Making Retrofit Decision with Multi-criteria Fuzzy Comprehensive Evaluation System for Girder Bridges in Wenchuan Earthquake

Yong-Jiu Qian, Qi-Wu Fan and Xiao-Qian Zeng
Southwest Jiaotong University, the school of civil engineering, Chengdu, China

SUMMARY:
In order to provide a tool for making retrofit decision on damaged bridges, multi-criteria fuzzy comprehensive evaluation system is established considering economic-social facts and the engineering circumstances in the effected regions of Wenchuan earthquake. The novel damage scales which built the relationship between the probability distribution of damage states and seismic loss can be derived from the damage database. Within this system, overall bridge's damage state is assembled with three damage levels based on fuzzy logic and RVM classifier. Furthermore this paper introduces a procedure to Bayesian update scheme for fragility curve utilizing bridge empirical damage data as the prior distribution obtained from Wenchuan earthquake. Moreover, the method is applied to make retrofitting decision for Huilan overpass by means of comparing seismic risk .

Key words: damage assessment and retrofitting database, multi-criteria fuzzy comprehensive evaluation system, Bayesian update scheme for fragility curve

1. INTRODUCTION

Due to Wenchuan earthquake, 670 highway bridges were damaged in Sichuan Province, some of which suffered severe damage, even collapse. Thousands of bridges in the affected regions were destroyed. To restore earthquake damaged community, many bridges are needed to be retrofitted or rebuilt. Post earthquake rehabilitation decisions require estimation of damage level to assess and determine which is reasonable as quickly as possible. With a rational method to evaluate damage potential and to predict probable bridge losses, the seismic fragility assessment can be performed as a decision-making aid in both the pre- and post-earthquake settings to make better-informed decisions on the allocation of resources for retrofit. Post-earthquake damage assessment provides the reliable results.

In this paper, the damage database from the damage data of 469 bridges were compiled with the surveys of structural characteristics, earthquake parameters and seismic loss. By way of observation, comparison and analysis, novel damage scale can be establish which is described with repair cost and downtime statistics probability. Consequently, based on the new damage scale, multi-criteria fuzzy comprehensive evaluation system is assembled with three damage levels using fuzzy logic and RVM classifier. Another objective of this paper is to illustrate the procedure to Bayesian update scheme for fragility curve utilizing bridge empirical damage data.

2. DAMAGE DATABASE

During the post-earthquake investigation for Wenchuan earthquake, more than 1000 bridges were inspected and recorded. 469 concrete bridges were complied into damage database composed of simply-supported and continuous beams. Furthermore, more than 90 percent of bridges in database required repair measures.

Damage database provides four main types of data: structural characteristics, bridge damage, earthquake parameters and seismic loss. Structural characteristics required to classify bridges will include: location, year of construction, structure material type, girder type, span continuity, bridge skew angle, number of spans, maximum span length, pier type and pier parameter (height, longitudinal and transversal reinforcement ratio), abutment information, bent pattern, foundation type and seismic design level. Fig. 1 shows the number of bridges in damage database classified by built year. The distribution of bridges by maximum span length and maximum column height is shown in Fig. 2.The ratio of the superstructure pattern and pier type in damage bridges database can be found in Fig.3 and Fig. 4.

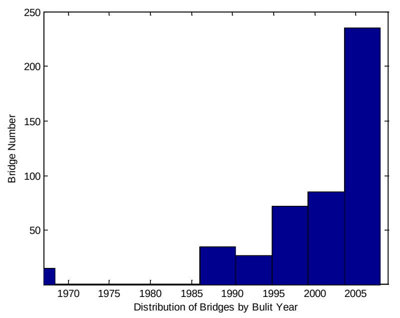


Figure 1. Database classified by built year

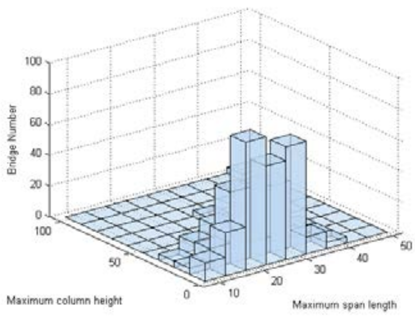


Figure 2. Database classified by maximum span length and maximum column height

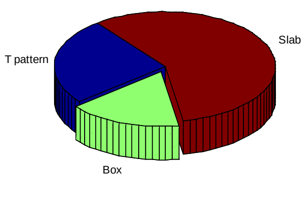


Figure 3. Superstructure pattern ratio

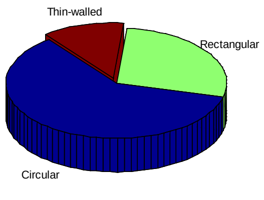
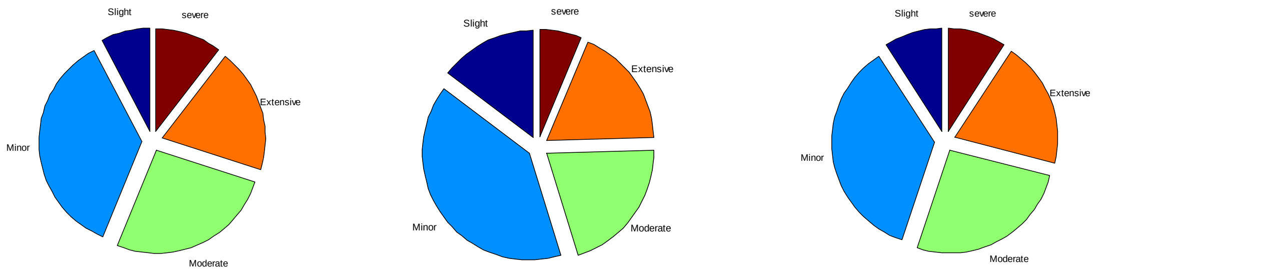
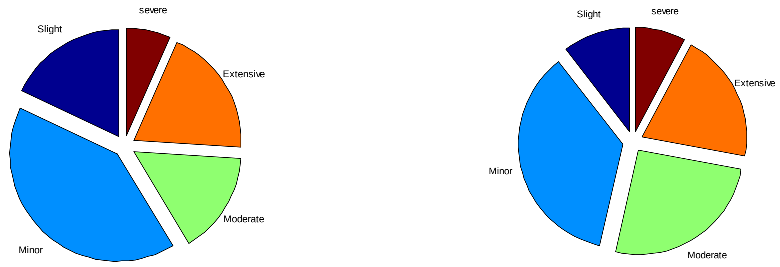


Figure 4. Pier type ratio

The types of bridges damage induced by earthquake are complicated and multifold depend on structure system and seismic intensity. Major damage patterns for different components are described with observations of structural performances and were directly accessible to quantification by detection measures. The damage patterns and damage indicators during post-earthquake inspection which were record in the damage database are given in Tab.1.Figure 5(a) ~ (e) represent the distribution of observed damage indicators and damage levels.



(a) abutment damage states ratio (b) bearing damage states ratio (c) damage states ratio of deck crack width



(d) damage states ratio of pier bending (e) damage states ratio of pier shear

Figure 5. The distribution of observed damage indicators and damage levels

Table 1. Damage patterns and damage indicators during post-earthquake inspection

Components	Observed phenomena		Quantitative damage indicators
Superstructure	superstructure unseating		residual displacements
	transverse superstructure shifting		residual displacements
	pounding damage		spalling area and cracks widths
	cracks in deck		crack widths
Pier	concrete cracks		crack widths
	spalling of concrete cover		spalling area and cracks widths
	shear failure		diagonal shear crack widths and sliding distance
	reinforcements condition exposed to surface	bar yield	inelastic deformations
		bar buckling	inelastic deformations
		bar fracture	inelastic deformations
Abutments	pounding damage		spalling area and cracks widths
		movements and rotations due to	deformations

	soil-structure interaction	
Bearings	bearing failure	relative displacements
Nonstructural components	handrail damage and expansion joints damage	deformations

Direct seismic loss parameters in database consist of repair cost to bridge components and downtime in the form of loss of traffic function. Defined as the ratio of repair cost to replacement cost of a bridge, the estimated repair cost and more detailed information on retrofitting work and cost for 74 bridges that were retrofitted are presented in the database. In addition to structural characteristics, soil type, epicentral distance and fault distance at each bridge site are also illustrated in the damage database.

3. MULTI-CRITERIA FUZZY COMPREHENSIVE EVALUATION SYSTEM

Composed of three subsequently performed steps, holistic evaluation procedure is proposed. With the help of trapezoidal fuzzy-membership functions and experiences, damage levels for every damage pattern of different components can be determined using post-earthquake screening data or nonlinear time-history simulation results. Adopting fuzzy-algorithm, the weighted damage extent and risk can be calculated for secondary subsystem. In order to build the relationship between the damage index of bridge system and seismic loss, damage scale classification is carried out by using relevance vector machine. Damage data of 450 bridges is chosen to train RVM classifier. Consequently classifier is verified with 19 bridges damage data. Thirdly the fuzzy damage score of secondary subsystem can be converted to seismic damage scale and loss level. Multi-criteria fuzzy comprehensive evaluation system is shown as Fig.6.

3.1. Fuzzy Damage Assessment System for Bridge

Fuzzy logic - the logic underlying approximate, rather than exact, modes of reasoning - was put forward in 1965 by Dr.Zadeh. It is widely used in earthquake engineering, including earthquake prediction, structural analysis and design, assessment for existing structures capacity. Owing to the complexity and vagueness, bridge damage assessment system is divided into three primary subsystems: superstructure, including girders and bearings, substructure involving piers and abutments, and appendages which chiefly refers to expansion joints and handrails. In accordance with each secondary subsystem, evaluation system is built. After numerous damage surveys and combining with experts' experiences, it is convenient and suitable to use trapezoidal fuzzy-membership functions for damage evaluations. Therefore membership function for every single factor can be determined as shown in Fig.6. The Y-axis of the plots is on the scale of 0 to 1, indicating a range of membership from no membership to full membership. Once single component factor evaluation matrix is established based on membership function, result matrix can be got through compositional operations after considering factors' weight vector for each component. Then single factor evaluation matrix for every secondary component can be aggregated. Because Sugano inference output is a constant or polynomial function, Sugano damage scores for secondary subsystems can be adopted in multi-criteria fuzzy comprehensive evaluation system.

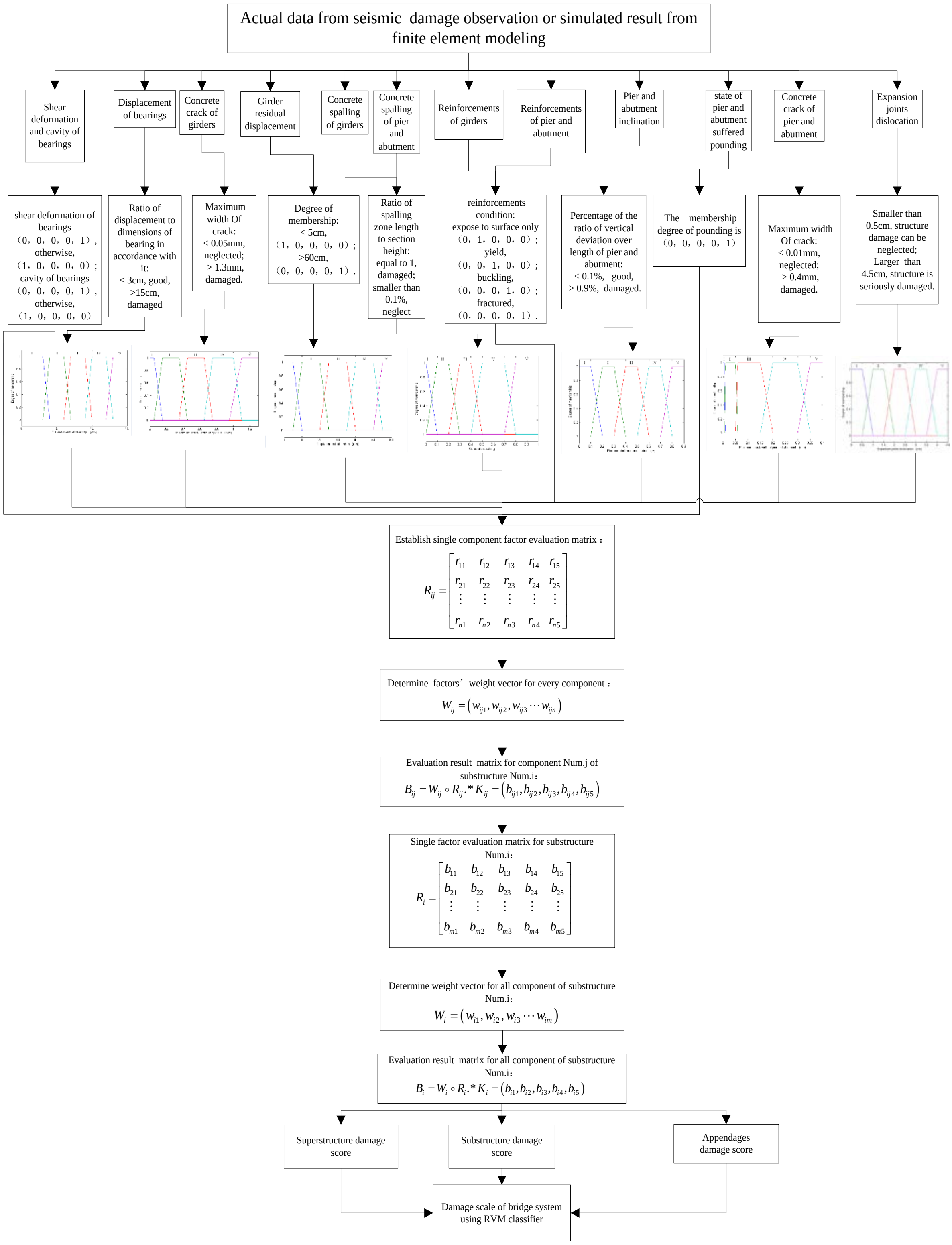


Figure 6. The multi-criteria fuzzy comprehensive evaluation system

3.2. New Damage Scales Based on Statistics Study of Bridge Damage Database

The evaluation of the repair cost after earthquake plays a guiding role in restoration projects, which should be as realistic as possible and reduce repair costs. To establish the relationship between damage indices and damage scales, damage classifications were adopted. Park, Ang and Wen (1987) used a simple classification based on visual signs of damage to correlate damage indices with observed damage. Another different classification which Park-Ang damage index model was applied based on 82 round piers pilot assessment was proposed by Stone (1993). The restoration curves used by HAZUS were developed based on a best fit to ATC-13 data consistent with damage states defined. The curves shown are normal curves characterized by a mean and a standard deviation, and approximate discrete functions for the restoration curves developed. The damage classification proposed by EERI is based on the risk of non-structural damage, casualties and structural closing time. ATC-13 damage state, HAZUS99 damage state, FEMA 273 performance levels, and Vision2000 performance level have their own evaluation systems.

Fitted to be applied for bridges in China, damage classification system combining retrofitting cost with damage scale was proposed by Yong-Jiu Qian (1992). After Wenchuan earthquake, in order to make retrofit decision for many damage bridges, modified damage evaluation system is proposed as the guideline for rehabilitation combined economic with social facts, such as the feasibility and safety of retrofitting plan, retrofit fee which is defined by the proportion to construction cost and loss function involving lane closures, reduction in traffic volume, or complete bridge closure are useful for traffic network modeling. In multi-criteria fuzzy comprehensive damage evaluation system, by means of observation and summary of the bridge damage due to Wenchuan earthquake, the engineering circumstances, retrofitting technology and material value in the affected regions of Wenchuan earthquake have been taken into account, and the relationship among damage classifications, modified damage index and residual seismic capacity is established based on surveys and statistics study of more than 400 damaged bridges in damage database as shown in tab.2.

Table 2. Novel damage classifications

Damage State	Degree of Damage	Repairs Required	Retrofit cost ratio			Expired time		
			mean	standard deviation	95% confidence bounds	mean	standard deviation	95% confidence bounds
1	Slight	None	2.0%	0.8%	3.4%	3 days	1days	5days
2	Minor	Adjust patching	9.0%	4.5%	16.2%	9days	3days	17days
3	Moderate	Repair components	26%	6.6%	36.7%	41days	13days	62days
4	Extensive	Rebuild components	47%	11.3%	63.2%	90days	21days	132days
5	Collapse	Rebuild structure	-	-	-	300days	-	-

3.3. Damage Scale Classification Based on Relevance Vector Machines

The utility of eight seismic damage classification techniques were considered in Tesfamariam's study, and the conclusion that kNN and SVM can achieve the best result has been made. Because of its simple implementation and consistently high classification accuracy when applied to many real-world classification situations, support vectors is popular which is training samples that define the optimal separating hyper-plane. However, SVM suffers the disadvantages, such as complexity parameter that must be found by using a hold-out method, linear combinations of kernel functions centered on training data points that must be positive definite and SVM does not provide posteriori probabilities. The relevance vector machine was introduced by Bishop and Tipping (2000) as an alternative to support vector regression method through the framework of sparse Bayesian learning. As a result of sparseness inducing prior, posteriors of many weights are sharply distributed around zero, hence these weights are pruned and the model becomes sparse. Being Chosen Sugano damage scores of 450 bridge-subsystems as ‘input’ and corresponding damage scales which were investigated after Wenchuan earthquake as ‘target’, RVM classifier can be applied and trained. The efficiency and accuracy of RVM classifier have calibrated with damage scores of 19 subsystems as testing samples as shown in Tab.3.

Table 3. RVM classifier results and actual repair cost

Bridge name	Secondary subsystem damage Sugano score			Estimated probability results of damage scale using RVM classifier (I II III IV V)	Repair cost ratio in post-earthquake investigations
	Superstructure	Substructure	Appendages		
Yu zi xi Bridge	0.81	0.73	0.54	0.00,0.02,0.13,0.70,0.15	37%
Bai hua Bridge	1	1	0.72	0.00,0.00,0.00,0.01,0.99	100%
Meng zi gou Bridge	0.51	0.51	0.61	0.00,0.02,0.11,0.73,0.14	48%
Xiao huang gou Bridge	0.12	0.43	0.34	0.03,0.12,0.67,0.13,0.04	27%
Da shui gou Bridge	0.71	0.34	0.53	0.01,0.04,0.14,0.67,0.14	39%
Meng zi gang Bridge	0.39	0.27	0.51	0.02,0.07,0.78,0.10,0.01	31%
Xiao ma xi Bridge	0.17	0.21	0.18	0.13,0.70,0.15,0.01,0.01	14%
Gu xi gou medium Bridge	0.72	0.32	0.55	0.01,0.10,0.76,0.10,0.03	36%
Hui lan Overpass	0.35	0.92	0.43	0.01,0.03,0.06,0.83,0.05	60%
Pa yan gou Bridge	0.51	0.23	0.49	0.03,0.09,0.75,0.10,0.03	31%
Qian jin gou Bridge	0.12	0.07	0.15	0.12,0.74,0.12,0.01,0.01	10%
K1033+909 minor Bridge	0.14	0.47	0.52	0.03,0.06,0.76,0.12,0.03	32%
Pu jia gou Bridge	0.5	0.53	0.64	0.01,0.14,0.67,0.17,0.01	29%
Bai shui xi Bridge	0.53	0.54	0.78	0.02,0.02,0.93,0.02,0.01	33%
Da gou medium Bridge	0.28	0.29	0.44	0.01,0.08,0.73,0.13,0.00	30%
Shui jing wan Bridge	0.21	0.2	0.2	0.06,0.88,0.04,0.01,0.01	18%
Overpass in Cheng-Guan highway (left lane)	0.24	0.27	0.21	0.02,0.12,0.71,0.11,0.01	30%
Overpass in Cheng-Guan highway (right lane)	0.27	0.28	0.45	0.01,0.07,0.84,0.07,0.01	34%
Zou ma he Bridge	0.19	0.13	0.36	0.01,0.86,0.13,0.00,0.00	21%

4. RETROFITTING DECISION MAKING WITH FRAGILITY CURVE

Fragility represents the conditional probability of exceedence for multiple damage states in a given ground motion parameter. Using two-parameter normal/lognormal distributions and estimated the two parameters with the aid of the maximum likelihood estimation method, the seismic fragility curves can be expressed. There are two methods which can be adopted to obtain fragility curves, empirical and analytical method traditionally. As known, empirical and analytical fragility curves have shown good agreement between theory and observation for the Northridge, Loma Prieta, Kobe and Chichi earthquakes. Analytical fragility curves are the only option for assessing the seismic performance of bridges when the actual bridge damage data or any expert opinion is not available. In addition, empirical fragility curves can't illustrate potential damage risk for site-specified bridge thoroughly and comprehensively. Incremental Dynamic Analysis (IDA) is an extremely powerful tool for investigating the performance of structures subjected to earthquake ground motions and can provide enough reasonable sources for analytical method. Combining multi-criteria fuzzy comprehensive damage evaluation system, the damage scores for bridge secondary subsystem of each ground motion can be transformed to damage scale with each time-history analysis result. Aiming to attempt to compensate for the scarcity of observational data, subjectivity of judgmental data and modeling deficiencies of analytical procedures by combining data from different sources, hybrid fragility curves can be derived from empirical and analytical fragility curves with Bayesian inferences. The process is shown in Fig.7.

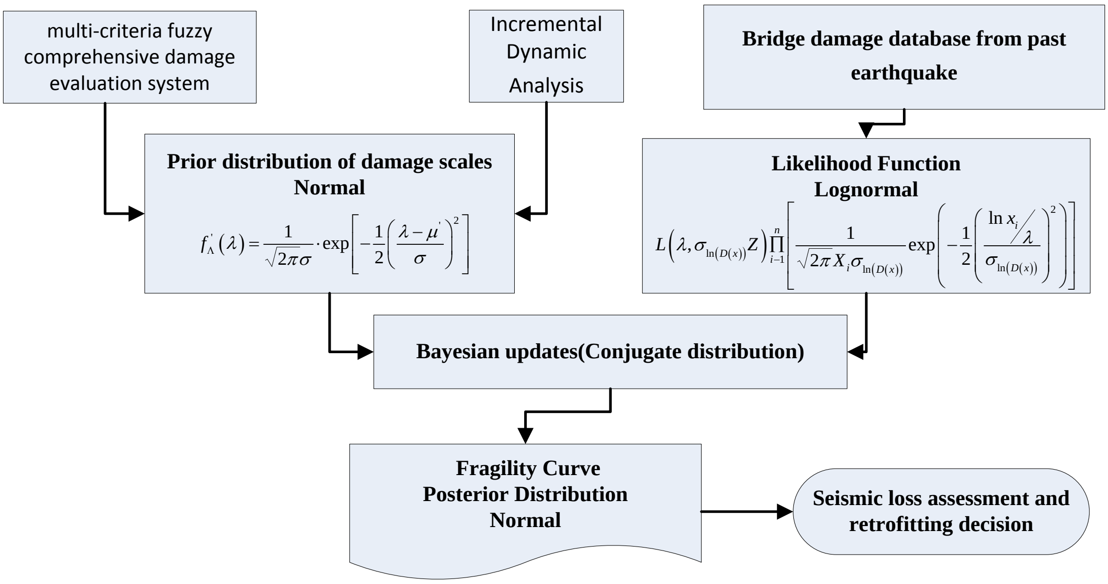


Figure 7. The process of retrofitting decision making

The pattern of Huilan Overpass which adopted 13-span continuous curved girder in Mianzhu city was spiral. Damage to Huilan Overpass can cause significant disruption to the transportation network, posing a threat to emergency response and recovery as well as resulting in severe economic losses for the Mianzhu region. According to post-earthquake damage assessment, damage scale to Huilan Overpass could be extensive and components need to be rebuilt in multi-criteria fuzzy comprehensive damage evaluation system, as shown in Tab.4. Chosen 20 ground motions with different frequency spectrum content for Incremental Dynamic Analysis, each record was scaled form 0.1g to 0.8g and nonlinear time-history analysis for Huilan Overpass is performed with forced-based fiber beam element models in Opensees. The set of ground motions is composed of 19 records recommended by Vamvatsikos (2001) and one ground motion record in Wenchuan earthquake (Location: CD2-EW, Data Source: CENC). Analytical and Bayesian updated fragility curves are shown in Fig.8, which shows that slight, minor, moderate damage state is prone to happen after Bayesian updating, while the probability of extensive and collapse damage states goes lower. As a result of the scarcity of actual data in database, it is so deficient that statistical data does not meet with the rule of large possibility event. Without retrofitting the bridge is safe when PGA is lower than 0.2g, but up to 0.4g, it will be likely to suffer severe damage. Combined with probabilistic capacity analysis and probabilistic hazard analysis, the seismic risk assessment for original structure and retrofitted structure with steel tubes can be built on the updated fragility curves. The retrofit decision can be made by comparing with seismic risk assessment results before and after retrofit, as shown in Tab.4.

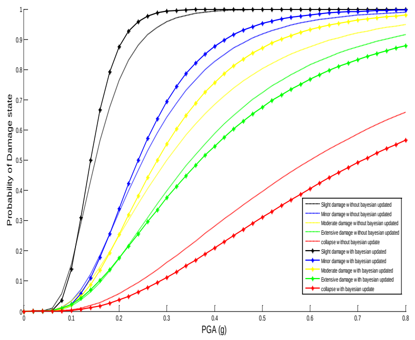


Figure 8. Empirical, analytical and Bayesian updated fragility curves

Table.4. Seismic risk of Huilan Overpass

Damage State	Damage scale	Seismic risk of original structure in per year	seismic risk of the retrofitted structure in per year
2	Minor	1.95E-03	7.98E-04
3	Moderate	1.17E-03	2.20E-04
4	Extensive	3.98E-04	6.68E-05

5. CONCLUSIONS

The novel damage scale described with the probability distribution of damage states and seismic loss is suitable to assess bridge system damage. With fuzzy logic and RVM classifier, multi-criteria fuzzy comprehensive evaluation system is proved to be useful for making retrofit decision to existing bridges and guiding the new bridge design effectively and accurately. The conclusion can be made that Bayesian updated fragility curves is more reasonable by combining empirical damage data and IDA results. By means of the updated fragility curves and multi-criteria fuzzy comprehensive evaluation system, the retrofit decision can be made effectively by comparison of seismic risks before and after retrofit.

ACCNOWLEDGEMENT

This research is supported by the National Science Foundation of China (No.50978221).

REFERENCES

Basöz, N. I., and Kiremidjian, A. S. (1998). Evaluation of bridge damage data from the Loma Prieta and Northridge, California earthquakes. Technical Report MCEER, (98-0004).

Bishop CM, Tipping ME. Variational relevance vector machines. In:Boutilier C, Goldszmidt M, eds. Uncertainty in Artificial Intelligence. Cambridge, UK: Microsoft Research; 2000:45–63.

Bishop CM, Tipping ME. Bayesian regression and classification. In:Suykens J, Horvath G, Basu S, Micchelli C, Vandewalle J, eds. Advances in Learning Theory: Methods, Models and Applications(NATO Science Series. Series III, Computer and Systems Sciences.Vol. 190). Amsterdam: IOS Press; 2003:267–285.

Chao, Li- Chung, F.: „Fuzzy Logic for Evaluating –Alternative Construction Technology", Journal of Construction Engineering and Management 124, pp. 297-304; 1998.

Clough, R.W., and S.B. Johnston（1966）, Effect of Stiffness Degradation on Earthquake Ductility Requirements, Proceedings, Second Japan National Conference on Earthquake Engineering, 1966, pp.227-232.

HAZUS MH. (2008). Earthquake loss estimation methodology, Technical Manual. National Institute of Building Sciences for Federal Emergency Management Agency, Washington, DC, MR3 edn.

JBDPA The Japan Building Disaster Prevention Association (2001a). Guideline for Post-earthquake Damage Assessment and Rehabilitation of Reinforced Concrete Buildings. (in Japanese).

Maeda, M., and Bun-no M. (2001). Post-earthquake damage evaluation for R/C buildings based on residual seismic capacity in members (in Japanese). The 3rd U.S.-Japan Workshop on Performance-based Earthquake Engineering for R/C Building Structures: 157-170.

M. Shinozuka, M.Q. Feng, J. Lee, and T. Naganuma, Statistical analysis of fragility curves, Journal of Engineering Mechanics, Vol. 126, No. 12, (2000), pp1224-1231.

PEER strong motion database. Available online at: http://peer.berkeley.edu/smcat/; 2004.

Priestley MJN（2000）. Performance based seismic design. In: Proceedings of 12th world conference on earthquake engineering, Auckland, New Zealand, 2000; Paper no. 2831.

Stone WC, Taylor AW.（1994） ISDP: integrated approach to seismic design of reinforced concrete structures. J Struct Eng ASCE 1994; 120(12):3548–66.

Straub, D., and Der Kiureghian, A. (2008). Improved seismic fragility modeling from empirical data. Structural Safety, 30(4), 320-336.

Vamvatsikos D, Cornell CA.(2001) Tracing and post-processing of IDA curves: Theory and software implementation. Report No. RMS-44, RMS Program, Stanford University, Stanford, 2001.

Yong-Jiu Qian（1992）. The evaluation and diagnosis for the existing reinforced concrete bridges. Doctoral thesis, Southwest Jiaotong University, Chengdu , China (in Chinese).

Yousef Bozorgnia and Vitelmo V. Bertero, (2003) Damage Spectra: Characteristics and Applications to Seismic Risk Reduction. Journal of Structural Engineering,22(Oct), 1330–1340.

Yu-Long Peng (2000), Bayesian analysis method for updating earthquake ground motion versus damage relationship, Master thesis, National Central University ,Taiwan (in Chinese).

Zadeh, L.A. (1979), The role of fuzzy-logic in the management of uncertainty in expert systems,Approximate Reasoning in expert systems, Gutpa, M.M eds.North-Holland Amsterdam, pp. 3-31.