Structural health assessment of 3D simple reinforced concrete bridge girders using FE-ANN procedure

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Presentation Overview

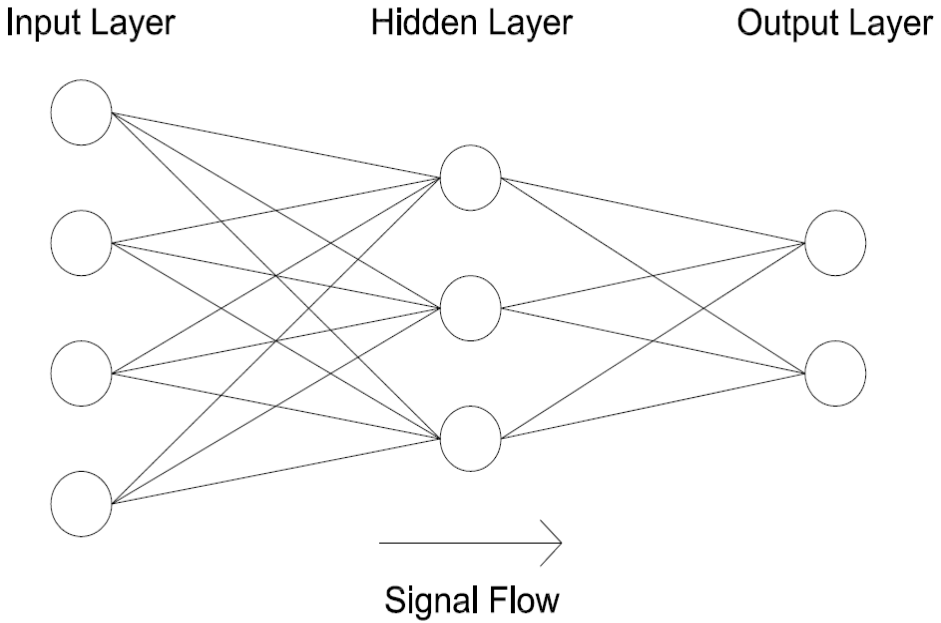
1. Introduction
2. Artificial Neural Networks (ANNs)
3. Generation of Reinforced Concrete Beam Database
4. ANN Modeling for Structural Health Prediction
5. Results and Discussion
6. ANN User Interface Application
7. Conclusions and Recommendations
8. Acknowledgements
9. Questions

1. Introduction

- Structural Deterioration of Aging Infrastructure
- Structural Health Monitoring (SHM) for Damage Evaluation
  - Visual Inspection and Condition Rating
  - Alternative SHM Techniques
- ANN Approaches for Structural Health Prediction
  - Al-Rahmani, Rasheed, and Najjar (2013, 2014)

2. Artificial Neural Networks

- Definition
- Structures
  - Feedforward (Static)
  - Recurrent (Dynamic)
- Learning Techniques
  - Supervised
  - Reinforcement
  - Unsupervised



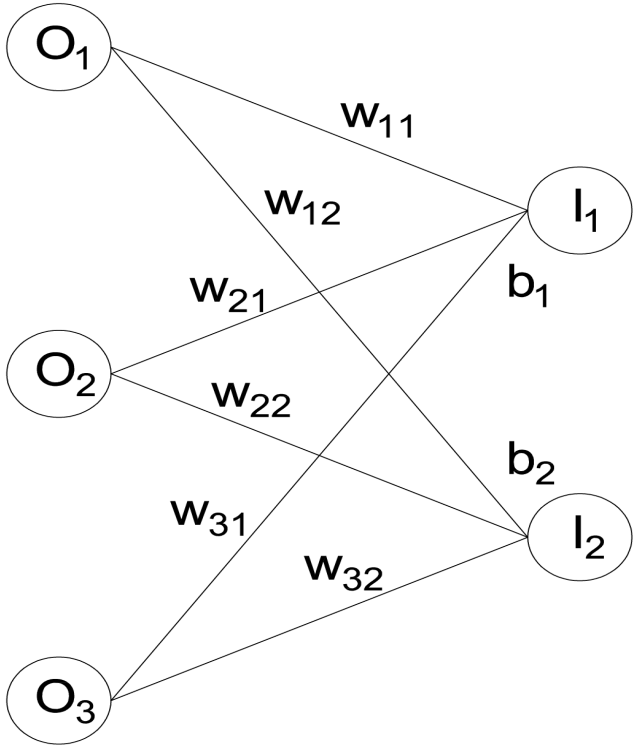
2. Artificial Neural Networks

- Data Preparation
  - Analytical or experimental databases
  - Training, testing, and validation datasets
  - Input and output parameter range expansion

2. Artificial Neural Networks

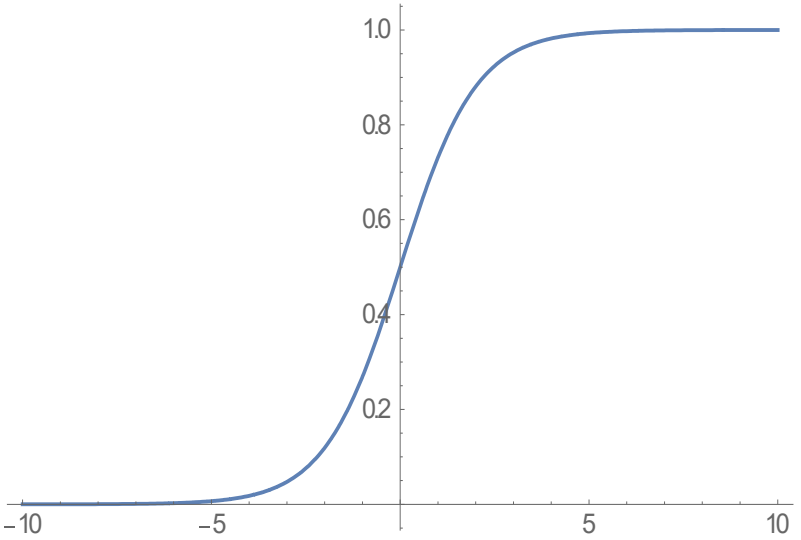
- Training Procedure
  - Normalization of input parameters
  - Layer-to-layer function

$$I_j = \sum_{i=1}^{n} w_{ij} O_i + b_j$$



- Training Procedure
  - Activation Function

$$O_j = f(I_j) = \frac{1}{1 + e^{-I_j}}$$



- Training Procedure
  - Convergence to solution
  - Maximum number of hidden nodes (MHN)

$$MHN = \frac{TR - O}{I + O + 1}$$

- Optimal Model Selection Criteria

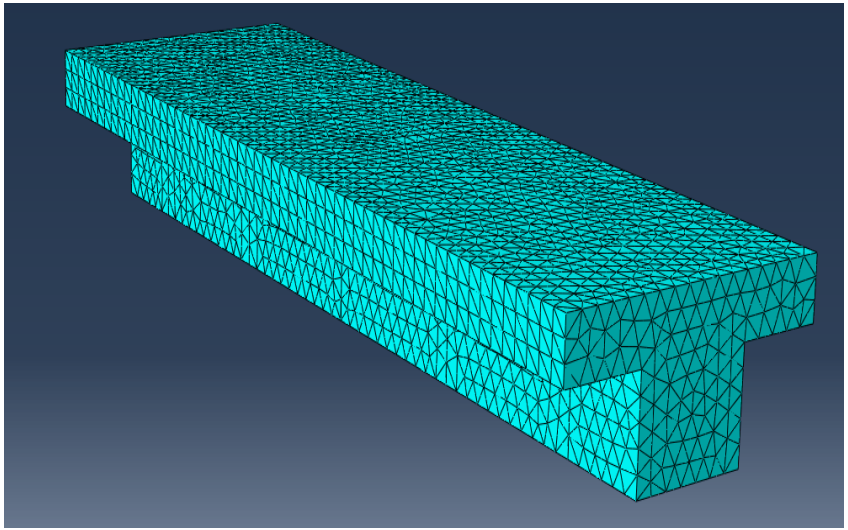
$$R^2 = \sum^{o} \left(\frac{n \sum^{n} xy - \sum^{n} x \sum^{n} y}{\sqrt{n \sum^{n} x^2 - (\sum^{n} x)^2} \sqrt{n \sum^{n} y^2 - (\sum^{n} y)^2}} \right)^2 \Big/ o$$

$$MARE(\%) = \frac{\sum^{o} \sum^{n} \left(\frac{|y - x|}{x} \times 100 \right)}{o * n}$$

$$ASE = \frac{\sum^{o} \sum^{n} (y - x)^2}{o * n}$$

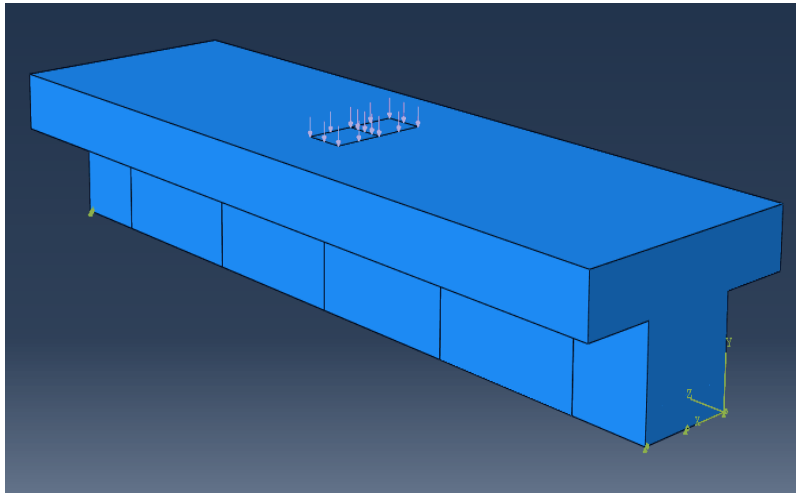
3. Generation of Reinforced Concrete Beam Database

- FE Analysis Software Program
  - Abaqus FEA version 6.13-2
- 3D Simply-Supported Reinforced Concrete T-beams Models
- Material Models
  - Concrete: ν = 0.2, $E = 4{,}700\sqrt{f_c'}$
  - Steel: ν = 0.3, E = 200,000 MPa
- FE Mesh
  - 10-node quadratic tetrahedral (C3D10) concrete elements
  - 3-node truss (T3D3) steel elements



3. Generation of Reinforced Concrete Beam Database

- Stiffness Nodes
  - 100 kN load applied at each stiffness node in turn and deflection measured
  - Load applied as small area load to avoid localized relative deflections
  - Al-Rahmani (2012) found that 9 stiffness nodes provided optimal results
- Cracks modeled as extruded cuts in beam web
  - Cracks limited to 0.06-0.94 of beam span length



3. Generation of Reinforced Concrete Beam Database

- Beam Stiffness
  - Stiffness at each node calculated

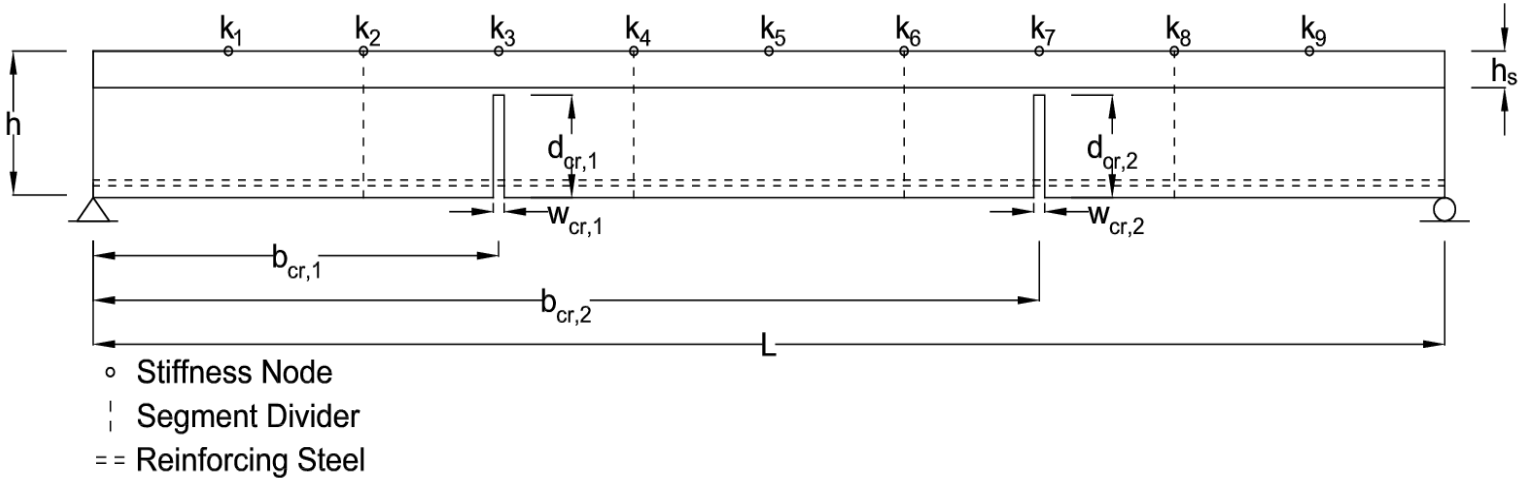
$$k_n = \frac{P_n}{\Delta_n}$$

- Stiffness Ratios
  - Damage in beams quantified by ratios of stiffness between cracked and healthy beams with identical geometric and material parameters

$$k\%_n = \frac{k_{n,cr}}{k_{n,h}}$$

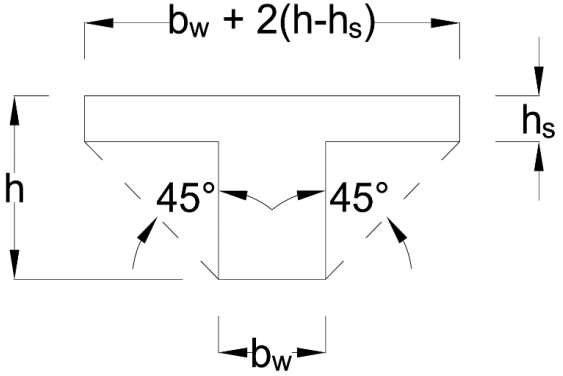
3. Generation of Reinforced Concrete Beam Database

- Geometric, Material, and Cracking Parameters
  - b_w, h, h_s, L, ρ, f'_c, $b_{cr,m}$, $d_{cr,m}$, and $w_{cr,m}$
  - Database consisted of beams with up to one crack allowed in each of 5 segments



3. Generation of Reinforced Concrete Beam Database

- Parameter normalization and constant parameters
  - Most parameters normalized to b_w = 250 mm
    - Normalized: b_w/h, h_s/h, L/h, $b_{cr,m}/L$, and $d_{cr,m}/h$
    - Not normalized: ρ, f'_c, and $w_{cr,m}$
  - Flange thickness, or slab height, constant at h_s = 100 mm
    - normalized parameter varies according to h
  - Flange width set according to the provisions of ACI 318-14 Section 8.4.1.8
  - Concrete cover set to 50 mm to center of steel for vertical and horizontal cover dimensions
  - Three mild steel reinforcing bars embedded in the beam web at equidistant spacing for all beams
    - Size of each bar: $A_s/3 = \rho b_w d/3$, where $d = h$ - cover



3. Generation of Reinforced Concrete Beam Database

- Reinforced Concrete Beam Database
  - Parametric variation used to create FE models of healthy (uncracked) beams and beams with one, two, three, four, and five cracks
  - 72 healthy beams created to serve as references for calculation of nodal stiffness ratios
  - Large number of beams with one and five cracks created initially
  - Smaller numbers of beams with two, three, and four cracks and additional beams with five cracks created to promote ANN interpolation
  - Following tables display parametric variation: 11,448 unique beam datasets generated in total

3. Generation of Reinforced Concrete Beam Database

- Parametric variation for beams with one crack

Parameters	Values				Variable Terms
b_w/h	0.5	0.7	0.9		3
L/h	7	10	13		3
ρ	0.005	0.01			2
f'_c (MPa)	20	30	40	50	4
Crack 1					
dcr/h	0.25 0.64				2
wcr (mm)	1 5				2
			Number of Beam Datasets =		6624

Parameters	Values					Variable Terms
	Segment 1	Segment 2	Segment 3	Segment 4	Segment 5	
b_{cr}/L	0.06 0.1 0.15 0.2	0.2 0.25 0.3 0.35 0.4	0.4 0.45 0.5 0.55 0.6	0.6 0.65 0.7 0.75 0.8	0.8 0.85 0.9 0.94	23

3. Generation of Reinforced Concrete Beam Database

- Parametric variation for beams with five cracks

Parameters	Values					Variable Terms
b_w/h	0.5	0.7	0.9			3
L/h	7	10	13			3
ρ	0.005	0.01				2
f'_c (MPa)	20	30	40	50		4
	Segment 1	Segment 2	Segment 3	Segment 4	Segment 5	
b_{cr}/L	0.1	0.3	0.5	0.7	0.9	2
	0.2	0.4	0.5	0.6	0.8	
	Crack 1	Crack 2	Crack 3	Crack 4	Crack 5	
d_{cr}/h	0.25	0.25	0.25	0.25	0.25	3
	0.5	0.5	0.5	0.5	0.5	
	0.64	0.64	0.64	0.64	0.64	
w_{cr} (mm)	1	1	1	1	1	3
	2.5	2.5	2.5	2.5	2.5	
	5	5	5	5	5	
			Number of Beam Datasets =			1296

3. Generation of Reinforced Concrete Beam Database

- Parametric variation for additional beams with five cracks

Parameters	Values					Variable Terms
b_w/h	0.5	0.9				2
L/h	7	13				2
ρ	0.005	0.01				2
f'_c (MPa)	20	50				2
	Segment 1	Segment 2	Segment 3	Segment 4	Segment 5	
b_{cr}/L	0.06	0.21	0.41	0.61	0.81	4
	0.19	0.39	0.59	0.79	0.94	
	0.19	0.21	0.59	0.61	0.94	
	0.06	0.39	0.41	0.79	0.81	
	Crack 1	Crack 2	Crack 3	Crack 4	Crack 5	
d_{cr}/h	0.64	0.1	0.64	0.1	0.64	6
	0.1	0.64	0.64	0.64	0.1	
	0.1	0.64	0.1	0.64	0.1	
	0.64	0.1	0.1	0.1	0.64	
	0.1	0.1	0.64	0.64	0.64	
	0.64	0.64	0.64	0.1	0.1	
w_{cr} (mm)	2.5	0.05	2.5	0.05	2.5	6
	0.05	2.5	2.5	2.5	0.05	
	0.05	2.5	0.05	2.5	0.05	
	2.5	0.05	0.05	0.05	2.5	
	0.05	0.05	2.5	2.5	2.5	
	2.5	2.5	2.5	0.05	0.05	
			Number of Beam Datasets =			2304

3. Generation of Reinforced Concrete Beam Database

- Parametric variation for beams with two cracks

Parameters	Values					Variable Terms
b_w/h	0.5	0.9				2
L/h	7	13				2
ρ	0.005	0.01				2
f'_c (MPa)	20	50				2
	Segment 1	Segment 2	Segment 3	Segment 4	Segment 5	
b_{cr}/L	0.1	0.3				6
	0.1				0.9	
		0.3	0.5			
		0.3		0.7		
			0.5	0.7		
				0.7	0.9	
	Crack 1	Crack 2				
d_{cr}/h	0.64	0.1				2
	0.1	0.64				
w_{cr} (mm)	5	0.05				2
	0.05	5				
			Number of Beam Datasets =			384

3. Generation of Reinforced Concrete Beam Database

- Parametric variation for beams with three cracks

Parameters	Values					Variable Terms
b_w/h	0.5	0.9				2
L/h	7	13				2
ρ	0.005	0.01				2
f'_c (MPa)	20	50				2
	Segment 1	Segment 2	Segment 3	Segment 4	Segment 5	
b_{cr}/L	0.1		0.5		0.9	7
	0.1			0.7	0.9	
	0.1	0.3	0.5			
	0.1	0.3		0.7		
	0.1	0.3			0.9	
		0.3		0.7	0.9	
			0.5	0.7	0.9	
	Crack 1	Crack 2	Crack 3			
d_{cr}/h	0.64	0.25	0.1			2
	0.1	0.25	0.64			
w_{cr} (mm)	5	2.5	0.05			2
	0.05	2.5	5			
			Number of Beam Datasets =			448

3. Generation of Reinforced Concrete Beam Database

- Parametric variation for beams with four cracks

Parameters	Values					Variable Terms
b_w/h	0.5	0.9				2
L/h	7	13				2
ρ	0.005	0.01				2
f'_c (MPa)	20	50				2
	Segment 1	Segment 2	Segment 3	Segment 4	Segment 5	
b_{cr}/L	0.1	0.3	0.5	0.7		5
	0.1	0.3	0.5		0.9	
	0.1	0.3		0.7	0.9	
	0.1		0.5	0.7	0.9	
		0.3	0.5	0.7	0.9	
	Crack 1	Crack 2	Crack 3	Crack 4		
d_{cr}/h	0.64	0.25	0.64	0.1		2
	0.1	0.64	0.25	0.64		
w_{cr} (mm)	5	2.5	5	0.05		2
	0.05	5	2.5	5		
			Number of Beam Datasets =			320

3. Generation of Reinforced Concrete Beam Database

- Parameter Selection for Segments Absent of Cracks
- Reinforced Concrete Beam Database Expansion
  - Expanded from 11,448 datasets to 42,480 datasets
  - Duplicated data applied in training sets only
- Python Scripting
  - Generation Script
  - Analysis Script
  - Extraction Script

3. Generation of Reinforced Concrete Beam Database

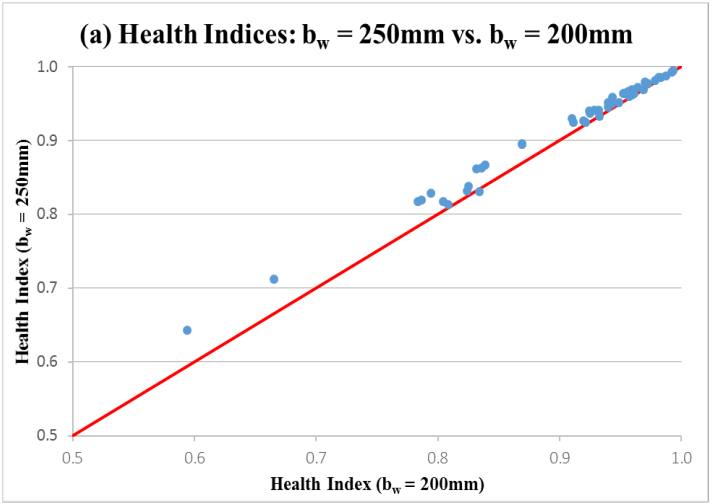
- Applicability of Research to Range of Girder Sizes
  - 50 cracked beams selected at random from unique database
  - Parameters kept constant and FE models generated for 200 mm and 300 mm web widths
  - Health indices (defined later) compared between 200 mm and 300 mm beams and reference 250 mm beams
  - In addition to R^2, MARE, and ASE comparisons, Lin's Concordance Correlation Coefficients (ρ_c) also calculated to assess reproducibility of work

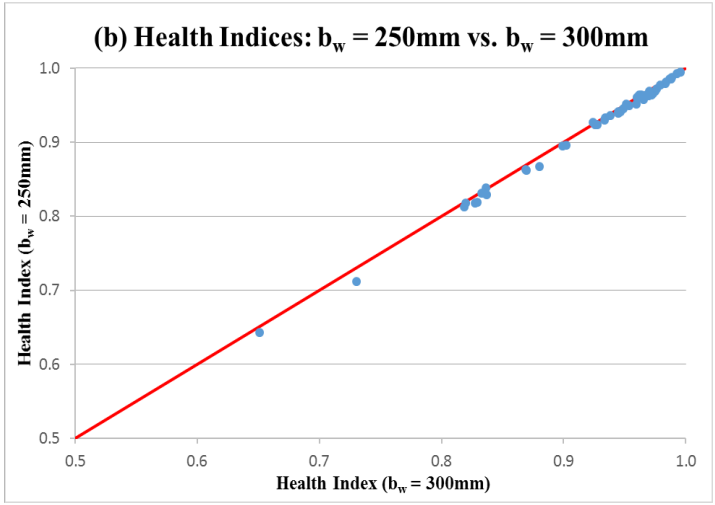
$$\rho_c = \frac{2\rho\,\sigma_r\sigma_t}{\sigma_r^2 + \sigma_t^2 + (\mu_r - \mu_t)^2}$$

3. Generation of Reinforced Concrete Beam Database

- Applicability of Research to Range of Girder Sizes (cont.)

	Beam Widths 250mm and 200mm	Beam Widths 250mm and 300mm
MARE	1.4525	0.5198
R^2	0.99103	0.99771
ASE	0.000295	0.000034
ρ_c	0.97667	0.99687



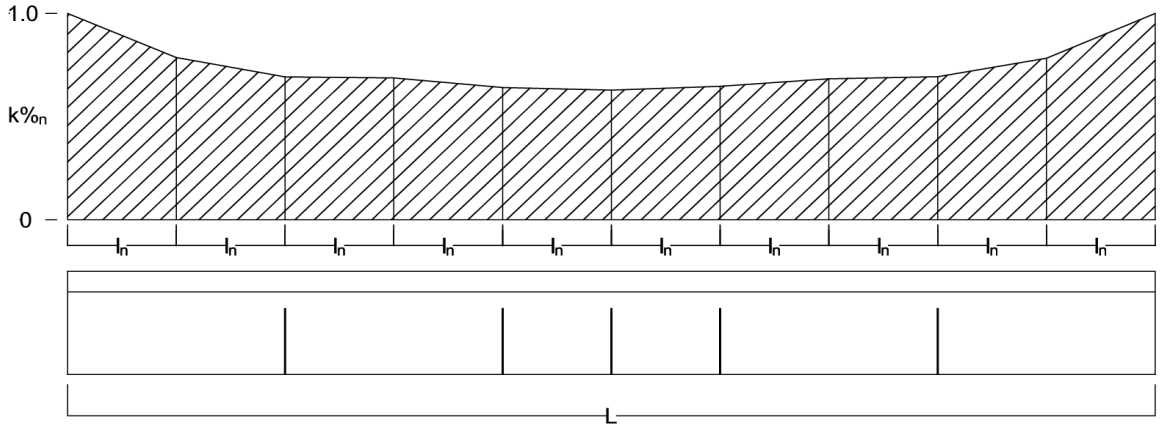


4. ANN Modeling for Structural Health Prediction

- Two ANNs Trained to Develop Structural Health Prediction Models
  - Nodal Stiffness Ratio Prediction ANN
  - Health Index Prediction ANN

- Health Index

$$k_i\% = \left(\frac{l_n}{L}\right)\left(1 + \sum_{n=1}^{n=9} k\%_n\right)$$



4. ANN Modeling for Structural Health Prediction

- Feedforward ANN program with single hidden layer utilizing backpropagation learning algorithm applied in this study
  - Initial number of hidden nodes set to vary between 2 and 10
  - Final number of hidden nodes of 20 found to be sufficient to facilitate learning
  - ANNs evaluated first by their ASE, and then by MARE and R^2 values
  - Final number of hidden nodes and training iterations at the final number of hidden nodes recorded for training and testing phase, and three optimal networks tested on validation sets then trained on all data
  - Model nomenclature: Initial number of hidden nodes-final number of hidden nodes-iterations at final number of hidden nodes

5. Results and Discussion

- Statistical measure performance for the three top-performing nodal stiffness ratio prediction models

		Model 1 (4-18-20000)	Model 2 (5-19-20000)	Model 3 (6-19-20000)
Training	MARE	0.575	0.532	0.512
	R^2	0.9832	0.98515	0.98572
	ASE	0.000188	0.000158	0.000157
Testing	MARE	0.884	0.808	0.894
	R^2	0.9817	0.98617	0.98358
	ASE	0.000414	0.000334	0.000422
Validation	MARE	0.965	0.837	0.938
	R^2	0.97637	0.98492	0.98098
	ASE	0.000496	0.00034	0.000451
All Data	MARE	0.611	0.619	0.594
	R^2	0.986	0.98411	0.98499
	ASE	0.00019	0.000221	0.000195

5. Results and Discussion

- Statistical measure performance for the three top-performing health index prediction models

		Model 1 (2-19-20000)	Model 2 (4-19-20000)	Model 3 (6-19-20000)
Training	MARE	0.17	0.144	0.162
	R^2	0.99762	0.99818	0.99778
	ASE	0.000018	0.000013	0.000017
Testing	MARE	0.262	0.204	0.233
	R^2	0.99808	0.9985	0.99808
	ASE	0.000041	0.000027	0.000035
Validation	MARE	0.259	0.25	0.282
	R^2	0.99761	0.99761	0.99683
	ASE	0.000038	0.00004	0.000052
All Data	MARE	0.171	0.258	0.179
	R^2	0.998	0.99578	0.99778
	ASE	0.000018	0.000041	0.00002

5. Results and Discussion

- No model displayed optimal prediction capabilities in all three phases
  - Additional small databases were generated to test optimal ANN architectures

- (1) Database of beams with two, three, and four cracks created
  - Parameters selected to be dissimilar from parameters of beams with two, three, and four cracks in main database
  - One healthy beam with $b_w/h = 0.7$, $h_s/h = 0.28$, $L/h = 10$, $\rho = 0.0075$, and $f'_c = 35$ MPa generated
  - 72, 72, and 54 beams with two, three, and four cracks, respectively, generated with cracking parameters varied by inspection

- (2) Database of 75 beams (15 of each 1-5 cracks) generated
  - Entirely random parameters to obtain unbiased assessment of optimal ANN model's prediction capabilities

5. Results and Discussion

- Statistical results for nodal stiffness ratio prediction ANNs for beam database with dissimilar parameters

	Model 1 (4-18-20000)	Model 2 (5-19-20000)	Model 3 (6-19-20000)
MARE	2.069	2.797	2.487
R^2	0.85052	0.79006	0.83598
ASE	0.002142	0.00326	0.002429

- Statistical results for health index prediction ANNs for beam database with dissimilar parameters

	Model 1 (2-19-20000)	Model 2 (4-19-20000)	Model 3 (6-19-20000)
MARE	1.646	1.94	0.984
R^2	0.74262	0.80498	0.86761
ASE	0.00118	0.001599	0.000542

5. Results and Discussion

- Statistical results for nodal stiffness ratio prediction ANNs for beam database with randomly generated parameters

	Model 1 (4-18-20000)	Model 2 (5-19-20000)	Model 3 (6-19-20000)
MARE	1.9571	2.4870	2.3765
R^2	0.86855	0.80863	0.84659
ASE	0.000885	0.001316	0.001222

- Statistical results for health index prediction ANNs for beam database with randomly generated parameters

	Model 1 (2-19-20000)	Model 2 (4-19-20000)	Model 3 (6-19-20000)
MARE	1.8234	1.7318	1.7237
R^2	0.80351	0.80246	0.81527
ASE	0.000845	0.000869	0.000932

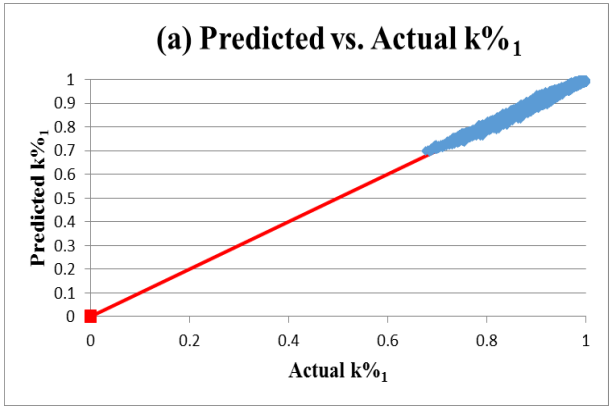
5. Results and Discussion

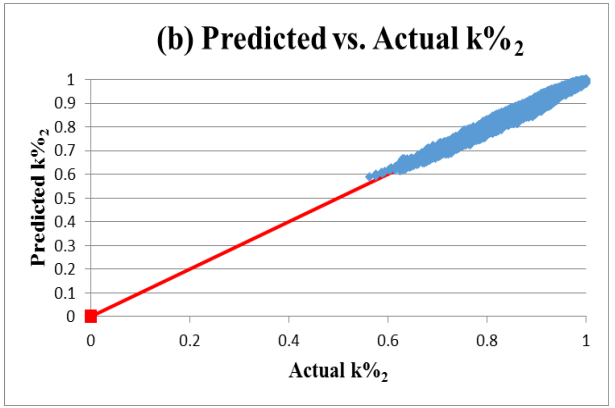
- Comparing all statistical results, the optimal models were found to be 4-18-20000 for nodal stiffness ratio predictions, and 6-19-20000 for health index predictions

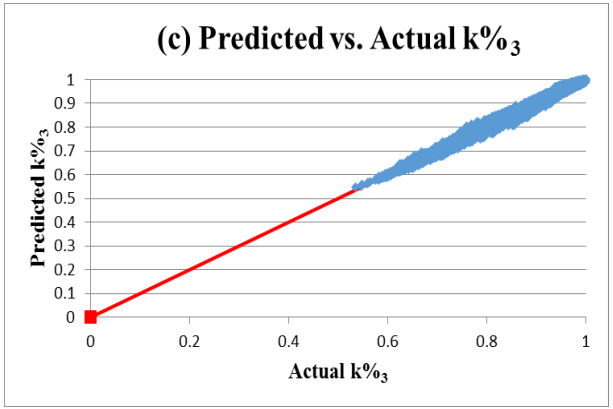
- Following figures plot ANN predicted nodal stiffness ratios or health indices against their actual values for the three databases
  - Points close to the 45° line indicate accurate predictions

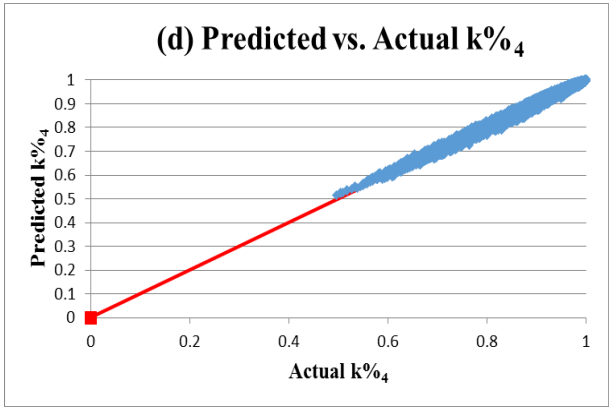
5. Results and Discussion

- Main Database



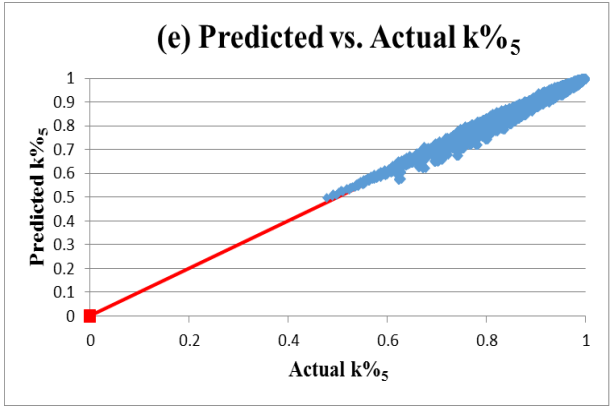


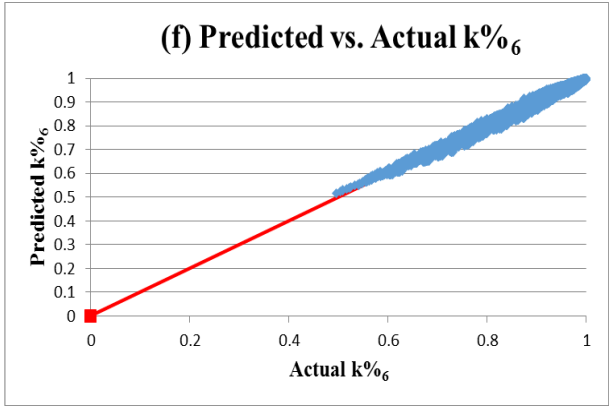


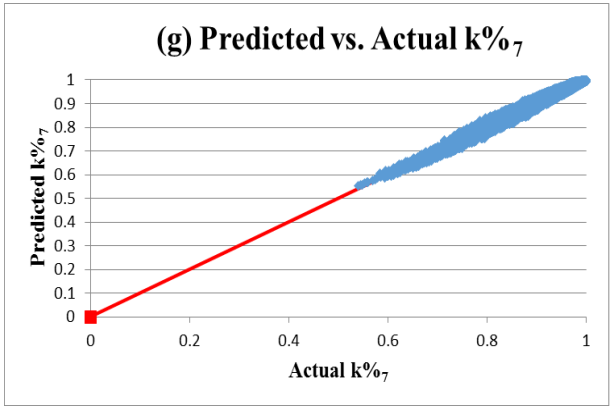


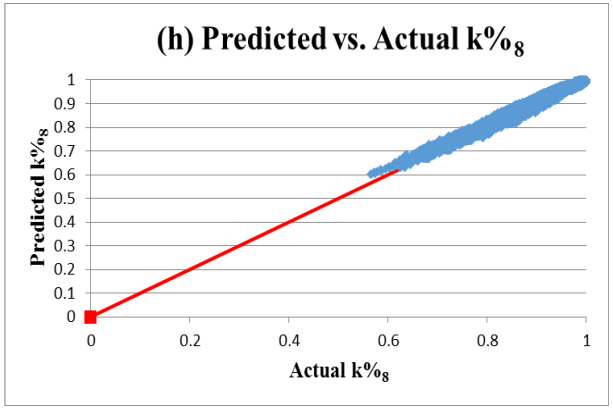
5. Results and Discussion

- Main Database



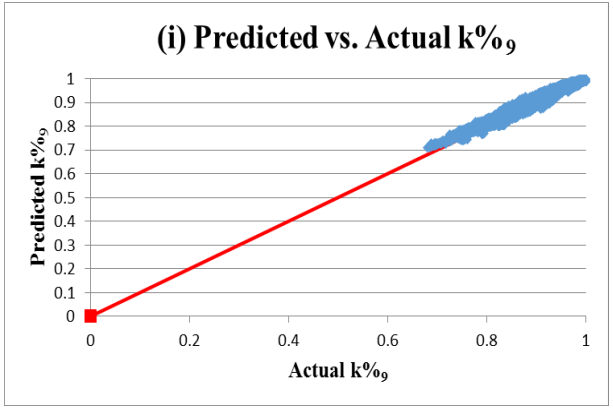


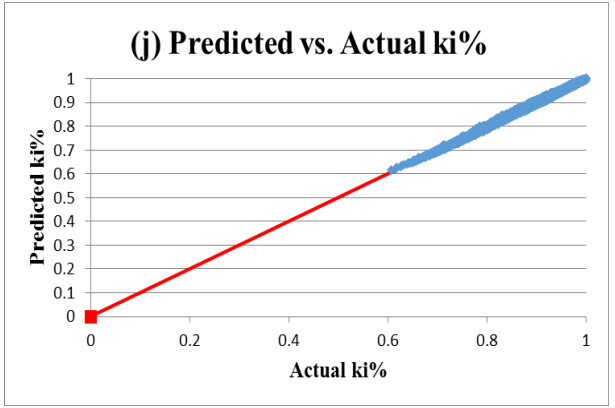




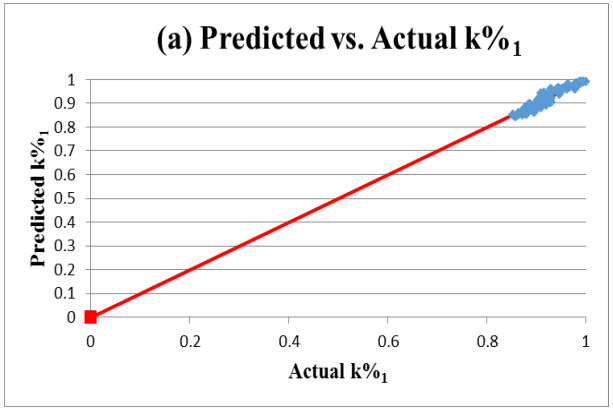
5. Results and Discussion

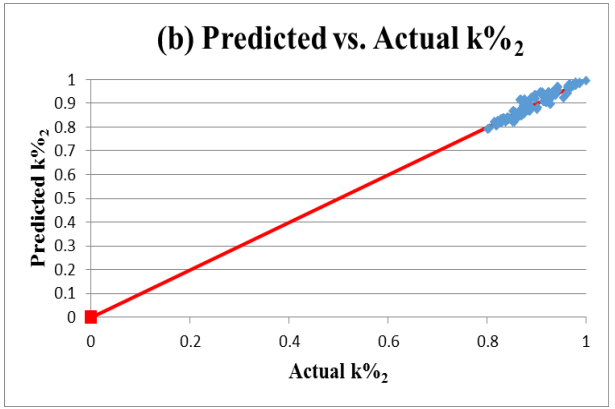
- Main Database





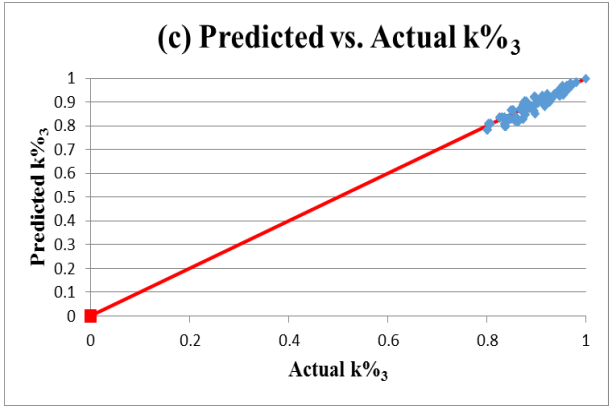
- Dissimilar Parameters Database

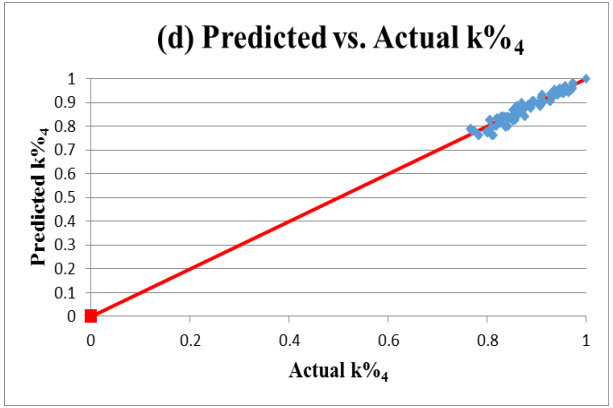


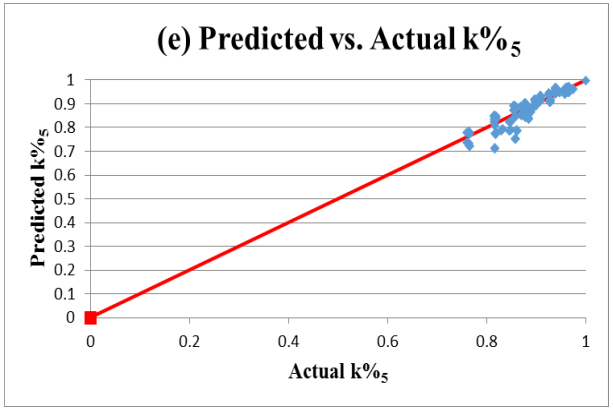


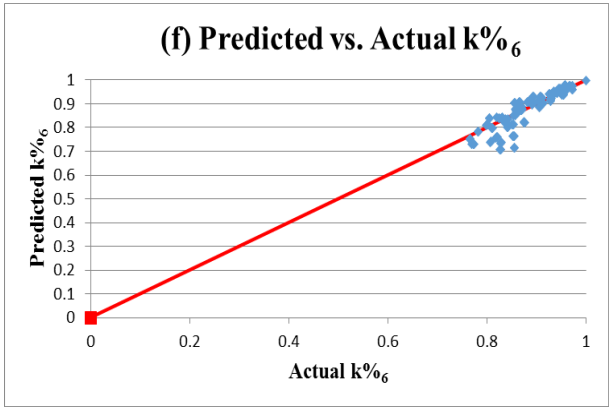
5. Results and Discussion

- Dissimilar Parameters Database



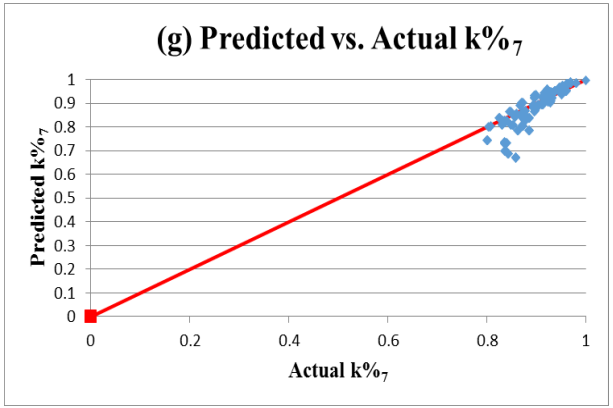


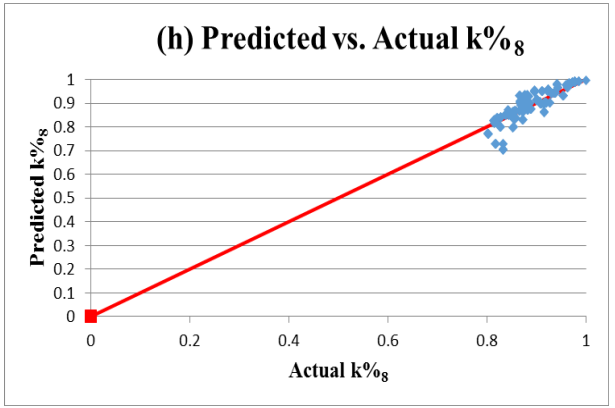


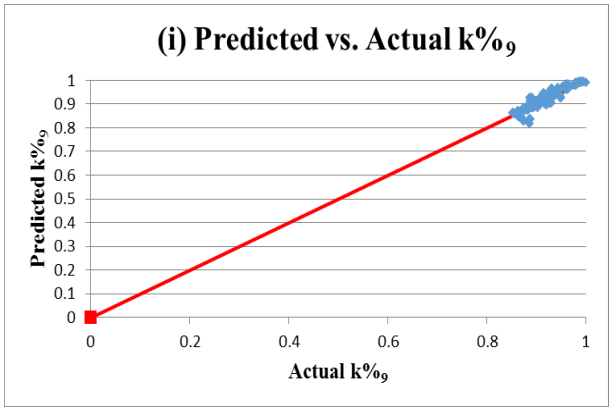


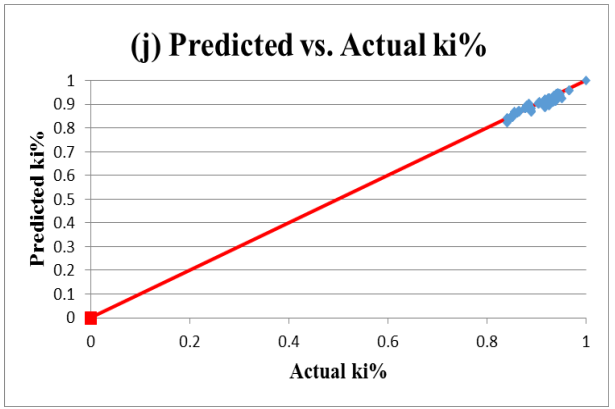
5. Results and Discussion

- Dissimilar Parameters Database



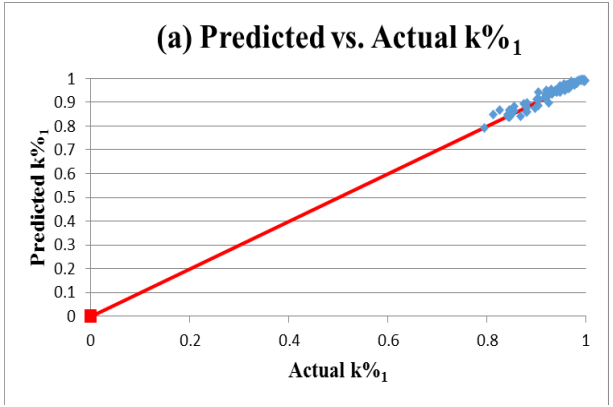


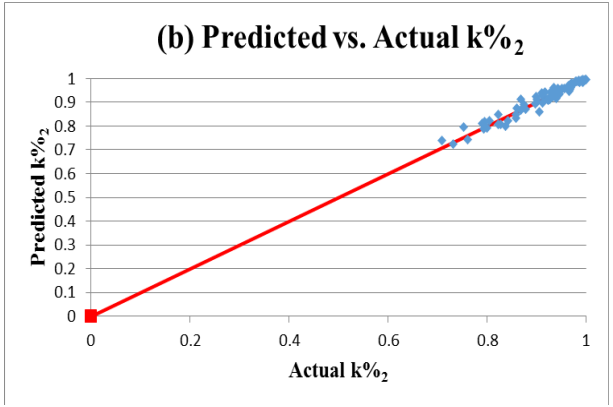


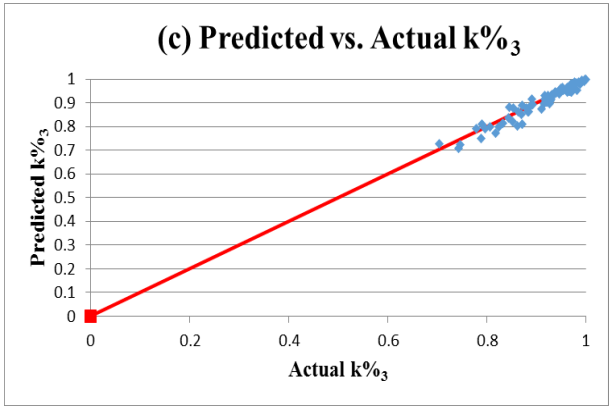


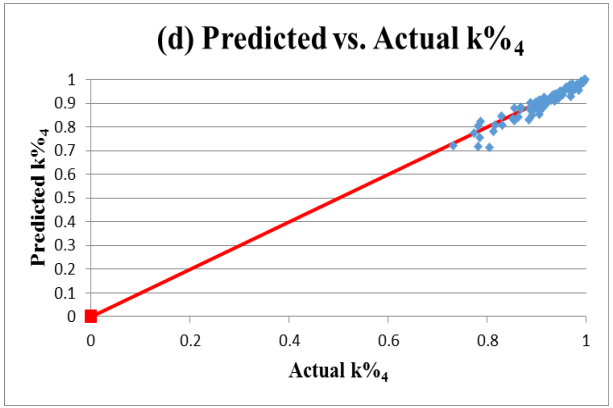
5. Results and Discussion

- Randomly Generated Parameters Database



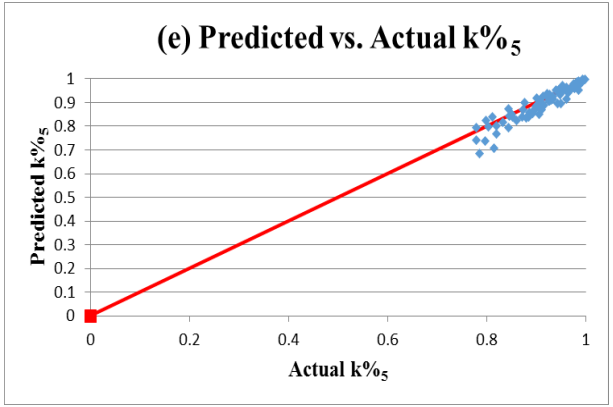


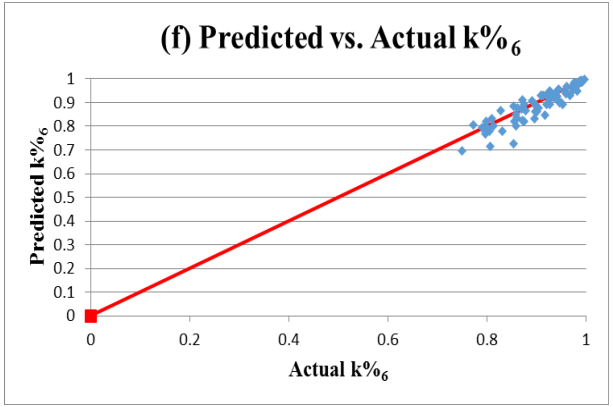


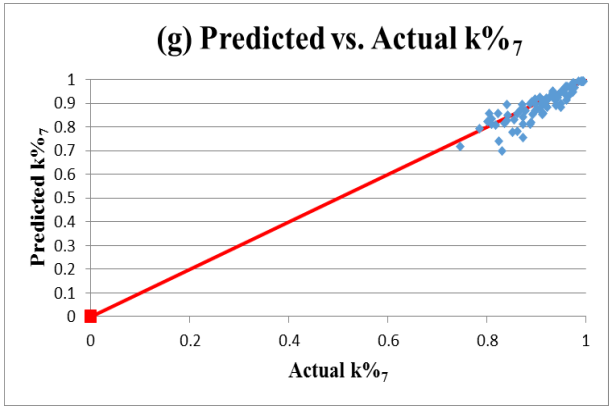


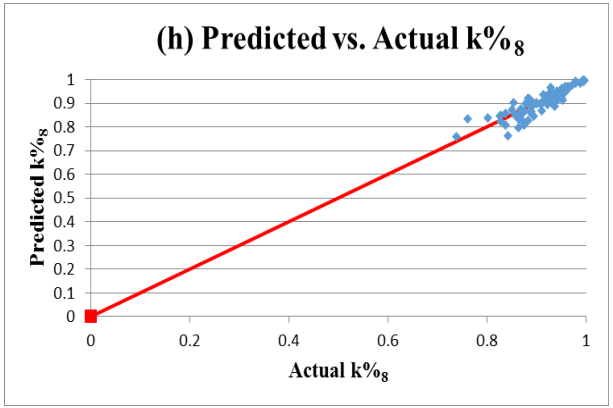
5. Results and Discussion

- Randomly Generated Parameters Database



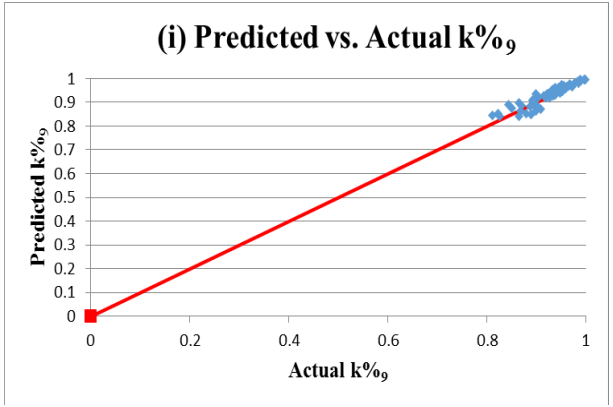


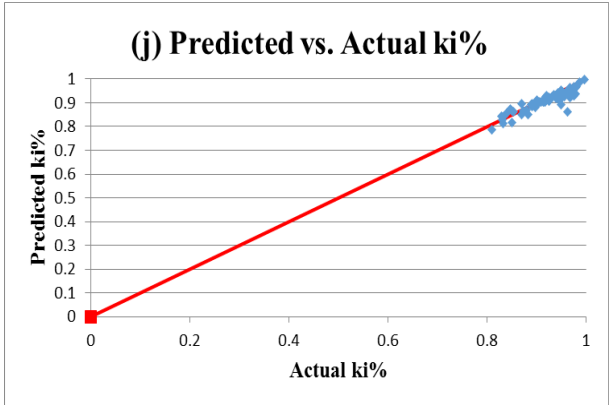




5. Results and Discussion

- Randomly Generated Parameters Database





6. ANN User Interface Application

- Touch-enabled user interface application developed to facilitate on-site structural health monitoring for damage evaluation
  - Connection weights and biases from the top-performing nodal stiffness ratio and health index prediction ANN models were utilized
  - Visual Studio WPF application framework was chosen due to integrated touch support and a wealth of user interface construction tools
- User interface demonstration

7. Conclusions and Recommendations

- Conclusions
  - Statistical results indicate that the integration of ANN and FE modeling approaches can provide accurate structural health predictions for damaged reinforced concrete T-Girders
  - ANNs developed from FE model databases can be used as effective and efficient on-site damage evaluation tools
  - The theory and techniques utilized in this study can be applied to any number of structural elements and structural health monitoring processes

7. Conclusions and Recommendations

- Recommendations
  - Further investigate the effects of different beam web widths
  - Increase the size of the beam database
  - Expand the number of cracks allowed in each beam
  - Add crack angle parameters
  - Consider additional beam configurations
    - Reinforcement types: Prestressing strands, FRPs
    - Boundary supports: Multi-span continuous
    - Structural elements: Slabs
  - Compare with experimental data

8. Acknowledgements

- InTrans at Iowa State University
- Dr. Yacoub Najjar
- Dr. Ahmed Al-Rahmani

9. Questions

Questions?