout their stipulated design life. However, after a natural disaster, such as an earthquake, the strength and serviceability of the structure becomes questionable due to possible damage induced in the structure. In addition, to prevent catastrophic failures, gradual deterioration of structures with time, environmental corrosion, lack of maintenance, accidental overloading and excessive usage needs periodical evaluation during the life span of the structures.

Due to the increasing number of infrastructures and the need of monitoring inaccessible areas, manual monitoring becomes less interesting and not applicable for most of the projects. In fact some of the important structures such as dams and nuclear stations need online continuous monitoring due to disastrous nature of failure. Online damage detection systems would reduce costs by minimizing maintenance and inspection cycles. One of the most promising means of developing such systems is through the integration of smart materials such as piezoelectric materials into the structure.

4.2 Preliminary test on beam-column joint in concrete structures

PZT has been used for SHM in various engineering systems. However there is little work on actual-sized structures. Beam-column connections are critical regions in reinforced concrete (RC) moment-resisting frame structures. The vulnerability of RC beam-column joints has been identified from structural damage investigations over the past decades, especially in the area of earthquake (cyclic loading). In the context of a terrorist bomb attack, the beam-column joints are most vulnerable as it comes into direct contact with the blast waves. More importantly, when the perimeter columns lose its load carrying capacity due to damage, it becomes one of the crucial load transfer mechanism of the structural frame. To avoid catastrophic failures, it is important to monitor the beam-column joints under existing gravitational loads.

In this section, an experiment is carried out on four actual-sized concrete frame structures with different detailing and subjected to gradually increased load. A number of PZT and MFC transducers are bonded to the frame structure to acquire the EMI signature. The structural mechanical impedance (SMI) is extracted from PZT EMI signature and the SMI sensitivity is compared with the electromechanical (EM) admittance signature. The relations between the damage index and the loading step, tip deflection and strain inside the concrete structure are obtained. Finally the sensitivity of the PZT transducers in detection of the critical loading level is discussed. The PZT transducers have shown to be capable of monitoring the integrity and behavior of the actual-sized concrete structures.

4.2.1 Experimental work

Prior to the experimental test, four actual-sized beam-column joints 11 to 14 were prepared. It is assumed that the exterior column has lost load bearing capacity thus it does not exist in the setup. The interior column is under constant statistic load of 2000 kN as result of proposed upper levels. The load cell on the beam at location of exterior column gradually increases the load up to the failure of the joint. Figure 4-1 shows the overall configuration of the experimental setup. The column section has dimension of 350×350 mm and the beam section has dimension of 470×250 mm. The sample has overall height of 3.275 meters and width of 4 meters. Figures 4-2 and 4-3

show the detailing of four specimens. In this work the capability and sensitivity of PZT and MFC transducers in detecting the cracks and critical loading step is studied. However, study on influence of different detailing on load bearing capacity and ductility is beyond the scope of this work. Figures 4-4 and 4-5 show the experimental setup during the test and the PZT and MFC transducers attached to the beam respectively.

Some of the selected bars were gauged to capture the strain. Acquired data from the gauges in the position of PZT and MFC transducers are used for comparison. An impedance analyzer with interrogation voltage of 2 volts and a multiplexer are used to acquire the electromechanical admittance signatures.

Figure 4-1 Configuration of experimental setup

Figure 4-2 Detailing of Specimens 11 and 12

Figure 4-3 Detailing of Specimens 13 and 14

Figure 4-4 Experimental setup during the test

Figure 4-5 PZT and MFC transducers on the beam near the joint

As shown in Figure 4-5, two pieces of MFC- d_{33} with dimensions of 28mm×14mm and thickness of 0.3 mm and two pieces of PZT with dimensions of 20mm×20mm and thickness of 0.5mm are attached to the first specimen. For the second and third specimens, two pieces of PZT of 20mm×20mm×0.5 mm and two pieces of PZT of 20mm×20mm×2 mm and finally for the forth specimen, four pieces of PZT of 20mm×20mm×2 mm are attached to the structure. The specifications and physical properties of the PZT transducers can be obtained from PI Ceramic (2010).

Figure 4-6 shows the forth specimen after failure and Figure 4-7 shows the position of PZTs and cracks which developed near the PZT transducers in the forth specimen.

Figure 4-6 Forth specimen after failure

Figure 4-7 Position of PZT transducers and cracks in forth specimen 14

4.2.2 Results and discussions

4.2.2.1 Comparison of PZT and MFC transducers

In the first setup, a small crack of 0.5mm width ran through the concrete beneath the PZT with 0.5 mm thickness and broke it apart as shown in Figure 4-8. However a thick PZT shows a better resistance against cracking and a similar crack beneath the PZT with 2 mm thickness did not break the PZT in the third specimen.

Figure 4-8 PZT with thickness of 0.5 mm on first specimen

From Figure 4-9, it was concluded that MFC was not suitable for the SHM of actual-sized concrete structures, if directly attached to the surface of the structure. Due to inclusion of epoxy layer in production of MFC, MFC is softer and less sensitive compared to PZT transducers. In fact, MFC is more suitable for actuation and vibration control (when the stiffness of host structure and MFC are comparable). In addition, MFC can be used for SHM of small structures or delaminating of thin composite materials. The impedance analyzer can provide maximum voltage of 2 volts. For this level of voltage, the PZT is more sensitive compared to the MFC. As shown in Figure 4-9, EM signature of PZT transducer with 2 mm thickness record more peaks compared to PZT transducer with 0.5 mm thickness.

Figure 4-9 Comparison of EM signature for three transducers on concrete specimens

To further study the MFC transducers, on separate experimental work, one piece of PZT of $20 \times 20 \times 0.5$ mm and one piece of MFC of $28 \times 28 \times 0.3$ mm are attached to the cantilever aluminum beam at the same location. Figure 4-10 shows the comparison of signature acquired for the same voltage level from the PZT and MFC transducers attached to thin aluminum beam. In the aluminum beam the attenuation of the wave is much lower compared to the concrete structure and more structural peaks can be identified. As shown in Figure 4-10, for the aluminum beam, the EMI signature of MFC is similar to that of PZT. However, MFC is not as sensitive as PZT for sensing applications, especially at the monitoring voltage of 2 volts. The equations developed in Chapter 3 for both actuation and sensing are valid for both the MFC and PZT transducers. However, an appropriate transducer should be selected based on the application. Therefore MFC transducers were only used on the first specimen. The higher applied voltage will not generally change impedance signature, but it may improve the signal to noise ratio and help to identify weak modes (Park et al., 2003b).

Figure 4-10 Comparison of PZT and MFC (seven times scaled) signatures for same voltage level

4.2.2.2 Study on EMI signature

Figure 4-11 shows the relation of load-displacement and internal strain gauge reading at the location of PZT transducers. For comparison purposes the strain gauge values are scaled as 0.1 time. During the test, the longitudinal strain gauge has been over stretched and failed at the early stage of the experiment. It happened for all four specimens, limiting the application of strain gauges for monitoring the ductility of the structure.

Figure 4-11 Load-displacement and strain gauge reading (Specimen 14)

As observed in Figure 4-11, up to loading level of 160 kN, the behavior of the structure was elastic but beyond that point the structure entered into elastoplastic deformation. Figure 4-12 shows the signatures collected from the same specimen before loading and at 40 kN loading step, up to 160 kN. It is obvious that there is a big change in the signature at 160 kN compared to 4 previous signatures which coincide with change in load-displacement behavior observed in Figure 4-11. This observation indicates the ability of the PZT transducers to identify critical loading level and local failure of the structure. Figure 4-13 shows the comparison of the EM signature before loading, at 160 kN and the final signature at 220 kN. It is obvious the great change in the signature at the final loading step which indicates the alarming condition of the structure. The last two measurements were recorded at 160 kN load and after failure. By increasing the load from 160 kN, the cracks progressively propagated in the structure due to the elastoplastic behavior. Even if the load was maintained at a constant level, the cracks would continue propagating. In addition, the duration of measurement for the four PZT transducers was around 7 min. Therefore, the condition of the structure was not stable, and it was not possible to collect meaningful data in between the last two loading steps.

Figure 4-12 Signatures collected during test (Specimen 14, PZT 3)

Figure 4-13 Compression of important signatures (Specimen 14, PZT 3)

Figure 4-14 shows the relation of load-displacement versus the RMSD result of PZT 3. The RMSD values are scaled 10 times for comparison purpose.

Figure 4-14 Load-displacement and RMSD results (Specimen 14, PZT 3)

As shown in Figure 4-14, the RMSD values vary in very similar manner as the load-displacement curve. The RMSD value of 120 kN for this PZT on specimen 14 is 6 percent. It suddenly increases to 16 percent for 160 kN loading.

4.2.2.3 Structural mechanical impedance

Bhalla and Soh (2003) introduced the decomposition of the electromechanical admittance signatures to derive the structural mechanical impedance (SMI) as follows

$$\bar{Y} = \bar{Y}_P + \bar{Y}_A \quad (4.1)$$

$$\text{where } \bar{Y}_P = \omega j \frac{b_c l_c}{t_c} (\bar{\epsilon}_{33}^T - d_{31}^2 E) \text{ and } \bar{Y}_A = j \omega \frac{b_c l_c}{t_c} \left(\frac{Z}{Z + Z_a} \right) d_{31}^2 E \left(\frac{\tan kl}{kl} \right)$$

The first part $\bar{Y}_P$, depends on the parameters of the PZT transducer and it is not affected by any damage to the structure. The second part, $\bar{Y}_A$, represents the coupled interaction between the structure and the PZT patch. It is an active component which is affected by damage in the structure. Due to elimination of the PZT impedance, the resulting signature is more sensitive for SHM.

Figure 4-15 shows the comparison of the real part of SMI for different level of loading. Comparing Figures 4-12 and 4-15, it is obvious that the SMI can show more critical change for 160 kN compared to former cases.

Figure 4-15 Comparison of real part of SMI for different level of loading

Figure 4-16 shows the comparison of RMSD values for the EMI and SMI signatures. It is apparent that, at the same level of loading, the RMSD values of SMI

are much larger than those of EMI, indicating that the SMI is more sensitive to damage compared to the EMI signature.

Figure 4-16 Comparison of EMI and SMI values

4.2.3 Uncertainties and limitations

Not all the signatures of PZTs attached to the structure have shown the trend that follows the loading steps reported above. This inconsistency in the PZT signatures can be attributed to the facts that (1) there are many cracks developed around the PZTs during the loading process and their patterns are complicated; and (2) a small crack close to a PZT may cause larger variations in the signature compared to a big crack far away from the PZT. Furthermore, in the above experiment, no information on damage location can be obtained by using the RMSD method for the analysis of EMI signatures. Therefore, to eliminate the complex nature of crack development in the above experiment, a simplified experiment to study the effect of crack location and severity on the EMI signature is needed.

4.3 Preliminary test on variation of RMSD results for various frequency range

The principle behind the EMI technique is to apply high-frequency structural excitations (typically higher than 30 kHz) through the surface-bonded PZT transducers, and measure the impedance of structures. Park *et al* (2003a) recommended a frequency range from 30 kHz to 400 kHz for PZT actuation. To

achieve high sensitivity to damage, high frequency signatures (>200 kHz) have been used to monitor the region close to the PZT location while low frequency signatures (<100 kHz) have been traditionally ignored. For damage assessment, statistical methods such as RMSD have been used to calculate the variations in the EMI signature. However, it has been reported that the use of RMSD as the damage indicator in the EMI technique is difficult to specify the damage location and severity. To overcome the difficulty, wave propagation techniques in time domain were proposed to locate the damage in structures (Park et al., 2003b).

The wave length reduces with the increase in frequency. Furthermore, the attenuation of wave increases at high frequencies (Gaydecki et al., 1992). As reported by Park *et al* (2000b), frequency higher than 500 kHz limits the sensing region of the PZT to the area very close to the PZT. The PZT signature shows adverse sensitivity to structural damage since the bonding condition of PZT rather than the structural damage has more prominent effect on the signature. In order to understand the effect of monitoring frequency range, an experiment is carried out on an actual-sized concrete structure subjected to artificial damage. The EMI signatures are acquired in frequency range of 30 kHz to 400 kHz. Distribution of RMSD results in 10 kHz intervals are plotted for different damage. Sensitivity of RMSD results to damage is studied.

4.3.1 Experimental setup

Totally five sets of experimental tests have been carried out. All tests were conducted on an actual-sized concrete structure with dimensions of $3.5 \times 1.5 \times 1$ m. Figure 4-17 shows the concrete structure used in these experimental tests. Two different sizes of PZTs with dimensions $20 \times 20 \times 0.5$ mm and $20 \times 20 \times 2$ mm were used in the experimental work. An impedance analyzer and a multiplexer were used to acquire the EM admittance signatures of the PZTs. In the first experimental test, three PZTs were attached to the structure and the holes which simulate the damage were randomly drilled in the area around the PZTs. In the second, third and forth experimental tests, a single PZT was used and the holes were drilled in a circular manner from a distance far away from the PZT to the area close to the PZT. In the last experimental test, three PZTs were used and the holes were drilled at one side from

the distance far away from the PZTs to the area around the PZTs. After drilling each hole, the admittance signatures of single PZT or multiple PZTs were acquired. Figures 4-18, 4-19 and 4-20 illustrate the progress of some experimental tests.

Figure 4-17 Concrete structure

Figure 4-18 Holes drilled randomly around PZTs

Figure 4-19 Holes drilled in circular manner from certain distance to PZT

Figure 4-20 Holes drilled at right hand side from certain distance to PZTs

4.3.2 Results and discussions

In this section a large frequency range is divided into a number of sub-frequency intervals with width of 10 kHz. After that the RMSD values of the EM admittance for each sub-frequency intervals are calculated and plotted against the frequency. With increase in severity of damage, the RMSD value is expected to increase. Figure 4-21 shows the RMSD values with the increase in damage severity by drilling holes at 10 cm from the PZT transducer with dimension $20 \times 20 \times 0.5$ mm. All of the EMI signatures in Figure 4-21 were compared with the healthy state (same baseline signature). Therefore, the severity of damage was defined by the number of the holes, from one hole to 14 holes. It is obvious that by increasing the number of holes, the RMSD values increase except for few sub-frequency intervals where the RMSD values only have minor increases. For other PZTs, the similar effect of the damage severity on the RMSD is observed, regardless of the location of the damage.

Figure 4-21 Variations in RMSD value with increase in damage severity for different sub-frequency intervals

Figures 4-22 to 4-26 show the variations in RMSD for damage points at distances of 50, 30, 10, 5 and 2 cm from the PZT, respectively. As expected, by reducing the distance of damage from the PZT, the RMSD values increase, e.g., the RMSD values in Figure 4-24 are larger than those in Figure 4-23. These Figures also indicate that for the damage far from the PZT, the RMSD value at low frequency range (40-100 kHz) varies more significantly. This observation would be useful for damage detection using low frequency range.

Figure 4-22 RMSD for PZT at 50 cm from damage

Figure 4-23 RMSD for PZT at 30 cm from damage

Figure 4-24 RMSD for PZT at 10 cm from damage

Figure 4-25 RMSD for PZT at 5 cm from damage

Figure 4-26 RMSD for PZT at 2 cm from damage

4.3.3 Uncertainties and limitations

One concern from Figures 4-22 to 4-26 is that damage points with the same severity at different distances from the PZT transducer can change the RMSD value dramatically (from 0.2 to 13 percent in this case). For online monitoring of the inaccessible areas in a structure, it is crucial to discriminate the effects of an incipient damage occurring close to the PZT and a severe damage occurring far away from the PZT. Considering the RMSD for 10 kHz intervals, a big variation exists in the RMSD results, from one interval to another. Not all the results in five experiments were consistent. Drill hammer created lots of hair line crack which causes some uncertainties in the results. In addition, the relation between the frequency range and

sensing region needs to be further studied. Therefore a new set of experiment is planned to further explore the idea.

4.4 Study on location and severity of damage in concrete structures

In the EMI technique, the elastic waves generated by the PZT transducer propagate in the structure. The waves are reflected back to the PZT transducer when they encounter geometric discontinuity or damage in the structure. The reflected wave thus contains the vital information of structural damage, which can be recorded by the impedance analyzer in the PZT admittance signature in the frequency domain. The attenuation of waves is very high in concrete structures in comparison to metallic structures due to higher porosity and inconsistent nature. In addition, the attenuation of waves increases with the frequency of monitoring. Thus, higher frequency results in smaller sensing region. However, no attempt has been made to quantitatively correlate the frequency range with the sensing region. This section proposes a new approach by dividing the large frequency (30-400 kHz) range into sub-frequency intervals and calculating their respective RMSD values. Instead of a single value of RMSD used in the existing EMI technique, the RMSD of sub-frequencies (RMSD-S) will be used to study the severity and location of damage. An experiment is carried out on an actual-sized concrete structure subjected to artificial damage. The PZT admittance signatures in a frequency range of 30 to 400 kHz for different structural damage are recorded and the RMSD-S values are calculated. It is observed that the damage close to the PZT changes the RMSD-S at high frequency range significantly; however the damage far away from the PZT changes the RMSD-S at low frequency range significantly. The relationship between the frequency range and the PZT sensing region is also presented. Finally, a damage identification scheme is proposed to estimate the location and severity of damage in concrete structures.

4.4.1 Experimental Work

Five pieces of 20×20×0.5 mm PZTs were attached to a concrete mass of 2.0×1.5×1.5 m. A two-component adhesive, 3M's DP 460 epoxy was used to bond the PZTs to the surface of concrete. Waterproofing agent called Plastic DIP (2010) was used to cover the exposed surface of PZTs to prevent deterioration of the transducers

over time. An impedance analyzer with interrogation voltage of 2 volts and a multiplexer were used to acquire the electromechanical admittance signatures of the PZTs. A 16 channel parallel data acquisition unit was used to study the PZT generated wave propagation on the surface of concrete structure. Figure 4-27 shows the overall experimental setup. Figure 4-28 shows the arrangement of PZT transducers on the concrete structure.

Figure 4-27 Experimental setup

Figure 4-28 PZT transducers on the concrete structure

In the preliminary test presented in Section 4.3, a drill hammer was used to create the hole-type damage in the concrete structure. However, it was found that lots of hairline cracks formed near the holes due to hammering function, which caused some uncertainties in results. To avoid the problem, in this study, a handy cutter shown in Figure 4-29 was used to create the crack-type damage in concrete. Figure 4-30 shows the location and sequence of damage points. Free signatures of PZT transducers acquired before attaching them to the structure are presented in Figure 4-31, which shows the good repeatability of the free signatures.

Figure 4-29 Handy cutter used to create the damage points

Figure 4-30 Location and sequence of damage points on structure

Figure 4-31 Free signatures of PZT transducers

4.4.2 Results and discussions

4.4.2.1 Sensing region

PZT transducers have been used for monitoring of structures based on two principles, (1) using multiple PZTs in the surface wave propagation or the wave transmission techniques, and (2) using single PZT transducer in the EMI technique or the pulse-echo technique. The wave propagation technique is similar to the conventional ultrasonic technique. One piece of PZT transducer is used to generate high frequency waves with constant frequency in structure; one or more PZT transducers acquire the signal. Then, the acquired signal in time domain is investigated to assess the damage. Usually, to find the location of damage demands complex modeling of wave propagation.

The wave velocity changes in concrete with frequency (Philippidis and Aggelis, 2005). In addition, the wave modes and velocity changes as it hits boundaries. Figure 4-32 shows the wave propagation signals at 50 kHz frequency with an actuation voltage of 10 volts applied on PZT 1 (Figure 4-30). PZT 1 was used as actuator and other PZTs as sensors. Figure 4-33 shows the similar signals but at 120 kHz frequency. Comparison between the acquired signals in Figures 4-32 and 4-33 reveals obvious changes in speed and amplitude of the signals. Higher attenuation of wave at frequency of 120 kHz is also observed in comparison to that at 50 kHz for distance far away from PZT (in this case comparing the signal received by PZTs 4 and 5 in Figures 4-32 and 4-33).

Figure 4-32 Surface wave propagation at frequency of 50 kHz with PZT 1 as actuator

Figure 4-33 Surface wave propagation at frequency of 120 kHz with PZT 1 as actuator

In the EMI technique, similar to the plus-echo technique, one PZT transducer is used as both actuator and sensor. However, instead of studying the surface wave propagation signal at one particular frequency in the time domain, the EMI focuses on the admittance signal in the frequency domain obtained by sweeping the signal in a pre-selected frequency range. At each frequency, the PZT transducer which is controlled by the impedance analyzer generates a steady state wave propagating through the structure and receives the reflected wave signal in the form of EM

admittance. For each frequency one value of admittance is measured. If there is no change in structure, this value will remain the same in repetitive measurements. The impedance analyzer generates a high frequency signal with voltage level of one or two volts. In health monitoring of small metallic structures, the generated wave is strong enough to cover the whole structure, activate the vibration modes and locate their corresponding natural frequencies. Figure 4-34 shows a typical EMI signature for an aluminum beam structure with sizes of 30×5×0.2 cm.

PZT generated waves will be attenuated when propagating from the PZT to a structure through an epoxy layer, propagating in the structure and returning to the PZT. For actual-sized metallic structures or medium size concrete structures, the generated waves cannot activate the modal vibration of the structure due to insufficient energy in actuating signal. Thus, a PZT only monitors a limited area around itself. While the EM signature contains the local dynamic information of the structure, the major peaks in the signature do not represent the natural frequencies of the structure. Instead, they represent the PZT resonant frequencies, as shown in Figure 4-34. In addition, wherever waves hit any boundary or discontinuity such as cracks, they will be reflected back to PZT.

Figure 4-34 Typical EMI signature for a small metallic structures, a concrete structure and an actual-sized metallic structure

Figure 4-35 shows the maximum voltage received by PZT 1 to 4 by setting PZT 5 as actuator with voltage level equal to 2 volts which represents the current maximum voltage in impedance analyzer used in this work. Figure 4-35 reveals very useful information about sensing region of PZT transducers for health monitoring of concrete structures. It is noted that negligible signal was received by the PZT at 28cm away from the actuator for frequency above 160 kHz. Similarly, weak signal was received from PZTs at 21 cm, 14 cm and 7 cm for frequency above 190 kHz, 230 kHz and 270 kHz respectively. It means that when the monitoring frequency increases, the sensing region decreases. In the EMI technique, the sensing distance is half of these values as the wave needs to travel and return to the same PZT as it serves as both actuator and sensor. The major peaks near 80 kHz and 120 kHz correspond to the natural frequencies of PZT traducers shown in Figure 4-31.

Total induced force of PZT transducer can be calculated as follows (Yang et al., 2010)

$$F = \bar{E}whl(\varepsilon_p - d_{31}\frac{V}{h}) \quad (4.2)$$

where ε_p is the free strain inside PZT and V is the applied voltage. It can be seen that the generated force is proportional to the applied voltage, the length and the width of PZT. Increasing the voltage from 2 to 10 volts amplifies the received signal exactly five times. The sensing region depends on monitoring frequency range, size of PZT, concrete material properties and monitoring voltage (Hu and Yang, 2007). The attenuation of wave for various frequency ranges can be studied by considering the results presented in Figure 4-35 or other literatures (Philippidis and Aggelis, 2005; Cui and Zou, 2006). Therefore, the sensing region can be determined and controlled by considering these parameters.

Figure 4-35 Maximum voltage received from PZT 1 to 4 by setting PZT 5 as actuator

4.4.2.2 Damage detection

As mentioned earlier, an impedance analyzer with maximum voltage of 2 volts was used to acquire the EM admittance signature of the structure. The monitoring range was selected from 30 to 400 kHz with a stepping frequency of 0.1 kHz. Figure 4-36 shows the location and sequence of damage points and PZT locations, where D1 represents the first damage and D9 the last damage. The signature obtained from PZT 3 was not repeatable and reliable in healthy condition of the structure. In addition, PZT 1 was more than 22 cm away from the nearest damage and it could not sense any of the damage points. Therefore the signatures of PZTs 5, 4, and 2 were recorded. Tables 4-1, 4-2 and 4-3 present the RMSD-S results of the admittance signatures acquired after damage points for PZTs 5, 4 and 2, respectively.

Figure 4-36 Location and sequence of damage points for EMI method

Table 4-1 RMSD-S for PZT 5

	D 1	D 2	D 3	D 4	D 5	D 6	D 7	D 8	D 9
Distance (cm)	15	10	8	5	3	2	1	9	10
Frequency (kHz)									
30-400	0.16	0.30	0.41	0.95	1.9	2.1	3.1	0.1	0.4
(A) 30-99.9	0.68	2.21	2.59	2.86	3.9	4.6	7.9	1.1	2.5
(B) 100-149.9	0.44	1.07	1.75	3.33	6.7	5.4	5.5	0.3	1.5
(C) 150-199.9	0.20	0.36	0.48	1.40	2.5	3.3	4.6	0.2	0.6
(D) 200-249.9	0.10	0.14	0.22	0.61	1.2	2.6	2.8	0.1	0.2
(E) 250-299.9	0.14	0.14	0.19	0.75	1.6	2.1	4.1	0.1	0.3
(F) 300-400	0.12	0.10	0.13	0.23	0.6	0.7	1.3	0.1	0.1

Table 4-2 RMSD-S for PZT 4

	D 1	D 2	D 3	D 4	D 5	D 6	D 7	D 8	D 9
Distance (cm)	22	17	15	12	10	9	8	16	10
Frequency (kHz)									
30-400	0.11	0.17	0.16	0.23	0.33	0.33	0.51	0.12	0.36
(A) 30-99.9	0.44	0.91	0.93	1.58	2.22	2.21	3.04	0.38	2.39
(B) 100-149.9	0.17	0.40	0.59	0.91	1.52	1.41	2.40	0.18	1.48
(C) 150-199.9	0.07	0.31	0.22	0.34	0.38	0.50	0.47	0.19	0.69
(D) 200-249.9	0.09	0.16	0.08	0.15	0.14	0.22	0.27	0.12	0.22
(E) 250-299.9	0.12	0.16	0.07	0.15	0.16	0.15	0.22	0.13	0.15
(F) 300-400	0.08	0.10	0.10	0.07	0.08	0.11	0.14	0.08	0.09

Table 4-3 RMSD-S for PZT 2

	D 1	D 2	D 3	D4	D 5	D6	D7	D 8	D 9
Distance (cm)	36	31	29	26	24	23	22	30	10
Frequency (kHz)									
30-400	0.10	0.11	0.09	0.06	0.07	0.14	0.12	0.12	0.26
(A) 30-99.9	0.18	0.19	0.24	0.27	0.37	0.33	0.34	0.19	2.13
(B) 100-149.9	0.14	0.08	0.06	0.08	0.11	0.16	0.12	0.11	0.75
(C) 150-199.9	0.13	0.12	0.04	0.05	0.06	0.14	0.12	0.13	0.43
(D) 200-249.9	0.09	0.08	0.09	0.06	0.07	0.16	0.12	0.12	0.16
(E) 250-299.9	0.15	0.08	0.06	0.04	0.07	0.20	0.17	0.14	0.13
(F) 300-400	0.07	0.12	0.11	0.05	0.05	0.08	0.09	0.12	0.10

The signature obtained in healthy condition was considered as the baseline for damage D1; and the signature acquired after damage D1 was considered as the baseline for damage D2. That is, the signature after one damage point was used as the baseline for the next damage.

The whole monitoring frequency range of 30-400 kHz is divided into six sub-frequency intervals, i.e., (A) 30-99.9 kHz, (B) 100-149.9 kHz, (C) 150-199.9 kHz, (D) 200-249.9 kHz, (E) 250-299.9 kHz and (F) 300-400 kHz. The RMSD values for the entire frequency range and the sub-frequency intervals (RMSD-S) are calculated for each damage state.

Figure 4-37 shows the RMSD-S of damage D1 to D7 at 15 cm, 10 cm, 8 cm, 5 cm, 3 cm, 2 cm and 1 cm from PZT 5 respectively. For the damage points far from PZT 5, namely D1, D2 and D3, the low frequency range (A) shows more changes compared to the other frequency ranges. These results are expected as the high frequency waves cannot travel and return to PZT 5 from D1, D2 and D3 due to the longer distance for wave traveling. In other words, the high frequency signals are not able to sense those damage points far from the PZT. As the damage points D4, D5 and D6 are getting closer to PZT 5, the mid range RMSD-S for intervals (B), (C) and (D) show more sensitive changes. There is a clear increase in RMSD-S compared to earlier cases for damage D7 at 1 cm for frequency range (E) which can monitor a very small region close to PZT.

Figure 4-37 RMSD-S of damage D1 to D7 for PZT 5

Figure 4-38 shows the RMSD-S of damage points D1 to D7 for PZT 4. D1 to D7 are at 22 cm, 17 cm, 15 cm, 12 cm, 10 cm, 9 cm and 8 cm from PZT 4, respectively. Again, the results agree with the expectation. D1 to D4 are far way from PZT 4 and only range (A) exhibits more sensitive changes. For damage points D5 to D7 which are closer to PZT 4, ranges (B) and (C) show more sensitivity as well. However, as expected, the high frequency ranges (D) to (F) cannot pick up the damage.

Figure 4-38 RMSD-S of damage D1 to D7 for PZT 4

Damage points D3, D5, D7 are at 15 cm, 10 cm and 8 cm from PZT 4 respectively. Damage D1, D2 and D3 are also at 15 cm, 10 cm and 8 cm from PZT 5. Thus, the RMSD-S for these cases are compared in Figure 4-39. Damage points are not identical and result in different amount of change in RMSD-S values, however the patterns of RMSD-S are very well repeatable which shows the potential of the proposed method.

Figure 4-39 RMSD-S for PZTs 4 and 5 for similar distance to damage

Damage D8 was created between D2 and D3. The purpose is to investigate the applicability of proposed method in presence of existing damage in between PZT and new damage. As shown in Table 4-1 column D8, only low frequency range shows significant change in RMSD-S. However the values are smaller compared to the RMSD-S of damage points D2 and D3 due to the interference from the existing damage which increases the wave attenuation. Damage D9 was created on top of the three PZTs at distance of 10 cm. As the distance is the same, three PZTs show very good repeatability in the RMSD-S results as shown in Tables 4-1 to 4-3, column D9.

Analyzing the effect of cumulative damage is useful and may produce consistent results in RMSD-S. In this case, the baseline is set as the healthy state (no damage) and all the signatures are compared with the healthy signature. Figure 4-40 shows the RMSD-S for cumulative effect of one to nine damage points (damage D1 to D9). Based on the location of damage, four separate patterns of RMSD-S for (1) one and two damage points, (2) three, four and five damage points, (3) six damage points and

(4) seven damage points can be identified. As expected, addition of damage D8 and D9 does not change the pattern as they both occurred far away from PZT 5. Thus, comparing with one common baseline can be used as alternative way in the analysis of RMSD-S results.

Figure 4-40 RMSD-S for cumulative effect of damage for PZT 5

4.4.2.3 Comparison of RMSD-S with RMSD

The total RMSD or RMSD has been used as the damage indicator in the EMI technique, which is calculated over the entire frequency range of the EMI signatures. Considering the RMSD-S instead of the total RMSD can reduce uncertainties in damage identification. For instance, in case of damage D2 (at 10 cm from PZT 5) in Table 4-1, the RMSD-S for range (A) changes 2.2 percent while the total RMSD changes 0.3 percent and RMSD-S for higher frequencies (>200 kHz) changes less than 0.15 percent. This damage could be overlooked if a limited high frequency range is monitored. Figure 4-41(a) illustrates this problem. In other words, if a major crack exists at that distance, it may change the RMSD-S for range (A) significantly but may only cause minor changes in the total RMSD and the RMSD-S for higher frequency ranges. The occurrence of major crack at that distance could be measured by considering RMSD-S. Similar damage at two different distances from the PZT may change the RMSD-S in different patterns. For example, damage points D2 and D5 are comparable in size but at 10 cm and 3 cm from PZT5, respectively. The

corresponding total RMSD increases by 0.3 and 1.95 percent respectively. From these two values, one cannot ascertain whether D5 is a bigger damage at the same distance as D2 or it is a similar (or smaller) damage closer to the PZT than D2. This problem can be resolved by considering the RMSD-S values. For the damage closer to PZT, in this case D5 at 3 cm, the RMSD-S for higher frequency shows more sensitive changes, as shown in Figure 4-41(b).

Figure 4-41 Possible issues of using RMSD as single value instead of RMSD-S, (a) Damage occurred far away from PZT (b) Similar damage occurred at two different distances from PZT

In addition, selecting the limited low frequency range may not be suitable for damage identification. This is because both severe damage far away and small damage close to the PZT may change the RMSD for low frequency significantly. A possible way to distinguish between them is to look at RMSD-S at high frequency ranges simultaneously. Damage D7 which is at 1 cm from PZT5 changes the RMSD-S for range (A) significantly, and a major crack far away from PZT5 could change the RMSD of range (A) by the similar amount. For this case, considering the RMSD-S can reveal whether a small damage close to PZT or a major damage far away from PZT occurs. The damage close to PZT (1 cm) would change the RMSD-S at high frequency significantly compared to damage far from PZT which cannot be sensed by high frequencies.

Figure 4-42 reveals another limitation of considering limited frequency range. For frequency range of 100 kHz to 150 kHz, the RMSD value for damage D5 at 3 cm from PZT5 is higher than those for damage points D6 and D7 at 2 cm and 1 cm from PZT5 respectively. In addition, no information on location and severity of damage can be obtained. However, it can be solved considering the RMSD-S as discussed earlier in Figure 4-37.

Figure 4-42 Inconsistency in EMI result for RMSD of limited frequency range

As mentioned earlier, for actual-sized metallic and concrete structures, each PZT monitors limited area around itself and based on surface and boundary conditions near that PZT, the signature would be different. Figure 4-43 shows the EMI signatures obtained from five PZTs before inducing any damage. Signatures acquired from PZT 4 and 5 varies significantly from the other three. Figure 4-44 shows the surface condition around these PZTs. It can be seen that the concrete surface is more porous close to PZTs 4 and 5, which affect the wave propagation around PZTs 4 and 5 and hence the EMI signatures. Though the baselines look different, they will not affect the RMSD-S as the occurrence of new damage is monitored in comparison to the baseline signatures.

Figure 4-43 PZT signatures in healthy condition

Figure 4-44 Surface condition near PZTs

4.4.3 Damage identification scheme

Given the RMSD-S results, a method is presented here to investigate the location and severity of damage. Consider a section of the above concrete structure in Figure 4-45, where two PZTs 2 and 5 with distance of 21 cm apart are used for monitoring. Table 4-4 shows the RMSD-S results versus distance of damage from PZTs. For each frequency range, the RMSD-S values which changed noticeably are highlighted in the table.

Table 4-4 RMSD-S versus distance from PZT

Distance of damage from PZT (cm)	Frequency Range (kHz)						
	30-400	(A) 30-99.9	(B) 100-149.9	(C) 150-199.9	(D) 200-249.9	(E) 250-299.9	(F) 300-400
1	3.12	7.98	5.58	4.67	2.84	4.18	1.35
2	2.11	4.66	5.48	3.35	2.61	2.19	0.77
3	1.95	3.96	6.76	2.56	1.24	1.68	0.64
5	0.95	2.86	3.33	1.40	0.61	0.75	0.23
8	0.51	3.04	2.57	0.47	0.27	0.22	0.14
10	0.33	2.22	1.52	0.38	0.14	0.16	0.08
12	0.23	1.58	0.91	0.34	0.15	0.15	0.07
15	0.16	0.93	0.59	0.22	0.08	0.07	0.10
22	0.11	0.44	0.17	0.07	0.09	0.12	0.08
29	0.09	0.24	0.06	0.04	0.09	0.06	0.11
31	0.11	0.19	0.08	0.12	0.08	0.08	0.12
36	0.10	0.18	0.14	0.13	0.09	0.15	0.07

Considering the results presented in Table 4-4, the radius of sensing regions for the six frequency ranges of (A) to (F) can be determined as 22 cm, 15 cm, 12 cm, 8 cm, 5 cm and 3 cm respectively. These six sensing regions are illustrated using circles for both PZTs 2 and 5 in Figure 4-45. The monitoring area can be divided into three main regions, left hand side of PZT 2 (Region X), right hand side of PZT 5 (Region Z) and the region between PZTs 2 and 5 (Region Y).

Figure 4-45 Selected area of concrete wall

If any damage occurs in Region X, only PZT 2 can sense it. Similarly, damage in Region Z can only be detected by PZT 5. And damage in Region Y can be detected by both PZTs. It is therefore possible to estimate the location of damage from the RMSD-S values of two PZTs. Three cases with different RMSD-S values for two PZTs are presented in Figure 4-46. The RMSD-Ss are based on actual damage in Tables 4-1 and 4-3. In Case 1 presented in Figure 4-46 (a), the RMSD-S of PZT 2 is too small (around 0.2 percent) to sense the damage. Thus the damage should be outside the sensing region of PZT 2 and located in Region Z. The RMSD-S of PZT 5 is noticeable (around 0.7 percent) in low frequency range (A), indicating that the damage is at area (A) in Region Z. In Case 2 presented in Figure 4-46 (b), the RMSD-S of PZT 2 is very small and that of PZT 5 varies from 5 to 0.8 percent in frequency range (A) to (F). Thus, the damage is estimated in Region Z and close to PZT 5 in area (E) or (F). In Case 3 presented in Figure 4-46 (c), the RMSD-S of both PZTs is noticeable in low frequency ranges. Thus the damage is in region Y between two PZTs. The RMSD-S of PZT 5 is changed more significantly for higher frequencies. Therefore the damage is closer to PZT 5 in area (C) to (E) which overlaps with area (A) or (B) of PZT 2.

One of the applications of above scheme is to monitor remote areas such as column-beam joints. In column-beam load transfer system, safety of joint is very important. In the above illustration, by using two pieces of PZTs with maximum sensing region of 22 cm, an area of 66×44 cm can be monitored. Using more PZTs or decreasing the distance between PZTs will help to estimate the location of damage with higher accuracy.

Figure 4-46 Predicted location of damage for various RMSD-S, (a) Damage in area (A) of region Z, (b) Damage in area (E) or (F) of region Z, (c) Damage in region Y in area (A) or (B) for PZT 2 which overlaps with area (C) to (E) for PZT 5

4.4.4 Concluding remarks

In this section, a sub-frequency interval approach RMSD-S is proposed to analyze the electromechanical impedance (EMI) signature of piezoelectric transducers. Compared with the conventional approach which uses one RMSD value for the entire frequency range, the proposed technique is more reliable and robust for health monitoring of concrete structures. The damage severity and location can be estimated by single PZT transducer through the RMSD-S. As shown in Section 4.4.3, multiple PZTs can increase the accuracy of damage identification and provide larger sensing area. It is observed that the damage close to PZT changes the RMSD-S at high frequency range significantly; however the damage far away from the PZT changes the RMSD-S at low frequency range significantly. A damage identification scheme is proposed to study the location and severity of damage in concrete structures.

Using the proposed RMSD-S method, it is possible to qualitatively specify the damage severity and location, though it is still not able to quantitatively identify the damage. Quantification of damage severity and location will require tremendous effort in developing mathematical models to associate the damage with the EMI signal. In fact, for more complex structures, such models may not possible to achieve. On the other hand, the qualitative results on damage severity and location provided by the proposed RMSD-S method would be sufficient for many engineering applications.

4.5 Study on location and severity of damage in steel structures

4.5.1 Introduction

Steel structures have been monitored using the EMI technique in several studies (Giurgiutiu et al, 1999, Giurgiutiu and Rogers, 2001, Ayres et al, 1996, Lim et al, 2011, Bhalla et al, 2005, Park et al, 2006). For small steel structures (167×25.4×2 mm (Giurgiutiu et al, 1999), 100×100×1 mm (Giurgiutiu and Rogers, 2001)), significant changes in RMSD values due to induced damage have been observed. Giurgiutiu and Zagari (2001) recorded a measurable peak shift in the EMI signature by increasing the damage intensity. Ayres *et al* studied a steel bridge joint by loosening the bolts near the joint with 30 connection bolts (Ayres et al, 1996). The changes of RMSD of the

EM admittance signature increased with the number of loosened bolts. However, the effect of the distance of loosened bolts on the EMI signature was not discussed. Bhalla et al (2005) used multiple PZTs for health monitoring of an aluminium plate. However, due to limited frequency range (100-120 kHz) and low attenuation of the waves, it was not possible to find the damage location. Park *et al* tested a steel bridge component to obtain the EMI signature in a limited frequency range of 40-100 kHz (Park et al, 2006). A critical threshold was proposed to detect the existence of damage; however the location or severity of damage was not identified.

It has been recognized that the PZT transducers are more promising for SHM of steel structures than the concrete structures. Due to lower porosity and better surface condition of the steel material, the attenuation of wave is much lower and thus the PZT sensing region is larger compared to the concrete structures (Hu and Yang, 2007). In addition, the repeatability data obtained from multiple PZTs is better.

Section 4.4 has shown that the RMSD-S provides a better means to study the location and severity of damage compared to the conventional RMSD method. In this section, an I-section steel beam customized as load transfer system is subjected to artificial damage. The RMSD-S values corresponding to damage are acquired. To study the damage severity and location, a method combining the RMSD-S of multiple PZTs and the logarithmic attenuation of ultrasonic waves is proposed. The results demonstrate that the proposed method is robust and sensitive for damage assessment of steel structures.

4.5.2 Experimental work

An experiment was carried out on an I-section steel beam type HE160A with beam height of 15.2 cm, flange width of 16 cm and flange thickness of 0.9 cm. The section was customized as a load transfer system with stiffeners welded at middle section. Figure 4-47 shows the overview of the steel beam, where the clear distance between two end plates is 90 cm.

Figure 4-47 Overview of steel beam under monitoring

Three PZTs of 20×20×0.5 mm were attached to the beam. For better connectivity of PZT transducers, the coating paint on the steel surface was removed, as shown in Figure 4-48(a). The PZT was then bonded to the polished steel surface by two components epoxy (3M's DP 460). After installing the PZT transducer, a plastic DIP waterproofing layer was applied to protect the PZTs from the environmental moisture, as shown in Figure 4-48(b). Figure 4-49 shows the arrangement of three PZTs on the beam.

Figure 4-48 Removal of painting, installing and waterproofing of PZT transducer

Figure 4-49 Location of PZT transducers installed on the beam

A number of holes were drilled to induce different damage in the beam. During the drilling process, the temperature near the drilling area increased significantly. Therefore, the EM admittance signatures were obtained 20 minutes afterward to allow the heat to dissipate and the temperature to return to normal condition. The holes were drilled in sequence to simulate different stage of damage. Figure 4-50 shows the location of holes drilled near the three PZTs

Figure 4-50 Damage points induced near three PZTs

The schematic and sequence of the holes is presented in Figure 4-51, where D1 represents the first damage and D10 the last. The three PZTs are 30 cm apart from each other and the damage points (holes) are located from 2cm to 80 cm from the PZTs.

Figure 4-51 Location and sequence of damage points on steel beam

An impedance analyzer with interrogation voltage of 2 volts was used to acquire the EM admittance signature of the structure. The EM admittance signatures of three PZTs after damage points (D1 to D10) were recorded in the frequency range of 30 to 400 kHz with a resolution of 0.1 kHz. To calculate the RMSD-S values, the frequency range is divided to six sub-frequency intervals, *i.e.* (A) 30-99.9 kHz, (B) 100-149.9 kHz, (C) 150-199.9 kHz, (D) 200-249.9 kHz, (E) 250-299.9 kHz and (F) 300-400 kHz. The signature obtained under the healthy condition (without any hole) was considered as the baseline for damage D1; the signature acquired after damage D1 was considered as the baseline for damage D2. That is, the signature after one damage point was used as the baseline for the next one.

4.5.3 Results and discussions

4.5.3.1 RMSD-S results for various damage points

Figure 4-52 shows the RMSD-S of three PZTs for Damage D1. Damage D1 is at 20, 50 and 80 cm from PZTs 1, 2 and 3 respectively. In this study, if the RMSD-S of one PZT in certain frequency range is greater than 0.8 percent after damage, then we say this PZT can “sense” this damage. The value 0.8 percent is used because the RMSD-S caused by measurement noise is generally less than 0.5 percent. As shown

in Figure 4-52, PZT 3 could not sense damage D1 due to its large distance from the damage. PZT 2 sensed the damage in low frequency ranges (A) and (B) because the wave attenuation is less in these ranges as compared to other higher frequency ranges. Lastly, PZT 1 sensed the damage in frequency ranges (A) to (E) as it was close the damage.

Figure 4-52 RMSD-S of PZT 1, 2 and 3 after Damage D1

Damage D2 is located at 15, 45 and 75 cm from PZTs 1, 2 and 3 respectively. As shown in Figure 4-53, PZT 3 shows noticeable changes in RMSD-S in low frequency range (A). Since the damage is at 75 cm from PZT 3, this indicates that the sensing region of PZT is around 75 cm.

Figure 4-53 RMSD-S of PZT 1, 2 and 3 after damage D2

By this arrangement of three PZTs, a rectangular area of 150×210 cm on the steel surface could be monitored. Obviously, using multiple PZTs and considering large frequency range helped to enlarge the sensing region. From Figure 4-53, it is apparent that PZT 1 can sense the damage in the entire frequency range (A) to (F). Therefore, for a PZT to sense the damage in the entire frequency range, the damage should be at 15 cm or closer to PZT location. In other words, the sensing region of PZT is highly localized (about 15 cm) in high frequency range of 300 to 400 kHz. Similar trends can be observed for Damage points D3 to D7 in Figures 4-54 to 4-58. PZT 1 can sense all these damage points in the entire frequency range because they are very close to PZT 1. PZTs 2 and 3 can sense the damage in larger frequency range as the damage points are getting closer and closer to them.

Figure 4-54 RMSD-S of PZT 1, 2 and 3 after damage D3

Figure 4-55 RMSD-S of PZT 1, 2 and 3 after damage D4

Figure 4-56 RMSD-S of PZT 1, 2 and 3 after damage D5

Figure 4-57 RMSD-S of PZT 1, 2 and 3 after damage D6

Figure 4-58 RMSD-S of PZT 1, 2 and 3 after damage D7

One common pattern of RMSD-Ss for Damage D1 to D7 in Figures 4-53 to 4-58 is that the RMSD-S of PZT 1 is always the largest and that of PZT 3 the smallest. We can draw two conclusions from this observation: (1) Damage D1 to D7 are close to PZT 1 and far away from PZTs 2 and 3 since the RMSD-Ss of PZT 1 are greater than those of PZTs 2 and 3; and (2) these damage are at the right side of PZT 1 (i.e. further away from PZT 3 than PZT 2) since the RMSD-Ss of PZT 3 are always smaller than those of PZT 2. Without the signals from PZTs 2 and 3, it is not possible to determine whether these damage points are at left or right side of PZT 1.

Damage D8 is at 2, 30 and 60 cm from PZTs 3, 2 and 1 respectively. As shown in Figure 4-59, PZT 3 senses this damage in all frequency ranges. PZT 1 senses this damage in low frequency ranges (A) to (B) and PZT 2 senses this damage in frequency ranges (A) to (D).

Figure 4-60 shows the RMSD-S for Damage D9 which is at 2 cm from PZT 2 and 30 cm from PZTs 1 and 3. As PZT 2 senses this damage in all frequency ranges. PZTs 1 and 3 sense this damage in frequency ranges (A) to (B).

Figure 4-59 RMSD-S of PZT 1, 2 and 3 after damage D8

Figure 4-60 RMSD-S of PZT 1, 2 and 3 after damage D9

Damage D10 is a combined effect of three holes at 2 cm from PZT 2 and at 30 cm from PZTs 1 and 3. As shown in Figure 4-61, although the RMSD-S changes more significantly, but the trend and pattern of changes are similar to Damage D9. PZT 2 senses this damage in all frequency ranges and PZTs 1 and 3 sense it in frequency ranges (A) to (D). In Figures 4-60 and 4-61, the RMSD-S values of PZTs 1 and 3 are quite similar because they are at the same distance of 30 cm from the damage. It shows the good repeatability of the EMI signature in the steel structures.

Figure 4-61 RMSD-S of PZT 1, 2 and 3 after damage D10

4.5.3.2 RMSD-S Results for Three PZTs

Figure 4-62 shows the RMSD-S of PZT 1 after Damage points D1, D2, D6, D7, D8, D9 and D10. As shown, for damage points very close to PZT (D6 and D7), the RMSD-S values in all frequency ranges can clearly indicate the existence of damage since all the values are greater than the defined threshold. In other words, all frequency ranges can sense the damage in a close range to PZT. Since PZT 1 cannot sense damage D1 (20 cm away) and can barely sense D2 (15 cm away) in the highest frequency range (F), we can conclude that this range is about 15 cm from the PZT in the steel structures. Moving further away from PZT 1, only low frequency ranges can sense the damage. The frequency ranges (C) to (F) cannot sense Damage D8 at 60 cm from PZT 1 and the high frequency ranges (E) to (F) cannot sense Damage points D9 and D10 at 30 cm from PZT 1 as their RMSD-S values are less than 0.8 percent.

Figure 4-62 RMSD-S of PZT 1 after various damage points

Figure 4-63 shows the RMSD-S of PZT 2 after Damage points D1, D2, D7, D8, D9 and D10. For Damage points D9 and D10 which are very close to PZT 2, all frequency ranges can sense them. As D9 and D10 have the same distance from PZT 2 and the RMSD-S of D10 is larger than that of D9 for all frequency ranges, it can be concluded that D10 is severer than D9. Damage D8 at 30 cm from PZT 2 cannot be sensed by frequency ranges (E) and (F). Damage D7 at 32 cm from PZT 2 cannot be sensed by frequency ranges (D) to (F). Damage D1 and D2 at 50 cm and 45 cm from PZT 2 can only be sensed in low frequency ranges (A) and (B).

Figure 4-63 RMSD-S of PZT 2 after various damage points

Figure 4-64 shows the RMSD-S of PZT 3 after Damage points D1, D2, D6, D7, D8, D9 and D10. As shown, PZT 3 can sense damage D8 in all frequency ranges. Damage points D9 and D10 at 30 cm from PZT 3 can be sensed in frequency ranges (A) to (D). Damage points D7, D6 and D5 at 62 cm, 64 cm and 75 cm from PZT 3 can be sensed only at frequency range (A). Damage D1 at 80 cm from PZT 3 cannot be sensed by any frequency range.

Figure 4-64 RMSD-S of PZT 3 after various damage points

Considering the results presented above, we can determine the sensing regions for all the frequency ranges (A) to (F). Based on the defined threshold, the sensing regions for frequency ranges (F) to (A) are 15 cm, 25 cm, 35 cm, 45 cm, 60 cm and 75 cm, respectively. Figure 4-65 shows the radius of sensing region for these frequency ranges. These ranges are in line with the sensing regions determined by authors for concrete structures. The sensing regions of PZT for steel structures are approximately 3 to 4 times larger than those of concrete structures reported by Yang and Sabet (2010).

Figure 4-65 Sensing region for frequency ranges (A) to (F)

It is worth pointing out that the size of structure under monitoring affects the EMI signature. Unlike small steel structures where a measurable shift in EMI signature can be observed (Giurgiutiu and Rogers, 2001), the location of peaks may not change for larger steel structures. To illustrate this point, Figure 4-66 shows the EMI signature in healthy condition and after 12 holes drilled on the structure. As shown, only minor shift in high frequency signal is detected.

Figure 4-66 EMI signature of PZT 1 before and after damage

The total RMSD changes (calculated in the entire frequency range) of PZT 1 for Damage points D5 and D10 are 1.49 and 0.95 percent, respectively, and they are at 6 and 30 cm from PZT 1 respectively. Damage D5 (one hole) can be considered as a small damage close to PZT and damage D10 (three holes) as a large damage far away from PZT. From the total RMSD changes obtained above, one could not determine the location or severity of these two damage points. However, by examining the RMSD-S for different frequency ranges, it is possible to provide useful information on damage location. Figure 4-67 shows the comparison of RMSD-S for damage D5 and D10. By considering RMSD-S values, it is even possible to determine the location of damage with single PZT. Damage D10 cannot be sensed in high frequency ranges (E) and (F) but it can be sensed by other frequency ranges. Therefore it should be at 25 to 35 cm from PZT 1. Damage D5 can be sensed in all frequency ranges, and therefore it should be at 15 cm or closer to PZT 1. Considering the RMSD-S values of multiple PZTs as presented earlier in Figures 10 and 15 for damage D5 and D10, it is easier and more reliable to determine the location of damage. However, it is difficult to identify the damage severity yet.

Figure 4-67 RMSD-S of PZT 1 after Damage points D5 and D10

4.5.3.3 Logarithmic Wave Attenuation

In the PZT generated wave propagation, the attenuation of waves is known to have a logarithmic relation with the distance between the actuation point and the sensing point (Philippidis and Aggelis, 2005; Cui and Zou, 2006). To verify if this relation is applicable in the current experiment, Figure 4-66 plots the total RMSD changes versus distance of damage for the three PZTs. As shown, a fitting curve follows a logarithmic variation with a correlation coefficient of 92 percent.

Figure 4-68 RMSD versus distance for three PZTs

The attenuation coefficient can be determined by measuring the reduction in amplitude of ultrasonic wave for a given distance of x as follows (Philippidis and Aggelis, 2005)

$$\alpha = -\frac{20}{x} \log \frac{A_x}{A_0} \quad (4.3)$$

in which A_x is the amplitude of signal at distance x and A_0 is the amplitude of actuation signal. Since in the EMI technique, the PZT generated elastic waves need to travel from and return to the PZT, the actual traveling distance of the waves is twice of the values in Figure 4-66. Thus the distance value in the figure should be rectified to double. Figure 4-67 shows the normalized RMSD values versus the rectified distance travelled by the elastic waves. Again, a fitting curve can be obtained to describe the relation between them, as shown in the figure.

Figure 4-69 Normalized RMSD versus wave traveling distance

The attenuation of wave in a steel pipe was measured between 0.06 to 0.1 db/mm by Senior and Szilard (1984) and the attenuation of wave for forged chrome-nickel steel was reported around 0.1 db/mm (Schlengerma, 1983). For this study, Figure 4-68 shows the wave attenuation coefficient back calculated from the results using Eqn. (4.3) in Figure 4-67.

Figure 4-70 Calculated wave attenuation

The results match with the expectations. The attenuation is frequency dependent and increases with the frequency of monitoring. Since lower frequency waves can travel longer distance, the EMI signatures measured at longer distances (above 30 cm) are mostly influenced by lower frequency waves. Therefore the calculated attenuation coefficient is lower (0.04-0.06 db/mm), which is comparable to Senior and Szilard's result (0.06-0.1 db/mm). On the other hand, high frequency waves attenuate fast and the EMI signatures measured at locations close to PZT are more affected by high frequency waves. Therefore, the calculated attenuation close to PZT is larger (0.08-0.18 db/mm), which is comparable to Schlengerman's result (0.1 db/mm).

The concept of logarithmic decrease in the amplitude of EMI signal versus the distance from PZT is very important as it will help to determine the size or severity of the damage. For instance, considering Figure 4-66, the total RMSD change for damage at 6 cm from the PZT is approximately three times that of a similar damage at 30 cm from the PZT. Figure 4-69 compares damage D5 at 6 cm from PZT 1 with Damage points D9 and D10 at 30 cm from PZT1.

Figure 4-71 RMSD-S of PZT 1 after Damage points D5, D9 and D10

Even from the RMSD-S of PZT 1 alone, it is obvious that Damage D5 is at 15 cm or closer to PZT as high frequency range of (F) sensed the damage and Damage points D9 and D10 are further away at 25 to 35 cm from PZT 1. Since both D9 and D10 were sensed in frequency ranges (A) to (D), they should be at similar distance to PZT 1. D10 shows larger RMSD-S changes compared to D9, indicating that D10 is severer. However, without considering the logarithmic reduction in total RMSD, it is difficult to differentiate the severity of D5 and D10 which are different in both severity and location. The total RMSD of damage D5 is 1.49 percent and that of damage D10 is 0.95 percent. It seems that D5 is severer than D10 by conventional RMSD technique, but it is not true. By using the results from Figure 4-68, the total RMSD of D5 (at 6 cm) should be around three times that of D10 (at 30 cm). However, it is only about 1.5 times (1.49%/0.95%). This implies that D5 is a smaller damage compared to D10 or D10 is a severer damage compared to D5. Therefore, by pre-calibrating the relation between the RMSD values and the distance from PZT and considering Eqn. (4.3), a good assessment of damage severity can be achieved. However, more parametric studies are needed for detailed guideline.

The present experimental study was carried out at the laboratory temperature. The variation in temperature is minor and its effect on admittance was ignored. For real-world applications involving temperature variations, the study presented in this thesis

should be further extended by considering the effect of temperature on the EMI signature and compensating this effect by certain algorithms (Park et al., 1999; Bhalla et al., 2001) on the RMSD-S readings.

4.5.4 Concluding remarks

In this section, the RMSD-S values of PZT transducers were used in the health monitoring of a steel structure. The sensing regions of PZT for six frequency ranges were measured. The EMI signatures from multiple PZTs were used to study the location and severity of damage. With one-dimensional arrangement of 3 PZTs and monitoring voltage of 2 volts, an area of 150×210 cm was monitored. Two dimensional arrangements of PZTs will increase the accuracy of damage detection and by increasing monitoring voltage; a larger sensing region can be achieved.

The experimental results show that the RMSD-S of multiple PZTs combined with the logarithmic attenuation of ultrasonic wave is robust and sensitive for damage assessment of steel structures. A complete diagnostic study on damage severity and location is possible by the RMSD-S results derived from an array of PZT transducers. Automated software could be developed to acquire the signatures, compare the RMSD-S results and deduce the condition of structure without the need of professional supervision. The proposed method is thus promising for damage identification in the EMI based SHM.

CHAPTER

5

REUSABLE PZT TRANSDUCER FOR MONITORING INITIAL HYDRATION OF CONCRETE AND STRUCTURAL HEALTH

5.1 Introduction

As mentioned earlier, surface-bonded PZT transducers have been commonly used for monitoring hydration of concrete or structural health monitoring. A few researchers have studied the applicability of PZT transducers embedded in concrete structures (Chen et al., 2006; Song et al., 2008b; Lei and Zongjin, 2008; Annamdas and Rizzo, 2010; Meng et al., 2010). PZT transducers are relatively cheap compared to other sensors available for SHM. However, they seem still expensive for some of applications involve repetitive use such as monitoring the hydration of concrete in precast plants. Furthermore, smart aggregates (prefabricated embedded PZT transducers) are not sensitive when using EMI to monitor concrete hydration and direct embedding of brittle PZTs in concrete is not feasible for commercial concrete casting plants. Thus, development of reusable PZT transducers which can be detached from structure for future use seems interesting and valuable.

The hydration of cement is a complicated physical and chemical process which determines the microstructure of the concrete. Various methods have been developed

to monitor and characterize the hydration of cementitious materials (Lei and Zongjin, 2008). During the construction of a concrete structure, strength monitoring is important to ensure the safety of both personnel and the structure itself. The collapse of several structures during their construction highlights the importance of early concrete strength monitoring (Song et al., 2008b). Furthermore, to increase the efficiency of *in situ* casting or precasting of concrete, determining the optimal time of demolding is very important for concrete suppliers. In the first few hours after mixing, the fresh concrete gradually achieves solid properties with reasonable compressive strength. Due to different type and amount of cementitious materials, concrete additives (e.g., retarder, deicing) and curing temperature, different rates of hardening are expected. In addition, some other factors like the quality of the cementitious materials further increase the uncertainty in determining the appropriate time for demolding of concrete.

The ultrasonic technique, which needs to have access to both sides of the structure, has been employed to monitor the hydration process (Lee et al., 2004; Ye et al., 2004; Voigt et al., 2006), and any gap because of shrinkage or framework movement can significantly affect the results. A surface-bonded PZT transducer has been used for hydration monitoring (Soh and Bhalla, 2005; Shin et al., 2008; Tawie et al 2010). However their method could not monitor the early hydration. The concrete needed to be hardened, followed by surface drying and one more day for hardening of the epoxy. This means that the first three days of hydration could not be monitored. Concrete is the most widely used construction material because it is relatively strong and cheap to produce. The notion of embedded PZT transducers for ultrasonic application or as smart aggregates has been reported in the literature (Song et al., 2008b; Lei and Zongjin, 2008). For these methods, at least two PZT transducers, one as sender/actuator and the other as receiver/sensor need to be permanently buried inside the concrete. PZT transducers are cheap but compared to concrete materials, they are still expensive. For repetitive applications, such as in the precast industry, a method to reuse the PZT transducers is essential. Furthermore the buried transducers are not sensitive enough for localized monitoring and the wire connections can easily be damaged during casting, due to framework movement or shrinkage cracks. Other methods such as thermal analysis, x-ray diffraction and scanning electron microscopy,

non-contact electrical resistivity and dielectric constant measurement have been reported in the literature (Sun, 2008; Xiao and Li, 2008).

In this chapter, a reusable PZT transducer setup for monitoring hydration of concrete and structural health is developed, where a piece of PZT is bonded to a piece of aluminum or plastic enclosure with two bolts tightened inside the holes drilled in the enclosure. During concrete casting, the bolts and the bottom surface of the enclosure is set to penetrate part of the fresh concrete. At different stages of the first 48 hours after casting, the PZT admittance signatures are acquired. RMSD indices are calculated to associate the change in concrete strength with changes in the PZT admittance signatures. For the three test samples, the reusable PZT setups are not removed from the structure after curing of concrete. The samples are further tested under gradually increasing compressive loading to examine the capability of the reusable setup for structural health monitoring (SHM). The results show that the developed reusable setup is able to effectively monitor the initial hydration of concrete and its structural health. It can also be detached from the concrete for future re-use.

5.2 Experimental study

5.2.1 Reusable PZT setup

The acquired signature of the PZT is sensitive to moisture and will change if the PZT is submerged in water. In addition, the enclosure in which the PZT is bonded on needs to be strong enough such that it can be easily detached from the hardened concrete without any damage to the PZT or the enclosure. For these reasons, commercial aluminum and plastic enclosures with dimensions of $50 \times 45 \times 30$ mm and a thickness of 1.5 mm were used. Two holes were drilled at the bottom of the enclosure and two bolts were tightened inside to ensure a solid connection of the reusable setup to the concrete. After concrete hardening, the two bolts will be unscrewed and the PZT and enclosure will be removed for future applications. Cement hydration residues will remain on the surfaces of the aluminum enclosure, so the repeatability will be slightly affected after a few reuses.

In the reusable transducer setup, there are two holes at the bottom of the enclosure where water may permeate into the enclosure along the bolts, resulting in circuit shortcut during PZT admittance measurement. To avoid this problem, a waterproofing agent called Plastic DIP (Plastic-DIP, 2010) was used for waterproofing the PZT transducers. This procedure results in much better signature repeatability for repetitive use; however the PZT sensitivity reduces due to the damping effect of the waterproofing layer.

PZTs with two different sizes of $20 \times 20 \times 0.5$ mm and $20 \times 20 \times 2$ mm developed by PI Ceramic Co. (PI-Ceramic, 2010) were used in this experiment. A two-component adhesive, 3M's DP 460 Epoxy recommended by Smart Material Co. (Smart-Materials, 2010) were used to attach the PZTs to the enclosures. Figure 5-1(a) shows three developed reusable PZT setups using the aluminum enclosure. Figure 5-1 (b) shows two reusable PZT setups with waterproofing coating on the plastic enclosure. And Figure 5-1 (c) illustrates the schematic of the sensor setup.

Figure 5-1 Developed reusable PZT setups

5.2.2 Initial hydration tests

In this work, the same mix proportion was cast four times (called Cast 1 to 4) and the same reusable PZT setup called Setup 1a, was used to evaluate the hydration rate. This process is meant to ensure the reusability of the setup for hydration monitoring. To check the repeatability from one sample to another, in mix Cast 4, a bigger volume was cast to compare the acquired signatures obtained from different reusable setups.

Two more mixes (Casts 5 and 6), one with retarder and the other with faulty retarder which leads to a very weak hydration in the first 48 hours, were also cast. The results from retarder and faulty retarder specimens are compared to show the ability of the developed setups to distinguish various rates of hydration. The experimental work is summarized in Table 5-1. Figure 5-2 shows the monitoring setup used in Cast 4.

Figure 5-2 Monitoring hydration rate with reusable PZT transducers in Cast 4

Table 5-1 Summary of experimental work

Casting name	Number of samples	Name & type of sensors * a-Aluminum enclosure * p-Plastic enclosure * Sb- surface-bonded PZT	Purpose
Cast 1	1	Setup 1a	Study the reusability of the sensor
Cast 2	1	Setup 1a	
Cast 3	1	Setup 1a	
Cast 4	3	Setup 1a, Setup 2a, Setup 3a	Study the repeatability of results from one setup to another
Cast 5	1	Setup 1a	Retarder
Cast 6	1	Setup 1a	Faulty retarder
Cast 7	1	Setup 4p, Setup 5p	Test not directly under loading
Cast 8	2	Setup 4p, Setup 5p, Sb1,Sb2	Test directly under loading

5.2.3 Structural health monitoring (SHM)

For the three samples in Casts 7 and 8, the reusable PZT setups were not removed from the structure after curing. These three samples were further tested under normal laboratory compressive loading. Surface-bonded PZTs were additionally bonded to the two samples in Cast 8 to compare the sensitivity of surface-bonded PZTs with the reusable setups for SHM. The tests were performed in two conditions of cyclic and on-hold loading. As shown in Figure 5-3, for cycling loading, two reusable setups were installed on one rectangular sample with dimensions of $100 \times 100 \times 500$ mm from Cast 7 and neither of them was under direct loading. After recording the initial signatures, the sample was loaded till 10 kN, then the load was released and the PZT admittance signature was acquired. The sample was further loaded to 20 kN, 30 kN and finally till failure, and each time the load was released before recording the EMI signature.

Figure 5-3 Cycling loading setup for Cast 7

The two 100 mm cube samples from Cast 8 were tested under on hold loading, *i.e.*, after acquiring the initial signature, the sample was held under 1, 10, 20, 30 kN and till failure and the signatures were obtained without releasing the load. For each sample, one reusable setup and one surface-bonded PZT transducer were attached to the structure. Both the reusable setup and the surface-bonded PZT were under direct loading area in fairly equivalent distance from the loading point on two opposite sides. Figure 5-4 (a) shows the reusable PZT transducer and the surface-bonded PZT on the sample. Figure 5-4 (b) shows one of the samples during on hold compressive loading. Even after failure of the sample, the reusable setup can be detached from the

structure without any damage. Figure 5-5 shows the reusable setup un-screwed and detached from the structure.

(a)

(b)

Figure 5-4 (a) Reusable PZT transducer and surface-bonded PZT transducer, (b) 100 mm cube sample under on hold loading

Figure 5-5 Reusable setup detached after compressive loading

5.3 Results and discussions

5.3.1 Repeatability and reliability

Repeatability of the results is a key criterion for reliability of any health monitoring technique. The repeatability of results could be affected by PZT transducers quality, human errors during production of reusable setup including the epoxy thickness and modulus of elasticity and finally damage during the initial hydration or health monitoring process. For all the setups, 2-meter thin wires have been soldered to the PZTs and their signatures were obtained prior to attaching them to the enclosure. Figure 5-6 shows the free signatures acquired from five pieces of 2 mm thick PZT transducers. Apparently, the signatures are well repeatable which shows the high quality of the PZT transducers. Although near resonance peak (83 kHz), there is around 10 percent variation in amplitude.

Figure 5-6 Free signatures obtained from PZT transducers

Figure 5-7 Repeatability of signatures for three setups

The signatures should also be repeatable in the same initial condition for all the reusable setups. Figure 5-7 shows the repeatability of the initial signatures for three setups with 0.5 mm thick PZTs. Although the thickness of the epoxy and the quality

of bonding may vary from one PZT to another, but with careful preparation, repeatable signatures for different setups can be obtained. For commercial production under controlled environment, repeatable signatures could be obtained. The setups created with 0.5 mm thick PZTs were not used in this work.

The signature obtained at the initial condition should be similar to that obtained after the setup is used and removed from several tested sample. To verify this, Setup 1a was used four times to check the reusability of the setup. Figure 5-8 shows the initial signature of this setup and those after the setup was used and detached from several concrete specimens.

Figure 5-8 Initial signatures obtained from setup 1a at initial condition and after removing from samples

As shown in Figure 5-8, the process of removing the aluminum enclosure from one concrete specimen and reusing it in another specimen has a minor effect on the signatures. The repeatability of signature is very good, even if no waterproofing coating was applied on this setup. For the plastic enclosure with waterproofing coating used in Casts 7 and 8, better repeatability was obtained.

Figure 5-7 shows the signatures acquired from a thinner PZT ($20 \times 20 \times 0.5$ mm) and Figure 5-8 shows those acquired from a thicker PZT ($20 \times 20 \times 2$ mm). It can be seen that the magnitude of the signature for the thicker PZT is around four times of that for the thinner PZT. This indicates that the sensitivity of the thicker PZT is higher than the thinner PZT. As for controlled bonding conditions, the repeatability of the signatures for the thicker PZTs is also better. The above results demonstrate the reliability of developed reusable PZT setup for initial hydration and structural health monitoring of concrete.

Furthermore, Figure 5-9 compares the signatures just after installing the same setup inside different concrete specimens. As can be seen, these signatures are quite repeatable, even though they were obtained from four different mixes cast at different times. Comparing Figures 5-8 and 5-9, it is obvious that the magnitude of the signature reduced after the reusable setup was inserted in the fresh concrete, due to the damping effect of the soft fresh concrete.

Figure 5-9 Initial signature obtained from setup after installing inside the concrete

5.3.2 Monitoring initial hydration of concrete

Slump is the measure of the fluidity of concrete. Depending on the amount of water content in the aggregates, the size of aggregates, the temperature during casting and other parameters, the initial slump of concrete can change from one mix to another though the mix proportion is the same. Even the delay time before casting can change the slump of concrete. To eliminate the initial variation of water content and slump from one sample to another, the signatures were obtained from the third hour onwards after casting. After that, the signatures were acquired every three hours. It means that the signatures of the structure at 3, 6, 9,..., 48 hours were acquired for comparisons. Figure 5-10 shows the typical variation of the signatures in the first 24 hours for one concrete specimen, where the initial signature was obtained just after the PZT setup was installed on the mix.

Figure 5-10 Variation of PZT signatures at different hydration time

As shown in Figure 5-10, as time passes, the concrete becomes stronger and stronger and, as expected, the signature shifts to the right and the conductance values reduces. Generally, if the host structure becomes stronger, implying less vibration

freedom for PZT, the peaks in signature which correspond to natural frequencies of the structure will shift to the right. Also if the PZT is connected to a structure, the magnitude of peaks will decrease as compared to the free PZT signature. On the other hand, if there are cracks or damage in the host structure, the peaks of the signature will shift to the left due to the reduction in the structural stiffness. However, it may not be true for all the peaks in the signature. Figure 5-11 illustrates the above points. Curve (1) in Figure 5-11 shows the free signature obtained from 2 mm thick PZT. Curve (2) shows the signature after waterproofing the PZT surfaces (except one surface). Due to the addition of waterproofing, the overall setup became softer and the peak of signature shifted to the left. However, due to the damping effect induced by the waterproof coating, the magnitude of peak decreased. Curve (3) shows the signature after installing the PZT setup in the concrete structure. Both stiffness and total mass increased, therefore the peak of signature shifted to right and the magnitude of peak decreased. Finally, Curve (4) shows the EMI signature after loading. There were numerous cracks in the concrete sample which made it weaker, thus the peak shifts to the left.

Figure 5-11 Variation of PZT signatures in different conditions

Figure 5-12 Repeatability of RMSD for same mix proportion

The RMSD values based on comparison between the signatures measured at different measurement points and the signature at the third hour are calculated for each mixes. Figure 5-12 shows the good repeatability of RMSD values for setup 1a in Cast 1 and 2.

The reusable PZT transducers are very sensitive to small changes in free condition (as presented in Figure 5-8). When the reusable PZT transducer is detached from the structure, some residual hydrated cement may remain on the bolts or sides of the container. This small variation compared to initial condition caused noticeable change in the EMI signature.

However, as shown in Figure 5-8, after each re-use, the peak amplitudes in EMI signatures were closely matched. For instance, the highest peak in the EMI signatures for the original condition, reuse 1, reuse 2, and reuse 3 were 0.012, 0.011, 0.014, and 0.011, respectively (approximately 10 percent variation). When the reusable PZT transducer was inserted in fresh concrete, this variation was significantly reduced. As shown in Figure 5-9, the highest peak in the EMI signatures for all four cases was 0.007.

The repeatability of the results for monitoring the early hydration of concrete was presented in Figure 5-12 for two repetitive measurements. The RMSD readings for the two measurements were closely matched (variation less than 3 percent). Therefore, quantifying the exact changes for reusable PZT transducer in free condition (as it was presented in Figure 5-8) may not provide a useful basis to evaluate the repeatability of results for the reusable PZT transducer.

As shown in Figure 5-12, the RMSD value after 12 hours of casting does not change significantly where the baseline signature is measured at the third hour after casting. Thus, for this mix, 12 hours curing was enough to remove the molds. However, if the RMSD values are calculated based on the difference between two consecutive signatures, the continuous progress of hydration can be observed, as shown in Table 5-2. The signature at the 24th hour varies by 11.8 percent as compared to that at the 12th hour, and the signature at the 48th hour varies by 6.12 percent as compared to that at the 24th hour, though the RMSD compared to the third hour does not change significantly.

Table 5-2 Continuation of hydration by comparing the signatures in various hours

Signature at Time:	RMSD change (%) Compared to 3rd Hour:	Compared to Hours:	Time difference (Hrs)	RMSD change (%)	Repeatability (%)
12	26.5	3	9	26.5	0.7
24	25.7	12	12	11.8	0.3
48	28.2	24	24	6.12	0.12

As mentioned in Section 5.2.2, two more mixes (Casts 5 and 6), one with retarder and the other with faulty retarder were cast in order to study the ability of the reusable PZT setup for monitoring different hydration rates. The RMSD changes for these two mixes in comparison to the normal concrete are illustrated in Figure 5-13.

Figure 5-13 Effect of retarder and faulty retarder on hydration rate

It can be seen from Figure 5-13 that the concrete containing retarder gains strength rather gradually, hence to safely remove the molds, the minimum curing time is around 36 hours. For the faulty retarder, the RMSD changes show that the concrete undergoes some initial changes but progresses at much slower hydration rate.

The criteria could be set based on the total RMSD changes and rate of the change in the RMSD values. For instance, it could be set as follows:

- 1) The total RMSD changes for reusable PZT transducer should be larger than 20 percent compared to the third hour; and
- 2) The rate of RMSD change per hour (two consecutive readings) should be less than 1 percent.

According to above criteria, the demolding time is 12 hours and 36 hours for the mixes without and with retarder respectively. However, detailed experimental work is needed to fine tune the criteria for real-world commercial application.

5.3.3 Structural health monitoring

As mentioned in Section 5.2.3, the tests were performed under two conditions of cyclic loading on the sample from Cast 7 and on-hold loading on the two samples from Cast 8. Table 5-3 shows the summary of the RMSD values for two reusable setups installed in the sample under cyclic loading. Neither of them was under direct loading but setup 5p was slightly nearer to the center of loading.

Table 5-3 RMSD values of two reusable PZT setups

Loading Level (kN)	Setup 4p (RMSD %)	Setup 5p (RMSD %)
0	0	0
10	5.8	9.47
20	7.4	13.62
30	14.65	16.45

As shown in Table 5-3, the RMSD values are approximately in the same range, which shows the repeatability of the reading from one setup to another; and the results are not sensitive to very fine localized cracks very near to the PZT location. This is advantageous over surface-bonded PZTs, for which fine cracks very near to the PZT bonding location can cause large RMSD variations which may lead to misinterpretation of the condition of the monitoring region.

For the on-hold loading, both reusable setup and surface-bonded PZT transducers were under direct loading area in fairly equivalent distance from the loading point at two opposite sides. Table 5-4 shows the summary of RMSD values for the two samples. Two signatures were acquired from each setup before loading and RMSD for repetitive reading were around 1 percent for both the surface-bonded PZT and the reusable setup. As shown in Table 5-4, the reusable setup is sensitive for SHM and the RMSD values are comparable to those of the surface-bonded PZTs.

Table 5-4 RMSD values for reusable PZT setups and surface-bonded PZTs

On-Hold Load (kN)	Sample 1		Sample 2	
	Setup 4p	Sb1	Setup 5p	Sb2
0	0	0	0	0
1	7.73	6.21	7.96	6.95
10	14.34	11.95	10.86	13.19
20	17.04	15.2	39.5	17.29
30	45.96	21.3	59	33.61
40	60.34	85.17	61.51	100.42

Figure 5-14 compares the RMSD values for the reusable setup and the surface-bonded PZT in sample 1 from Cast 8.

Figure 5-14 Comparison of RMSD values for reusable PZT setup and surface-bonded PZT

In Figure 5-14, the RMSD of 30 kN load of the reusable setup is larger than that of the surface-bonded PZT, which shows the higher sensitivity of the reusable setup. This is because the reusable setup can monitor both surface and certain depth inside the structure because of the two bolts penetrating into the concrete. For the 40 kN load, the surface-bonded PZTs were detached with piece of concrete from the main concrete block (as shown in Figure 5-5, left) for both samples, causing dramatic change in RMSD values. However, the reusable setup was still in full connection with

the host structure. The above results show that the reusable PZT setup can be used for SHM effectively and it can also be detached from the structure for future application.

5.4 Concluding remarks

The reusable PZT setup developed in this study is able to effectively monitor the initial hydration of concrete and can be used for SHM. With a controlled bonding layer, the repeatability of PZT signatures is confirmed and thus the reliability of the reusable PZT setup. It is also found that thicker PZTs have higher sensitivity as compared to the thinner ones. The device can be easily reused for many times with minor changes in sensitivity and initial signature. Various rates of hydration as a result of using retarders were monitored using this reusable setup. The reusable PZT setup showed good consistency in RMSD values as compared to the surface-bonded PZT SHM. It can also be detached from the structure for future application. In this Chapter, the size of host structure is comparably small for SHM. Therefore, the reusable setups were directly under loading or very near to lading point. In next Chapter, the applicability of this setup for an actual-sized structure is studied.

CHAPTER

6

EXPERIMENTAL WORK ON EMBEDDED, REUSABLE AND SURFACE-BONDED PZTS BY USING EMI, WAVE PROPAGATION AND WAVE TRANSMISSION TECHNIQUES

6.1 Introduction

A full-scale experimental work is conducted with following objectives:

- (1) Study of applicability and limitations of installation methods of PZT transducers for monitoring initial hydration of concrete and structural health;
- (2) Verification of the RMSD-S based damage-assessment method for cracks caused by loading versus the artificial damage presented in Chapter 4.
- (3) Combination of smart aggregates (embedded PZT transducers) using the wave transmission technique with surface-bonded PZT transducers using the EMI or wave propagation techniques for concrete SHM.

There are three methods to install the PZT transducers to structures—namely, surface-bonded, reusable setup and embedded PZTs. The embedded PZTs and

reusable PZT setups can be used for concrete structures during construction. On the other hand, the surface-bonded PZTs can be installed on the existing structures. In this chapter, the applicability and limitations of each installation method are experimentally studied. An actual-sized concrete structure is cast, where the surface-bonded, reusable setup and embedded PZTs are installed. Monitoring of concrete hydration and structural damage is conducted by the EMI, wave propagation and wave transmission techniques.

All of the experimental results on damage severity and location presented in Chapter 4 were obtained by creating artificial damage using the drill, the hammer drill, and the cutter. Therefore, verification was needed of the proposed RMSD-S approach for detection of damage severity and location under actual loading with random crack propagation. In this chapter, the EMI signatures of surface-bonded PZTs are acquired and the RMSD-S values are calculated. The results are correlated with the damage on the structure.

PZT transducers are used for monitoring various engineering structures based on two principles: first, by using the wave propagation or the wave transmission technique for multiple PZTs; and second, by using the EMI technique or the pulse-echo technique for single PZT. Due to very high damping of concrete, the EMI technique can only monitor small and local areas in concrete structures. By using an impedance analyzer with an interrogation voltage of 2 volts, the sensing region is limited to 30 cm around PZT. The wave propagation technique with high actuation voltage can monitor a larger area. However, the results are significantly affected by the surface condition. In addition, the calculation of damage location and severity demands complex modeling of wave propagation, especially for concrete structures with rough surfaces and boundaries. On the other hand, the wave transmission technique using smart aggregates (embedded PZT transducer) can be employed to monitor very large areas with a reasonably low actuation signal. Analysis of the wave transmission signal provides a convenient way to detect the discontinuities within the structure. The combination of embedded smart aggregates transducers (using the wave transmission technique) with surface bonded PZTs (using the EMI technique or the wave propagation technique) can provide an effective method to study both the

local and overall conditions of the structure. Experiments are carried out on an actual-sized concrete structure to integrate these techniques for SHM.

6.2 Experimental work

6.2.1 Preparation of PZT transducers

A total of 12 PZT transducers with sizes of 20×20×0.5 mm were used in this experimental work. Four PZT transducers were fabricated as smart aggregate (Song et al., 2008b) and embedded inside of concrete during the casting. Figure 6-1 shows the production process for the smart aggregates. Hydration of concrete during production of smart aggregates was monitored by using the EMI technique. The results represent the case of directly embedding the PZT transducers in concrete. To fabricate reusable PZT setups, three PZT transducers were attached to plastic enclosures with sizes of 50×45 mm and thicknesses of 1.5 mm. The PZTs were waterproofed with Plastic DIP coating, and the enclosures' cover doors were closed before attaching it to structure. Figure 6-2 shows the waterproof coating of the reusable PZT transducers, while Figure 6-3 shows one reusable PZT transducer after closing the cover door.

(a)

(b)

Figure 6-1 (a) waterproof coated PZTs and the molds, (b) Smart aggregates during hydration and after demolding

Figure 6-2 Waterproof coating of reusable PZT transducers

Figure 6-3 A reusable PZT transducer

Five PZTs were attached to the surface after preparation of the concrete beam.

6.2.2 Beam preparation

In this step, a concrete beam with dimensions of 220×40×20 cm was cast. Table 6-1 presents the concrete mix design.

Table 6-1 Concrete mix design

Item	Quantity (kg/m ³)
Cement	500
Water	250
Coarse aggregate	700
Fine aggregate	800

The water curing was limited to three days and the measured compressive strength was 40 MPa. The beam was designed as a single reinforced rectangular section under

bending. Two #16 rebars with nominal area of 200 mm^2 were placed under tension, and two #13 rebars were placed under compression. Five strain gauges were attached to the tension rebars. Figure 6-4 shows the installation of the strain gauges. Figure 6-5 shows the installation of smart aggregate and the whole formwork.

Figure 6-4 Installation of strain gauge (left) and strain gauge protection (right)

Figure 6-5 Installation of smart aggregate (Left), whole formwork (Right)

As shown in Figure 6-6, three holes were created on one side of the formwork for installation of reusable PZT setups during casting.

Figure 6-6 Three holes created on one side of formwork for installation of reusable PZT setup

Figure 6-7 shows reusable PZTs fixed in place with clay epoxy from the outside and inside of the formwork.

Figure 6-7 Reusable PZT setups installed, outside view (Left), inside view (Right)

Figure 6-8 shows the monitoring of beam during hydration. During the hydration period, the beam was monitored by the reusable PZT setups using the EMI technique, and by smart aggregates using the wave transmission technique.

Figure 6-8 Monitoring the hydration of concrete

Figure 6-9 shows the three reusable PZT setups on one side of the beam under loading. After concrete curing, five surface-bonded PZT transducers were installed on the opposite side of the beam, as shown in Figure 6-10.

Figure 6-9 Three reusable PZT setups on the beam

Figure 6-10 Five surface bonded PZTs on the beam

Finally, Figure 6-11 shows the schematic presentation of the beam and the locations of various PZT transducers.

Figure 6-11 Schematic presentation of the beam under loading

The beam was tested under two-point loading. The two loading points were 70 cm apart. As shown in Figure 6-11, the surface-bonded PZTs were attached at center of the beam (PZT3), and aligned to two loading points (PZT2 and 4) and near the two ends of the beam (PZT1 and 5). The four smart aggregates were installed inside the

beam, close to the tension rebar, at 20 cm and 80 cm from the central line of the beam. The strain gauges were attached to the rebar under tension (bottom of the beam) aligned with surface-bonded PZTs. The three reusable PZT setups were installed on the side opposite to the surface-bonded PZTs. One of them was at the center of the beam and the other two were aligned with the two loading points, as shown earlier in Figure 6-9.

Civil structures may undergo sudden overloading due to natural disasters or accidental loading during their lifetimes. It is important to evaluate the condition of the structure after overloading. A cyclic loading scenario is proposed in this study. Initially, the structure is loaded to 40 kN and unloaded. Then it is loaded to 80 kN and unloaded to 40 kN. The 40 kN load is considered the existing live load on the beam. Thereafter it is loaded to 100, 120, 140, 180, until failure at 240 kN, followed by releasing the load to 40 kN after each loading. These values are the central load generated by hydraulic jack which is applied to the structure at two loading points.

As mentioned earlier, five strain gauges were attached to tension rebars aligned with five surface-bonded PZTs. Strain gauge 3 was at the center of the beam. Strain gauges 2 and 4 were aligned with the two loading points, and strain gauges 1 and 5 were near two ends of the beam. Except for the 180 kN loading, after each loading and unloading to 40 kN, most of the cracks on the beam were closed and the beam returned to its original shape, indicating that the load-strain behavior of the beam was quasi-elastic. Figures 6-12 to 6-16 show all the strain gauge readings versus the applied load up to 180 kN (unloading to 40 kN afterward).

Figure 6-12 Readings of strain gauge 1

Figure 6-13 Readings of strain gauge 2

Figure 6-14 Readings of strain gauge 3

Figure 6-15 Readings of strain gauge 4

Figure 6-16 Readings of strain gauge 5

As shown in Figures 6-12 and 6-16, for strain gauges 1 and 5 near two ends of the beam, the behavior of the sections at locations of the two strain gauges was quasi-elastic with almost no residual strain up to 140 kN. However, slight residual strain was recorded after loading 180 kN. As shown in Figures 6-13, 6-14, and 6-15, after each loading, the amount of residual strain increases for strain gauges 2, 3, and 4. The maximum residual strain in the beam (at the middle part and measured by all three strain gauges) is around 400×10^{-6} . The readings for these three strain gauges were quite similar. This means that the moment was almost uniform in the middle of the beam, which was expected. Correlation of these loads with PZT readings will be presented in Section 6.3.

Figure 6-17 shows the readings of strain gauge 1 for the final loading step; i.e., the failure load of 240 kN. As shown, the slope of the loading curve changes after 180 kN, indicating that plastic strain has been developed in the beam. Therefore, significant amounts of residual strain were recorded after unloading to 40 kN (800×10^{-6}), and after completely releasing the load (400×10^{-6}).

Figure 6-17 Strain gauge 1 reading after failure

6.3 Results and discussions

In this section, the results for monitoring the hydration of concrete is presented first, followed by the results of monitoring the crack development when the beam is subjected to loading. The installation types of PZTs and monitoring techniques are also discussed.

6.3.1 Hydration of concrete

Hydration of concrete was monitored and studied through three procedures: (1) when the waterproofed PZT transducers were embedded in concrete during the production of smart aggregates, which represents the direct embedding of PZT in concrete; (2) when the reusable PZT setups were attached during the casting of the beam, which is similar to the study in Chapter 5; and (3) when the smart aggregates were embedded into the beam during casting. In procedures (1) and (2), the EMI technique was employed, and in procedure (3) the wave transmission technique was used. The results of procedure (2) are similar to those presented in Chapter 5, and hence will not be presented in detail here.

6.3.1.1 Direct embedding of PZT transducer in concrete

The EMI signatures of embedded PZT transducers are measured in the frequency range of 70 to 120 kHz to monitor the hydration of concrete. Figure 6-18 shows one typical admittance signature during the first 72 hours after casting. As expected, the signature peaks move to the right, which reflects the increase in the stiffness of the concrete. In addition, the reduction in the peak values indicates the decreased degree of freedom of PZT vibration.

Figure 6-18 Variation of signatures for embedded PZT transducer

Table 6-2 presents the RMSD changes of EMI signature compared to the previous readings; the total RMSD changes, as well as these two values divided by the delta time and total time, respectively. The delta time is the time difference between two consecutive readings as presented in column B of this table.

Figure 6-19(a) shows the total RMSD changes. Figure 6-19(b) shows the RMSD changes compared to the previous reading divided by delta time, and Figure 6-19(c) shows the total RMSD changes divided by total hydration time. Figures 6-19(b) and 6-19(c) reveal interesting information about the hydration of concrete. The rate of hydration increases from the third hour to nearly the seventh hour, followed by the decrease in hydration rate. The maximum changes occurred from the fourth hour to the seventh hour and the seventh hour to the tenth hour.

Table 6-2 RMSD results from embedded PZT transducer

A	B	C	D	E	C/B	E/D
Time	Delta time	RMSD (%) changes compared to previous reading	total time	Total RMSD (%) changes		
3	0	0.00	0	0.00	0.00	0.00
4	1	4.87	1	4.87	4.87	4.87
7	3	31.24	4	35.88	10.41	8.97
10	3	47.74	7	52.05	15.91	7.44
13	3	37.37	10	63.15	12.46	6.31
16	3	29.80	13	67.77	9.93	5.21
19	3	8.61	16	71.05	2.87	4.44
24	5	6.46	21	72.24	1.29	3.44
36	12	16.59	33	76.54	1.38	2.32
48	12	15.12	45	78.87	1.26	1.75
60	12	7.32	57	81.25	0.61	1.43
72	12	5.41	69	81.18	0.45	1.18

Figure 6-19 (a) Total RMSD changes, (b) RMSD changes compared to previous reading divided by delta time, (c) Total RMSD changes divided by total time

Figure 6-20 presents the RMSD changes in comparison to previous readings divided by delta time for both the embedded and reusable PZT transducers. As shown, the embedded PZT transducer is more sensitive to the hydration condition of the concrete. Although the reusable PZT transducer is less sensitive, it can be detached for future use.

Figure 6-20 Comparison between embedded and reusable PZT transducers

6.3.1.2 Monitoring hydration with smart aggregates

Smart aggregates are insensitive to the hydration condition of concrete using the EMI technique since the PZTs are already wrapped with a layer of concrete. However, they can be employed using the wave transmission technique. In this experiment, a 10 volts signal at constant frequency is sent from one smart aggregate (called the actuator/sender) and is acquired by one or more other smart aggregates (called the sensor/receiver). Figure 6-21 shows the maximum voltage received by smart aggregate 2 by setting smart aggregate 1 as the actuator.

Figure 6-21 Maximum voltage received by smart aggregate 2 by setting smart aggregate 1 as actuator

In a thick concrete section, the temperature of concrete may rise significantly during the initial hours of hydration. Variations in temperature will affect the reading of PZT transducers. As expected, Figure 6-21 shows an initial increase in voltage received by smart aggregate 2 due to the increase in temperature during the first few hours. The beam was water-cured for three days in the formwork and subsequently left in room environment to lose the excess of water. For health monitoring applications, PZT readings should be stable before the start of the loading test. The wave transmission signal depends on water content and it requires a longer time compared to the EMI signature to be stable. As shown, the reading was more or less stable after 10 days.

As shown in Figure 6-21, the maximum voltage acquired by the smart aggregate reduces with the curing time. Therefore, it is possible to monitor the hydration of concrete using this signal. However, calibration is needed to correlate the voltage with the concrete strength or water content in the concrete.

In the wave propagation technique, there is a time delay between the actuation signal and the signal received by sensors because the propagation of elastic waves takes time. The time delay increases with the distance between the actuator and sensor. However, for smart aggregates using the wave transmission technique, the signal transmits almost instantly. Thus, all the smart aggregates at different distances from the actuator receive the signal at the same time. Figure 6-22 shows the actuation signal from smart aggregate 1 and acquired signal by smart aggregate 2 two hours after casting. The actuation signal is scaled 0.1 times for comparison purposes.

Figure 6-22 Comparison of actuation signal and acquired signal

Figure 6-23 Comparison of the signal received after 2 hrs and 72 hrs by smart aggregate 2

It is difficult to control the thickness of the waterproof layer applied to PZT transducers. As a result, the sensitivity of smart aggregates varied from one to another. However, for one particular pair of smart aggregates, their initial transmitted signal decreases with the curing time and this pattern is consistent for all the smart

aggregates. Figure 6-24 shows the maximum signal acquired by smart aggregates 2, 3, and 4 at 60, 100, and 160 cm distances from smart aggregate 1, respectively.

Figure 6-24 Maximum signal acquired by smart aggregates 2, 3, and 4 at 60, 100, and 160 cm distances from smart aggregate 1, respectively

Figure 6-24 also illustrates the low attenuation of the wave transmission over the distance. This will make it possible to monitor a long distance with one pair of smart aggregates. Song et al. (2007) monitored a reinforced concrete specimen with a pair of smart aggregates six meters apart. The signal generated by smart aggregate 1 reached smart aggregates 2, 3, and 4 almost at the same time. Figure 6-25 shows the signal received by these aggregates. The velocity of transmitted waves in concrete can be calculated as follows (Büyüköztürk and Rhim, 1995):

$$V = \frac{c}{\sqrt{\epsilon_r}} \quad (7.1)$$

in which c is $3 \times 10^8 \text{ m/s}$ and ϵ_r is the dielectric constant of concrete. The dielectric constant of concrete is measured around 8 (Shen et al., 2008). The distance between smart aggregate 2 and 4 is one meter. The required time for wave transmission over this distance is 2.66×10^{-8} seconds. Therefore, all smart aggregates acquire the signal instantly.

The wave transmission signals were obtained at five frequencies: 30, 70, 100, 150, and 200 kHz. Depending on the frequency of the actuation signal, the amplitude of

acquired signal in transducers changes noticeably. Figure 6-26 shows the maximum amplitude of acquired signal by smart aggregate 2 by setting smart aggregate 1 as actuator for these frequencies. The first two natural frequencies of the free PZT are approximately at 83 and 120 kHz. This correlates with the large value of acquired voltage near 100 kHz because the PZT vibrates near resonance. However, regardless of the monitoring frequency, the amplitude of acquired signal decreases with the curing time.

Figure 6-25 Signal acquired by smart aggregates 2, 3 and 4

Figure 6-26 Variation of maximum voltage acquired at different frequencies

6.3.2 Structural health monitoring

After the concrete curing was completed, the beam was tested under two- point bending. As discussed earlier, the loads were applied in a cyclic pattern with magnitudes of 40, 80, 120, 140, 180 kN and finally until failure (240 kN). After each loading, the beam was unloaded to 40 kN, which represents the live load of structure. Figure 6-27 shows the overall experimental setup.

Figure 6-27 Overall experimental setup

The propagation of cracks was observed after each loading and marked on the surface of the beam. Figure 6-28 shows the cracks that developed between surface-bonded PZTs 1 and 2 after 240 kN loading. Figure 6-29 shows all the cracks that developed on one side of the beam after 240 kN loading.

Figure 6-28 Cracks developed between surface-bonded PZTs 1 and 2

Figure 6-29 All cracks developed on one side of the beam

In this section, the results obtained from various PZT transducers under different loads on the beam are presented. The results obtained from smart aggregates using the wave transmission technique are discussed first, followed by the results from the surface-bonded PZTs by the wave propagation technique. Finally, the EMI results for surface-bonded PZTs and reusable PZTs are presented.

6.3.2.1 Smart aggregates using the wave transmission technique

Figure 6-30 compares the signal acquired by smart aggregate 2 by setting smart aggregate 1 as actuator under 40 kN for the first loading step and under 40 kN after failure. Due to the crack opening in the structure, the continuity of the structure was affected and the amplitude of voltage acquired by sensors decreased. Figure 6-31 compares the actuation signal with the acquired signal under 40 kN loading for the first loading step. The actuation signal is scaled 0.1 times for comparison purposes.

Figure 6-30 Acquired signal under 40 kN for the first loading step and under 40 kN after failure

Figure 6-31 Comparison of auction signal with acquired signal under 40 kN loading

Figure 6-32 shows the location of smart aggregates and developed cracks on the beam. It can be observed that the area around smart aggregates 2 and 3 has many cracks since it is at the central part of the beam, which is subjected to the maximum bending moment.

Figure 6-32 Location of smart aggregates and developed cracks on the beam

Figure 6-33 compares the maximum voltage acquired by smart aggregate 2 when the loading on the beam was held and when the loading was released to 40 kN. It is apparent that the curve representing the released load has larger values. This is because when the beam was under loading, more cracks were open than when the load was released. Thus, the damage in the beam was more severe, which reduced the amplitude of voltage acquired by the sensor. In Figure 6-33, it is also shown that the amplitude of the acquired signal reduces with the increase in loading, for both cases—under loading and released loading. This is reasonable because with the increase in loading, new cracks may appear and old cracks may open further and propagate in the structure; i.e., the damage becomes more severe, reducing the amplitude of the signal.

Figure 6-33 Maximum amplitude of acquired signal under loading and released loading

It is apparent that the amplitude of the acquired signal directly correlates with the damage in the structure. Except for the final failure loading, after each loading and releasing the load to 40 kN, many cracks were closed due to material elasticity. The reduction in the amplitude of the acquired signal also depends on the number of cracks between the actuator and sensor. For example, as shown in Figure 6-32, the number and intensity of cracks developed between smart aggregates 3 and 4 are lower than those between 2 and 4.

Considering Case 1—: smart aggregate 4 as sensor and 2 as actuator—and Case 2—smart aggregate 4 as sensor and 3 as actuator—the effects of crack number and intensity on the reduction in signal amplitude can be observed. Figure 6-34 compares the reduction in signal amplitude under loading for the above two cases. Clearly the reduction for Case 2 is less than that for Case 1, owing to the lower number and intensity of cracks between smart aggregates 3 and 4.

Figure 6-34 Comparison of reduction in signal amplitude under loading between smart aggregates 3 and 4 and smart aggregates 2 and 4

6.3.2.2 Surface-bonded PZTs using wave propagation technique

The beam was also monitored by the surface-bonded PTZs using the wave propagation technique to study the development of cracks. The following five cases were studied using the wave propagation technique:

- Case 1, PZT 2 as actuator and PZT 1 as sensor (50 cm apart);
- Case 2, PZT 3 as actuator and PZT 2 as sensor (35 cm apart);
- Case 3, PZT 3 as actuator and PZT 4 as sensor (35 cm apart);
- Case 4, PZT 4 as actuator and PZT 2 as sensor (70 cm apart); and
- Case 5, PZT 4 as actuator and PZT 5 as sensor (50 cm apart).

The signals for distances greater than 70 cm were too weak for monitoring purposes; thus they are not included in the above five cases. The wave signals sent from actuators and received by the sensors for all five cases were recorded. A clear time lag between the actuation and sensing signals was observed due to the time of flight of the elastic waves propagating on the surface of the concrete. Figure 6-35 shows the actuation and sensing signals for cases 4 and 5, in which the actuation signal from PZT 4 is scaled 0.001 times for easy comparison. It can be seen that the amplitude of the acquired or sensing signal is significantly smaller than that of the

actuation signal, about 1/1000 of the actuation signal. This is attributed to the fast attenuation of surface elastic waves. By comparison, the attenuation of waves using the wave transmission technique is much less. The amplitude of sensing signal is around 1/50 of that of the actuation signal (see Figure 6-31).

Figure 6-35 Actuation and sensing signals in wave propagation technique

The sensing signals were recorded when the loading returned to 40 kN after each loading step. The summation of the square of the amplitude of the sensing signal during the first 0.05 second after the first wave reached the sensor is calculated after each loading step to study the crack development in the beam. The results of summation of the square of the amplitude are then normalized with that of no loading. Figure 6-36 shows the normalized results after each loading step for case 3. As shown, the normalized signal amplitude decreases considerably with the loading, indicating that surface wave propagation is very sensitive to the crack development on the surface of the concrete.

Figure 6-36 Normalized amplitude of sensing signal for Case 3

There is a sudden drop at loading step of 100 kN, as shown in Figure 6-36. This is because two critical cracks were developed between PZTs 2 and 3 after 100 kN loading. Figure 6-37 shows the area between these two PZTs after the failure loading of 240 kN.

Figure 6-37 Crack development between surface-bonded PZTs 2 and 3

Figure 6-38 shows the normalized signal amplitude for case 5. As shown, there are two sudden drops at the loading steps of 80 kN and 120 kN, indicating that critical cracks developed after the two loading steps. Figure 6-39 shows the crack patterns and development of two cracks on 80 kN and 120 kN.

Figure 6-38 Normalized amplitude of sensing signal for Case 5

Figure 6-39 Crack development between surface-bonded PZTs 4 and 5

Results for other cases are similar to those for cases 3 and 5 presented above. It can be concluded that the surface-bonded PZTs using the wave propagation technique are sensitive to the damage in the structure. However, it is difficult to identify the location of damage by the wave signal, which requires complex modeling of elastic wave propagation on the surface of the concrete.

6.3.2.3 Surface-bonded PZTs using EMI technique

In Chapter 4, artificial damage was created on the concrete surface for damage identification using the RMSD-S based method. This method is used here to assess

the actual damage (cracks) caused by the loading on the beam. EMI signatures in the range of 30 to 400 kHz of the surface-bonded PZTs were acquired in each loading step after the loading was released to 40 kN. Subsequently, the RMSD-S values for each sub-frequency range are calculated. The sub-frequency ranges (A) to (F) are defined in the same way as those in Chapter 4.

The effects of cracks developed in the area far from each PZT can be observed in the RMSD-S changes in low frequency ranges. Crack development close to PZT can be monitored by the RMSD-S changes in high frequency ranges. Here an area of approximately 10 cm around each PZT is considered close to that PZT. Thus, if there is any damage in this area, there should be a noticeable change in the RMSD-S at high frequency ranges.

Figure 6-40 Region close to PZTs 1 and 5

Figure 6-40 shows the region close to PZTs 1 and 5. It can be seen that no cracks developed close to these two PZTs even after the failure loading. Figure 6-41 shows the RMSD-S of PZT 5 at various loading steps. As expected, the RMSD-S values in high frequency ranges (C) to (F) are very small (<1%). However, the RMSD-S values in low frequency ranges (A) and (B) are noticeable, implying crack development far away from PZT 5, especially after the failure loading of 240 kN.

Figure 6-41 RMSD-S of PZT 5

Major cracks developed very close to PZT 2 after loading steps of 80 kN and 240 kN. The crack developed after 240 kN almost touched the PZT, as shown in Figure 6-42. Figure 6-43 shows the RMSD-S of PZT 2 after various loading steps. The crack developed after 240 kN significantly changed the RMSD-S in both low and high frequency ranges, due to its close proximity to PZT 2. The crack developed after 80 kN also significantly changes the RMSD-S in all frequency ranges except range (F). Due to the large magnitude of RMSD-S after 240 kN, the RMSD-S after 80 kN seems insignificant, but it is obvious compared to the RMSD-S after other loading steps. It is worth noting that the RMSD-S values after loading steps of 100 to 180 kN are smaller than that after 80 kN. This can be explained by two facts: (1) no major cracks developed around PZT 2 after 100 to 180 kN; and (2) the baseline for the calculation of RMSD-S is the EMI signature of the previous loading step.

Figure 6-42 Cracks developed close to PZT 2

Figure 6-43 RMSD-S of PZT 2

Figure 6-44 shows the cracks that developed close to PZT 3. Major cracks appeared after loading steps of 80 kN, 100 kN, and 240 kN. Thus, the RMSD-S values after these three loading steps are larger than the others, as shown in Figure 6-45. Since the cracks are not that close to PZT 3, compared with the cracks around PZT 2, the RMSD-S values are smaller.

Figure 6-44 Cracks developed around PZT 3

Figure 6-45 RMSD-S of PZT 3

Figure 6-46 shows the cracks that developed close to PZT 4. Major cracks appeared close to PZT 4 after 80 kN, 100 kN, and 140 kN. Figure 6-47 shows the RMSD-S of PZT 4. As shown, the RMSD-S for high frequency ranges of (D) and (E) changed more significantly for these loadings. Large cracks appeared far away from PZT 4 at 240 kN loading. Thus, the RMSD-S of PZT 4 shows change in low frequency ranges of (A) to (B) at 240 kN loading.

Figure 6-46 Cracks developed close to PZT 4

Figure 6-47 RMSD-S of PZT 4

The surface-bonded PZT using the EMI technique qualitatively determined the damage severity and location on the concrete beam. However, for a localized area such as a joint, the main concern would be the detection of major damage at the joint. Therefore, the RMSD-S technique can be utilized to distinguish between small cracks and large cracks in a defined localized area. This may avoid triggering the alarm due to an incipient crack very close to a PZT transducer location. Detailed experimental work, preferably on more complex structures involving joints, is needed to fully explore this condition.

6.3.2.4 Reusable PZT setups for SHM

Reusable PZT transducers were used to monitor structural health as presented in Chapter 5 (see Section 5.3.3). The reusable PZTs were installed on 100 mm cubes directly under compressive loading. It was shown that they were effective for monitoring of small specimens; however, such might not be the case for actual-sized structures. Therefore, three reusable PZTs are used here to examine if they are effective for actual-sized structures. As mentioned earlier, the reusable PZTs were installed on the side opposite to the surface-bonded PZTs for monitoring the crack development in the beam.

Figure 6-48 cracks developed around three reusable PZTs

Figure 6-49 shows the cracks that developed around three reusable PZTs. However, the RMSD-S results could not reflect the development of cracks, except for reusable PZT 1 where the cracks propagated beneath it. This is because the sensitivity of PZT is greatly reduced due to the plastic or aluminum enclosure used in the setup. Therefore, the reusable PZT transducers can only detect the damage if they are directly under loading or if the bonding of reusable PZTs to the structure weakens due to cracks. It is concluded that the reusable PZTs are not suitable for SHM of large structures. They are, however, suitable for hydration monitoring and can be easily detached from concrete for future use.

6.3.2.5 Combination of smart aggregates and surface-bonded PZTs

Consider the wave transmission results of smart aggregates presented in Figure 6-33. Due to the low attenuation of waves over longer distances, the signals acquired under loading can be used to assess the overall condition of the structure. On the other hand, the surface-bonded PZT transducers using the EMI or wave propagation techniques are not able to monitor the overall condition of the structure due to the high attenuation of elastic waves on the concrete surface. The combination of smart aggregates and surface-bonded PZTs seems promising.

Figure 6-49 Comparison of results from smart aggregates and surface-bonded PZTs

Figure 6-49 compares the normalized signals for surface-bonded PZTs using the wave propagation technique and smart aggregates using the wave transmission technique. Figure 6-49 shows readings for the released load condition (i.e., when the load was returned to 40 kN). As discussed in Section 6.3.2.1, before the load was increased to 180 kN, most of the cracks were closed when the load was released to 40 kN and the overall condition of the beam was sound. After loading to 100 kN and unloading to 40 kN, the cracks were closed and therefore, the change in the smart aggregate signal was minor.

The smart aggregates correctly identified the behavior and the readings were in line with the strain gauge readings and the visual inspection. As presented in Figure 6-33, under 80 kN and 100 kN load, the smart aggregate readings dropped by 10 percent and 23 percent, respectively. These reductions were due to the opening of the cracks, and the smart aggregate readings were in line with the strain gauge readings and the visual inspection. However, these readings jumped back as the load was released to 40 kN and the cracks were closed.

Major cracks formed on the surface of the beam at 80 and 100 kN around PZTs 2 and 3. These cracks resulted in reduction of wave amplitude received by PZT 2. Therefore, the surface-bonded PZTs successfully detected the existence of damage in their localized areas. Using the EMI technique, the surface-bonded PZTs are sensitive to the cracks developing around them. This makes the technique very suitable for monitoring the local areas. In some structures, such as column-beam load transfer systems, the safety of the joint is the most important. In fact, development of cracks or even failure of a beam may not be as disastrous as a failure in the joint. Combination of surface-bonded PZTs to monitor the critical joints (using the EMI or the wave propagation techniques) and smart aggregates to monitor large structural components (using the wave transmission technique) can be a promising approach for efficient and cost-effective SHM of large civil structures. The wave transmission signals of smart aggregates can be constantly monitored to evaluate the overall condition of structures online. If sudden variations in signal are observed, the EMI or the wave propagation signal of surface-bonded PZTs at important locations such as joints can be acquired to evaluate the amount of damage in those areas. Online monitoring using smart

aggregates can also help to detect the impact loading of structures at the same time (Song et al., 2008b).

6.4 Concluding remarks

A comprehensive experiment was carried out to study various installation types of PZTs for monitoring the hydration of concrete and the structural health by the EMI, wave propagation and wave transmission techniques. PZT transducers directly embedded in concrete structures can effectively monitor the hydration of concrete using the EMI technique. Reusable PZT setups are also suitable for monitoring the hydration of concrete. However, their sensitivity to structural damage is very weak. They can only monitor the cracks that propagate beneath them and weaken the bonding between them and the structure. Smart aggregates are capable of monitoring the hydration of concrete using the wave transmission technique. In addition, they can detect the discontinuities in the structure and monitor large areas in SHM applications. Surface-bonded PZTs using the EMI technique can monitor a limited area around the PZTs. They are sensitive to damage and can be used to identify the damage severity and location in close proximity, using the RMSD-S based method. Thus, they can be useful for monitoring the important components or critical parts (e.g., beam-column joints) with potential localized damage in the structure. Surface-bonded PZTs can monitor a slightly larger area using the wave propagation technique in comparison to the EMI technique. However, complicated calculation is needed to study the location and severity of damage. The combination of smart aggregates using the wave transmission technique to monitor the overall condition of the structure and surface-bonded PZT transducers using the EMI or the wave propagation techniques to monitor the important sections of structure can be an effective SHM method for large civil structures.

CHAPTER

7

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

7.1 Conclusions and contributions

The primary goal of this research is to address the current issues on modeling and applications of PZT and MFC for SHM. Towards this goal, extensive modeling and experimental work has been conducted.

- **Theoretical development of strain transfer model and modified EMI model**

The existing 1-D Bernoulli-Euler formulation for strain transfer has been modified to account for the strain inside the actuator. The model was then extended to the 2-D case, where the thickness and modulus of elasticity of epoxy layer can be considered. FEM modeling and experimental testing have been carried out and the results were compared with the analytical results. The experimental results validated the analytical model and FEM simulation. For quasi-static excitation, the 2-D Bernoulli-Euler model had better prediction ability compared to its 1-D counterpart, and the modified models helped to improve the accuracy of prediction. The results of FEM simulation

for both quasi-static and near natural frequency excitation were in good agreement with the experimental ones, showing its potential in modeling of the MFC actuation.

The existing EMI model for PZT transducers was based on the fully bonded assumption. However, it is not the case for real-world applications in which a PZT transducer is bonded to the structure with epoxy layer and the epoxy layer properties affect the sensitivity of PZT for SHM. The strain transfer model developed has been used to modify the existing EMI model for the inclusion of epoxy layer properties. A reduction factor was derived analytically to consider the epoxy layer properties. Parametric study was performed on the reduction factor. FEM simulation was conducted to investigate and verify the effects of the epoxy layer on the sensitivity of the PZT transducer. The analytical model developed for inclusion of epoxy properties in the EMI signature offers a close form solution that is applicable to host structures of any size. The results showed that the properties of the epoxy layer affect both the baseline and magnitude of peaks in the EMI signature. Both the analytical model and FEM simulation showed the considerable influence of the modulus of elasticity and thickness of epoxy on the sensitivity of the PZT for EMI applications. Inconsistency in the properties of two-component epoxies can significantly affect the monitoring results, especially in multiplexing PZT applications. Since the epoxy thickness has a significant effect on the sensitivity of PZTs, it should be carefully controlled to achieve repeatable results for structural health monitoring applications.

- **Identification of damage location and severity with PZT-based EMI**

To achieve high sensitivity to damage, high frequency signatures (>200 kHz) have been used to monitor the region close to the PZT location, while low frequency signatures (<100 kHz) have been traditionally ignored. However, it has been reported that the use of RMSD as the damage indicator cannot readily specify the damage location and severity due to the inconsistency in the RMSD results. In this work, a sub-frequency interval approach RMSD-S has been proposed to analyze the EMI signature of piezoelectric transducers. Experiments were carried out on actual-sized concrete and steel structures subjected to artificial damage. Compared with the conventional approach, which uses one RMSD value for the entire frequency range, the proposed technique is more reliable and robust for health monitoring of concrete

structures. The damage severity and location can be estimated by a single PZT transducer through the RMSD-S. As shown in Section 4.4.3, multiple PZTs can increase the accuracy of damage identification and provide larger sensing areas. It was observed that damage close to the PZT significantly changes the RMSD-S at high frequency range; however, the damage farther away from the PZT significantly changes the RMSD-S at low frequency range. Based on this observation, a damage identification scheme was proposed to study the location and severity of damage in concrete structures. Furthermore, the RMSD-S values of multiple PZT transducers were used in the health monitoring of a steel structure. The results showed that the RMSD-S is robust and sensitive for damage assessment of steel structures. A complete diagnostic study on damage severity and location is possible by combining the RMSD-S results derived from an array of PZT transducers. Automated software could be developed to acquire the signatures, compare the RMSD-S results, and deduce the condition of the structure without the need of professional supervision. The RMSD-S concept combined with the logarithmic attenuation of ultrasonic waves is promising for damage identification in the EMI based SHM.

- **Development of reusable PZT setup**

A reusable PZT setup for monitoring initial hydration of concrete and structural health was designed and fabricated, in which a piece of PZT was bonded to a metal/plastic enclosure with two bolts tightened inside of the holes drilled in the enclosure. During the concrete casting, the bolts and the bottom surface of the enclosure were set to penetrate part of the fresh concrete. With a controlled bonding layer, the repeatability of PZT signatures was confirmed, as was the reliability of the reusable PZT setup. It was also found that thicker PZTs had higher sensitivity as compared to the thinner ones. The device can be easily reused many times with minor changes in sensitivity and initial signature. Various rates of hydration as a result of using retarders were monitored using this reusable setup. The reusable PZT setup showed good consistency in RMSD values, as compared to the surface-bonded PZT for SHM of small concrete specimens. It can also be detached from the structure for future use.

- **Experimental study on embedded, reusable and surface-bonded PZTs using the EMI, wave propagation and wave transmission techniques**

A comprehensive experiment was carried out to study various installation types of PZTs for monitoring the hydration of concrete and the structural health by the EMI, wave propagation and wave transmission techniques. PZT transducers directly embedded in concrete structures could effectively monitor the hydration of concrete using the EMI technique. Reusable PZT setups were also suitable for monitoring the hydration of concrete. However, their sensitivity to structural damage was weak. They could only monitor the cracks that propagated beneath them and weakened the bonding between them and the structure. Smart aggregates were capable of monitoring the hydration of concrete using the wave transmission technique. In addition, they could detect the discontinuities in the structure and monitor large areas in SHM applications. Due to very high damping of concrete, the EMI technique could only monitor small and local areas in concrete structures. For surface-bonded PZTs using an impedance analyzer with an interrogation voltage of 2 volts, the sensing region was limited to 30 cm around the PZT. The PZTs were sensitive to damage, and can be used to identify the damage severity and location in close proximity, using the RMSD-S based method. Thus, they can be useful for monitoring the important components or critical parts (e.g., beam-column joints) with potential localized damage in the structure. Surface-bonded PZTs could monitor slightly larger areas using the wave-propagation technique in comparison to the EMI technique. However, complicated calculations are needed to study the location and severity of damage. On the other hand, the wave transmission technique using smart aggregates can be employed to monitor very large areas with a reasonably low actuation signal. Analysis of the wave transmission signal provides a convenient way to detect the discontinuities within the structure. The combination of smart aggregates using the wave transmission technique to monitor the overall condition of the structure and surface-bonded PZT transducers using the EMI or wave propagation techniques to monitor the important sections of the structure can be an effective SHM method for large civil structures.

In summary, this thesis has studied the current limitations and issues related to modeling and application of the EMI technique and proposed some solutions to

improve it. A refined model for the effect of epoxy thickness and modulus of elasticity for actuation and sensing was presented in Chapter 3. However, as discussed, even for a single sheet of two-component epoxy, the modulus of elasticity may vary significantly. In order to extend the modeling work presented in Chapter 3, a single-component epoxy or two-component epoxy with more reproducible mechanical properties is needed. Therefore, due to this limitation, it was not possible to consider the epoxy properties in other studies in this thesis. However, the work in Chapter 3 helped explain the discrepancies observed between the experiment and various EMI prediction models.

Two preliminary studies were presented in Sections 4.2 and 4.3, and the uncertainties and limitations of RMSD for analyzing the EMI results were highlighted. The RMSD-S was thus proposed to address these issues. The newly developed RMSD-S technique was compared with the conventional RMSD technique for the concrete structure in Section 4.4. Thereafter, the RMSD-S technique was utilized to study a steel structure, and the results are presented in Section 4.5. It was shown that this technique could qualitatively identify damage severity and location for artificial damage introduced on the surface. Moreover, the RMSD-S technique was utilized in Chapter 6 for damage detection of a concrete beam under actual loading.

In Chapter 5, a novel reusable PZT transducer was developed. The applications of the reusable PZT transducer to study the hydration of concrete and the concrete compressive strength directly under loading were presented. For these two applications, a limited frequency range was sufficient and RMSD-S of large frequency range could not provide additional information. However, the developed reusable PZT transducer developed could be utilized in other applications using the RMSD-S technique for health monitoring of smaller structures. The RMSD-S technique, however, is suitable to increase the sensing region and to identify damage severity and location.

7.2 Recommendations for future work

Despite the increasing research work on application of PZT transducers for SHM, real-world applications have not blossomed. In this work, extensive research was carried out to address current issues that limit the application of these transducers. From the experience of carrying out research in this field, the author believes that the present research work can be further extended as follows:

- (i) In Chapter 3, one- and two-dimensional strain transfer models with inclusion of an adhesive layer were developed. By incorporating the developed strain transfer model, the existing electromechanical impedance (EMI) model for SHM was improved. In the modified EMI model, a symmetrical piezoelectric transducer was considered. However, due to increasing numbers of unsymmetrical piezoelectric transducers such as MFC, further modification of the EMI model is needed.
- (ii) The study of inclusion of epoxy layer properties in the EMI model was presented in Chapter 3. The results showed that the properties of the epoxy layer affect both the baseline and magnitude of peaks in the EMI signature. Since the epoxy thickness has a significant effect on the sensitivity of PZTs, this work suggested that the thickness should be carefully controlled to achieve repeatable results for SHM applications. Therefore, study on alternative installation techniques and epoxy types that affect the sensitivity and reliability of EMI for SHM would be valuable. Alternatively, this problem may be resolved by examining the proposed hypothesis called “post-calibration process.” For instance, PZT A on structure one is used for calibration of damage severity and location. A standard non-destructive impact will be applied on the surface of structure one in healthy condition at one or more distances from the location of PZT A and the response of PZT A will be recorded. Various damage will then be introduced on the surface of structure one and the damage severity and location will be studied. The sensing region for sub-frequency intervals and critical thresholds for damage detection are determined. Thereafter, for repetitive application on the second structure, the same standard impact will be applied to the surface of structure and the responses of PZTs are recorded.

These PZT responses can be compared with PZT A to compensate for the possible variation in epoxy thickness and modulus of elasticity. The post-calibration process in particular can be used for the multiplexing of PZTs, with several PZTs attached to various parts of a structure. A systematic and extensive experimental study is required to investigate the hypothesis. The same hypothesis can be utilized to study and compensate the response due to the effect of temperature, in which the response of the PZT to a standard impact will be acquired at various temperatures.

- (iii) Identification of damage severity and location was presented in Chapter 4. The RMSD-S method developed increased the reliability and robustness of the PZT-based EMI technique for SHM. However, more parametric study on various conditions is needed to develop a reliable algorithm to correlate damage with RMSD-S for real-time online monitoring of structures. In addition, development of software for automatic data acquisition, analysis, and sending alarms to relevant personnel will definitely improve the applicability of the PZT-based EMI technique.
- (iv) As presented in Chapter 5, a reusable PZT transducer was developed. The reusable PZT transducer developed in this study was able to effectively monitor the initial hydration of concrete and could be used for SHM. However, detailed experiments are needed to calibrate the reusable PZT transducer for various applications.
- (v) As mentioned in Chapter 6, the combination of smart aggregates and surface-bonded PZT transducers could provide an effective SHM method for large civil structures. The smart aggregates can monitor the overall condition of the structure using the wave transmission technique and the surface-bonded PZTs can monitor the important sections of structure using the EMI or wave propagation technique. However, detailed experiments, preferably on more complex structures involving joints, are needed to fully explore the idea.

After analyzing the results of this study, the author strongly believes that there is great potential for SHM of large civil structures with piezoelectric transducers using the EMI, wave propagation and wave transmission techniques.

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APPENDIX: AUTHORS' PUBLICATIONS AND AWARDS

From this study

1. **Sabet Divsholi Bahador**, Yang Yaowen, “Health Monitoring of Steel Structures Using Sub-Frequency Electromechanical Impedance Technique”, *Journal of Nondestructive Evaluation*, 31(1), **2012**, pages 1-11. (<http://dx.doi.org/10.1007/s10921-012-0135-y>).
2. Yang Yaowen, **Sabet Divsholi Bahador** and Soh Chee Kiong, “A Reusable PZT Transducer for Monitoring Initial Hydration and Structural Health of Concrete”, *Sensors*, 10(5), **2010**, 5193-5208; doi:10.3390/s100505193. (<http://dx.doi.org/10.3390/s100505193>) (Citation by Scopus: 5).
3. Yang Yaowen, **Sabet Divsholi Bahador**, “Sub-Frequency Interval Approach in Electromechanical Impedance Technique for Concrete Structures Health Monitoring”, *Sensors*, 10(12), **2010**, 11644-11661. (<http://dx.doi.org/10.3390/s101211644>) (Citation by Scopus: 3).
4. Yang Yaowen, **Sabet Divsholi Bahador**, Tang Lihua and Lei Zhang, “Strain Transfer Models for Macro-Fiber-Composite Strain Actuators”, *Materials and Manufacturing Processes*, 25 (4), **2010**, pages 237 - 242. (<http://dx.doi.org/10.1080/10426910903425986>) (Citation by Scopus: 1).
5. **Sabet Divsholi Bahador**, Yaowen Yang, “Comparison of embedded, surface bonded and reusable piezoelectric transducers for monitoring of concrete structures”, SPIE, Smart Structures and Materials & Nondestructive Evaluation and Health Monitoring, Vol. 7981, **2011**, 7981181. (<http://dx.doi.org/10.1117/12.881471>).
6. **Sabet Divsholi Bahador**, Yang Yaowen, “Application of Reusable PZT Sensors for Monitoring Initial Hydration of Concrete”, Proc. SPIE, Smart Structures and

Materials & Nondestructive Evaluation and Health Monitoring, Vol. 7292, **2009**, 729273. (<http://dx.doi.org/10.1117/12.815877>) (Citation by Scopus: 2).

7. **Sabet Divsholi Bahador**, Yang Yaowen, “Application of PZT sensors for detection of damage severity and location”, Proc. SPIE, Smart Materials, Nano+Micro-Smart Systems, Vol. 7268, **2008**, 726813. (<http://dx.doi.org/10.1117/12.810696>) (Scopus citation: 2).

8. **Sabet Divsholi Bahador**, Yang Yaowen and Lei Zhang, “Strain transfer models for strain actuators”, Advanced Materials Research Vols. 47-50, **2008**, pp 254-257, First International conference on multi-functional materials and structures, 28-31 July 2008, Hong Kong. (<http://dx.doi.org/10.4028/10.4028/www.scientific.net/AMR.47-50.254>) (Scopus citation: 1).

9. **Sabet Divsholi Bahador**, Yang Yaowen, Li Bing, “Monitoring Beam-Column Joint in Concrete Structures Using Piezo-Impedance Sensors”, Advanced Materials Research Vols. 79-82, **2009**, pp 59-62. Second International Conference on Multi Functional Materials and Structures, Qingdao, China, 9-12 October, 2009. (<http://dx.doi.org/10.4028/www.scientific.net/AMR.79-82.59>),

10. **Sabet Divsholi Bahador**, Yang Yaowen, “Monitoring Hydration of Concrete with Piezoelectric Transducers”, 35th Conference on Our World in Concrete & Structures, **2010**, pp 41-48. (<http://cipremier.com/100035006>)

11. **Sabet Divsholi Bahador**, Yang Yaowen, “Combination of Embedded and Surface Bonded PZT Transducers for Concrete Structures Health Monitoring”, to submit.

12. **Sabet Divsholi Bahador**, Yang Yaowen, Lihua Tang, “Analytical and Numerical study on inclusion of epoxy layer in electromechanical impedance method”, to submit.

Other Publications from Master of Engineering

1. **Sabet Divsholi Bahador**, Jong Herman Cahyadi, "Concrete carbonation under wide range of conditions", August **2009**, ISBN: 978-3639192797, VDM Verlag Dr. Müller, Germany
2. **Sabet Divsholi Bahador**, Jong Herman Cahyadi, "Modeling of carbonation of PC and blended cement concrete", The IES Journal Part A: Civil & Structural Engineering, Volume 2, Issue 1, **2009**, pages 59 – 67 .
(<http://dx.doi.org/10.1080/19373260802518091>)
3. **Sabet Divsholi Bahador**, Jong Herman Cahyadi, "Effect of preconditioning of concrete under accelerated test", proceeding of 31st Our World in Concrete and Structures, August **2006**, Singapore, pp 127-134.
(<http://www.cipremier.com/page.php?72>).
4. **Sabet Divsholi Bahador**, Jong Herman Cahyadi, "The effect of environment conditions on concrete carbonation (numerical model)", The proceeding of the 5th conference on New Technologies for Urban Safety of Mega Cities in Asia, 16-17 November **2006**, Phuket, Thailand, pp 405-414.
5. **Sabet Divsholi Bahador**, Jong Herman Cahyadi, "Study on moisture transport and pore structure of PC and blended cement concrete by monitoring the weight loss during the drying process", 32nd Our World in Concrete and Structures, August **2007**, Singapore, pp 149-158.
6. **Sabet Divsholi Bahador**, Jong Herman Cahyadi, "Study on properties of the concrete contained Ground Granulated Blast furnace Slag", The First International Conference on Recent Advances in Concrete Technology, 19-21 September **2007**, Washington D.C., USA, pp 573-582.

7. **Sabet Divsholi Bahador**, Rahimi Arezoo, “Three years Natural carbonation of PC and Blended cement concrete in Singapore Exposure Condition”, 34th Conference on Our World in Concrete & Structures, 16 – 18 August, **2009**, Singapore.

Awards and Scholarships:

1. NTU (ARC) research Scholarship for PhD studies in Nanyang Technological University, Singapore from 2007 to 2010
2. A*-Star (IGS) scholarship for Master of Engineering (MEng) studies in Nanyang Technological University, Singapore from 2005 to 2007
3. M.C BAUCHEMIE Award 2006, 31st conference on our world in concrete and structures 16-17 August, 2006 for the paper “Effect of preconditioning of concrete under accelerated test”.
4. First place in structural light weight Concrete competition, second festival of Concrete, Mazandaran, Iran, 2005
5. First place in High strength and light weight Concrete competition, ICI concrete competition, Tehran, Iran, 2004