Real-time Fuzzy Synthetic Assessment for the Structure Safety Risk of Bridges

Zhibin Xu, Riqiang Chen, and Shaoding Li

***Abstract*—**The combination of analytic hierarchy process (AHP) with fuzzy contribution function is applied to evaluate the safety risk of bridge structure, automatically. The risk assessment model, at the first, is divided into multiple levels by the AHP method; all the data from sensor network are normalized to [0. 1] by Sigmoid fuzzy contribution function; after the set of the weights for the elements between any two levels are defined, the system can calculate output matrices or vectors for every level, and find out the highest value among the degrees of membership in same type of component as its results of risk assessment according to the principle of maximum degree of membership.

***Keywords*—**Analytic hierarchy process, fuzzy theory, structure safety, synthetic assessment.

I. Introduction

IT plays very important role for bridges in national economy and social life, as a hub of transportation system in a city. The more cars a city occupies, the more hazard the bridges become. There are some accidents of the bridge s around the world every year so that it has made experts be paying more attention on the architecture safety of the bridges recent years.

At the present, the most of safety assessment for the bridges are facing the following problems:

1) Human intervention: based on the data by specific devices or visual inspection in period, technicians derive the evaluating results in their experience.
2) Off-line assessment: applying Ansys or MIDAS/Civil professional tools for structure analysis of bridges offline.
3) Data garbage:even huge data are collected by bridge health monitoring system, their analysis couldn't be processed in real time.

In order to change the current status of the bridge assessment field and to reduce the human factors on the safety assessment, an online fuzzy synthetic evaluation system is designed to monitor the architecture safety of the bridges in real time. The system can give the safe grades of both components and entire bridge using quantitative and scientific computation.

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II. Architecture Design

The system is composed of the seven parts: sensor network, data collection, preprocessing, transmission, management, video control and safety assessment (Fig. 1).

III. Data Monitoring System

It's necessary to collect, process, transmit, manage and control the data from bridge structure in the safety assessment.

a. Sensors

There are much more selections as the modern sensor technologies are updated rapidly. Some of them have been deployed on the Foncha bridge in Beijing, China to monitor the structure status of the bridge[2]-[5]. The following principles could be considered depending upon the requirements of bridge structure safety:

1) Reliability: Integrated, two packages of seam gas techniques could be used to improve the reliability of sensors in serious environment under higher or lower temperature, higher humidity and so on.
2) Long life: because of the long-term activity to monitor bridge health, the sensor life cycle should be over 10 years.
3) Maintainability: it is convenient for sensors to be installed, exchanged and removed in the modular design of sensor structure.
4) Low cost: in order to the large range of deployment, lower-cost sensors with longer life should be adapted. The sensors with advanced MEMS platform and RS485 should be used in bridge health monitoring.

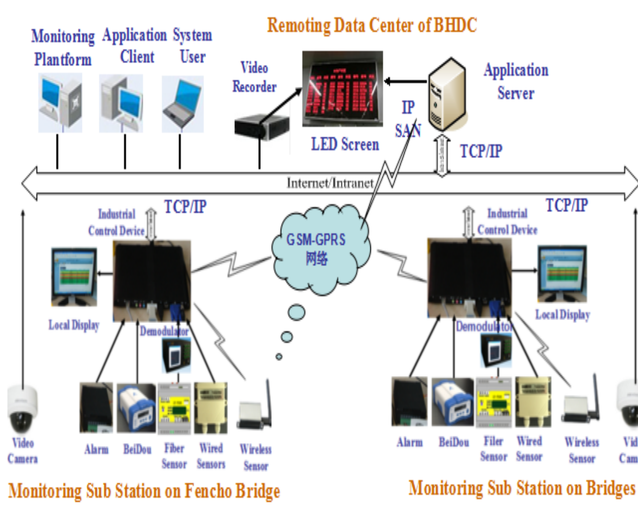

Fig. 1 Online fuzzy risk assessment system for bridge structure

TABLE I
TYPES, POSITIONS AND NUMBER OF SENSORS

Type	Position	Number
Temperature sensor	Bridge surface and inside box girder	2
Ultrasonic anemometer	On bridge	1
MEMS accelerometer	The middle part of cable,	30
Strain sensor	1/3 and 1/2 section of the main span	20
Deflection sensor	1/2 section of both main and side spans, root between main tower and beam.	5
Tilt sensor	The side of main and sub towers	2
BeiDou satellite receiver	Near main and sub tower, 1/2 section of main span and standard base station near the bridge	5
Displacement sensor	The same as the China BeiDou Satellite Positional System	
Crack sensor	The body pier of main and sub tower, 1/2 section of main span, and deck surface.	10
Sensor for expansion joints	Location between spans	2

b. Data collection

Some key techniques have been solved to obtain the information of bridge structure by an intelligent software system:

1) Adaptive intelligent interface: a module can read the data from sensors with the communication protocols such as RS485/232, TCP/IP, even ones defined by sensor manufactures. The most of sensors, wired, wireless or optical fiber, can be identified directly by the module. It makes much easy to install, exchange, or remove any sensors on the bridge. The time of deployment is saved, the costs for installation, maintenance and operation are reduced extremely.
2) Data preprocessing: strategies for static or dynamic parameters can be selected automatically. There are the number of programs to improve the quality of data collection, noise filters, refinement of FFT with adaptive windows etc.
3) Data cooperative transmission: the all of data are translated to unique format: TCP/IP
4) Adaptive organizing network: the system can make a wireless sensor network if necessary.

c. Data transmission

A industrial bus network is established on bridge because all of sensors except for wireless ones are RS485 protocol. Using the network, data are sent to a local computer insider box girder from the sensors.

After data preprocessing procedure, they are transmitted to remote center through Internet or GPRS.

d. Data management

An integration platform to monitor bridge health has been deployed on a remote data center[7]-[9].

1) The records from a number of sensors on bridges are transmitted to the unique platform by the intelligent data-acquisition system in the bridge area domain. It makes the application easier to maintain and saves lots of money because it is prevented from the multiple devices to handle the data from various sensors.
2) Based on web-GIS map, all of bridges is contributed on it. The more detail information about any bridge can be shown by clicking the icon of the bridge on the map.
3) Through web-service technology, the status and configuration of any sensor can be changed or controlled remotely so that fees for operators to maintain the device on the bridges can be reduced dramatically
4) The cloud computing cluster has satisfied with the mass of data storage, parallel processing, and disaster recovery.
5) There are kinds of modes to show the real-time records such as lists, 2D graphs, and 3D renderings. Historical records can be shown in histogram and lists,
6) The history data can be loaded to any computer to print statistical reports or for bridge experts to analyze the structure safety of the bridge by software: Ansys and MIDAS/civil offline.
7) Multiple level of pre-alarm threshold can be setup and modified on web page flexibly
8) The data from bridge inspectors can be migrated into the database seamlessly.
9) Both application server and DB server can be updated and increased without the stop of the data acquisition in the cloud computing center.
10) The permission and roles of a user can be controlled depending upon the job properties.

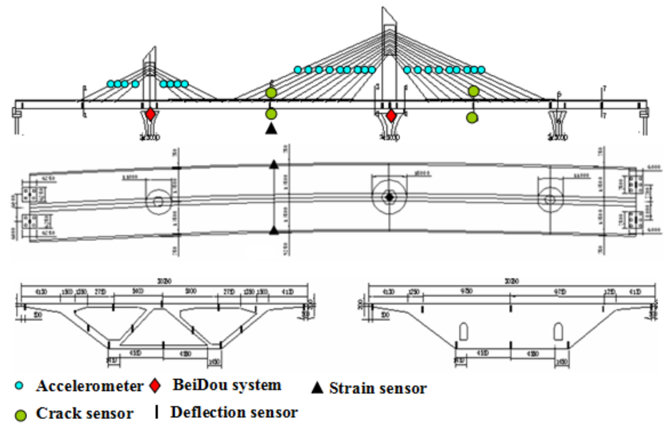

Fig. 2 Sensors located on the Foncha bridge

IV. FUZZY SYNTHETIC ASSESSMENT METHOD

Traditional safety assessment ways can't implement the tasks of monitoring operation status of modern large or super large bridges because they can't give objective and accurate safety evaluation to the body of the entire bridge[10]. Therefore, more advanced technologies should be explored to match with the fast development of large-structure bridge. The fuzzy logic combined with intelligent technique could be a good way to solve the issues[11],[12].

There are the number of factors effecting to structure safety of bridges. Relationship among the factors and structure safety can't be described precisely by a mathematical formula. Fortunately, the Analytic Hierarchy Process (AHP) could be a good one which can makes a complex thing be simpler.

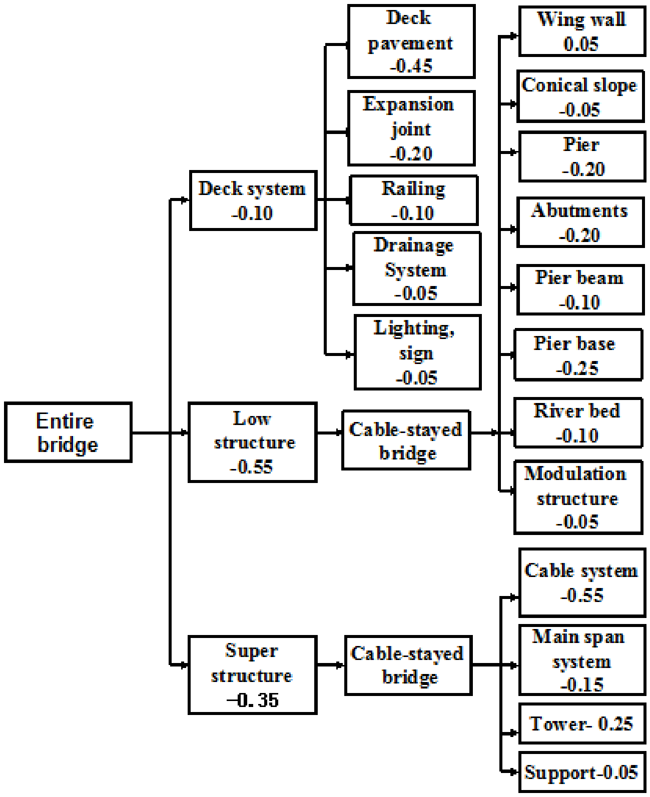

Fig. 3 Safety assessment model of cable-stayed bridge

The AHP will divide a decision problem into a general target, and one or more sub targets, i.e. Hierarchical structure. They in fact exist a weight between any element in a level and some one in higher level. The weights can be determined by the eigenvector of judge matrix, the weights could be reassigned in some situation. Finally, weight of the general target can be derived through the method of weighted sum, level by level. Final weight of the general target will be the largest value of elements in its weight vector.

a. Build hierarchical assessment model

Depending on superstructure, bridges are roughly divided into:beam bridge, arch bridge, suspension bridge and cable-stayed bridge. A bridge can consist of three positions: super structure, low structures and deck system. Each position could involve types of parts, for example, the super structure of cable-stayed bridge includes cables, girder system, towers, supports etc. The each part could have the number of components like the part towers could be composed of main and sub towers. Therefore, the structure of a bridge will be defined as four hierarchies, i.e. Entire bridge→Position→Part→ Component (Fig. 3 and Fig. 4). Hazards haven't been included here[1][6].

b. Assessment index

The index selection should be combined with the actual structure of the bridge to ensure the feasibility and rationality of the risk analysis process. Not only it effects on the most of information about the bridge structure, but also complexity of system analysis is reasonable. The assessment index should be chosen by the following conditions:

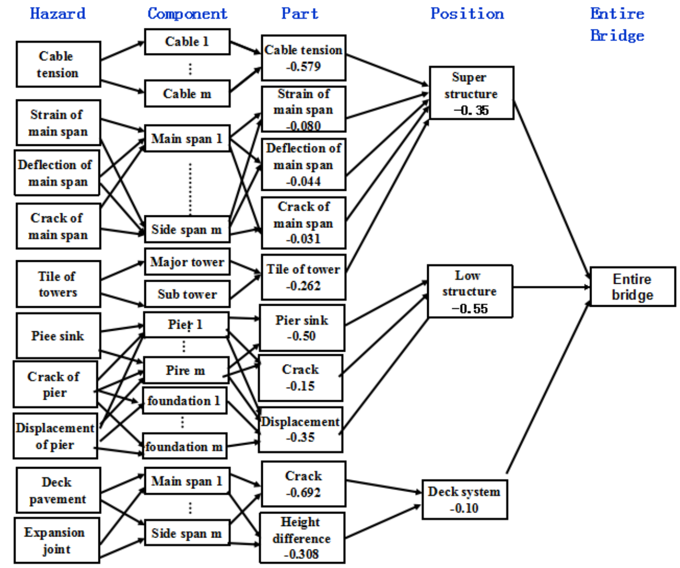

Fig. 4 Architecture of hierarchical weights of cable-stayed bridge

1) Highlight the major aspects of the bridge to make the assessment analysis simpler. The indexes with no or very little impact on the evaluation results must be neglected.
2) All the indexes should be independent of each other. Selected indexes should describe the different aspects of the characters of bridge structure. The selection should try to avoid the intersection or repeat among the indexes because it could result in the difficulty of the assessment or analytic errors.
3) The indexes should be available however from sensors, mathematical formula or experts.
4) All the indexes are comparable in the influence degree on the structure assessment of the bridge.

Based on the requirements, assessment model of the cable-stayed bridge and their indexes could be defined as:

Top hierarchy: The entire bridge

Second hierarchy: Position, its indexes:

V={super structure, low structure, deck system}

Third hierarchy: Part, its indexes:

Super structure: V'_1 =*{cable force, strain of main span, deflection of main span, crack, tile of towers }*

Lower structure: V'_2 =*{subsidence of main pier, crack, displacement}*

Deck system: V'_3 =*{expansion joint, crack}*

c. Weight set

1) Standard weight set: according to the Reference 1, the weights of all positions and major parts have been defined by the group of Chinese bridge specialists around nation. Therefore, the most of weights in our analysis can be obtained, some adjustment could be made of course for special situation of the bridge.
2) Weight reassign: in practice, some bridges could be missing some parts, for instance, single span bridge without piers, or some bridges without sidewalk. Under those situation, the weights of missing parts should be assign to other parts of positions in proportion by formula

TABLE II
REASSIGNED WEIGHT SET OF SUPER STRUCTURE OF CABLE-STAYED BRIDGE

Parts	Weight value	Parts	Assigned weight value
Cable system	0.55	Cable tension	0.579
Main span system	0.15	Strain of 1/2 main span	0.080
		Deflection of 1/2 main span	0.048
		Crack of main span	0.031
Tower system	0.25	Tile of towers	0.262
Support system	0.05	-	-

TABLE III
REASSIGNED WEIGHT SET OF LOW STRUCTURE OF CABLE-STAYED BRIDGE

Parts	Weight value	Parts	Assigned weight value
Wing wall ear wall	0.05	-	-
Conical slope, revetment	0.05	-	-
Pier	0.20	Sink	0.50
Abutments	0.20	Displacement	0.35
		Crack	0.15
Pier beam	0.10	-	-
Pier foundation	0.25	-	-
River bed	0.10	-	-
Modulation structure	0.05	-	-

Reassigned weight of a part=the part's weight/(weight sum of all existing parts)

3) Non standard weight: if the weight of a part are not defined in [1], its weight value could be calculated by a method: Comparing importance between any two parts defines the value of element in a judgment matrix; then, a eigenvector can be found, responding to maximum characteristic root of the matrix; the matrix consistency is double checked weather it is satisfied with consistent rule or not, the elements of the matrix should be adjusted properly unless it is true. At the moment, the eigenvector of the matrix will be the weight set of the judgment matrix.

d. Weight set among parts and positions

The weight sets among parts and positions are listed by the weight definition and reassignment.

TABLE IV
REASSIGNED WEIGHT SET OF DECK SYSTEM OF CABLE-STAYED BRIDGE

Parts	Weight value	Parts	Assigned weight value
Deck pavement	0.45	Crack	0.692
Expansion joint	0.20	Height difference	0.308
Sidewalk	0.10	-	-
Railing	0.10	-	-
Drainage System	0.10	-	-
Lighting, sign	0.05	-	-

TABLE V
WEIGHT VALUES OF POSITIONS

No.	Bridge position	Weight value
1	Deck system	0.10
2	Super structure	0.35
3	Low structure	0.55

TABLE VI
DEFINITION OF RISK RANK

Risk order	Description	Evaluation of boundary	Risk rank	Rank value
1	Intact or in good condition	(0.93, 1]	Optimal	A
2	Well, a slight defect, full function	(0.85, 0.93]	Good	B
3	A poor state with moderate defect, normal function	(0.65, 0.85]	Appropriate	C
4	Poor state, big defect of main component, not normal use	(0.40, 0.65]	Poor	D
5	Dangerous state, serious defect, endangered operation	[0, 0.40]	Inferior	E

e. Weight set among positions and entire bridge

The weights of positions could be found in [1](Tab. V).

f. Risk rank and normalization

In order to real-time and seamless connection with future artificial neural network method, the risk rank is divided to five levels:Optimal, Good, Appropriate, Poor, and Inferior.

Owing to the different magnanimity of indexes, it is difficult for the system to evaluate safety risk rank with various measurement. The values of all parameters are normalized to the range [0, 1].

g. Fuzzy definition and membership function

Fuzzy set is the basis of Fuzzy theory and defined as: *Suppose a domain X, a set A for any element* $x \in A$, *the element x belongs to the degree of the set A by a function* $\mu_A(x) \in [0,1]$ *the set A is called as Fuzzy set,* $\mu_A(x_i)$ *as the membership function of the set A,* $\mu_A(x_i)$ *as membership degree of the element* x_i .

There are distribution functions in fuzzy theory such as normal, rectangular, trapezoidal, triangular, Sigmoid, or π distribution functions. Comparing to them, Sigmoid has particular properties.

Sigmoid function is the characteristics of smooth and steady transition as well as the nonlinear characteristics of continuously differential. Sigmoid function is

$$\mu_A(x_i) = \frac{1}{1+e^{-(\varpi x_i + \theta)}} \tag{1}$$

Here $\omega x_i+\theta$ is weighted input, ω is slop of the function, θ is displacement in x axis, $x_i>0$ is the structure parameters of the bridge like strain, cable tension etc, i=1,2,...m is the number of components. ω and θ should be calculated by (1). Suppose $x_1<x_i<x_2$, and satisfy with the following conditions:

TABLE VII
NORMALIZED RISK RANK OF STRAIN OF MAIN SPAN

Strain value	Range (100m)	Normalized boundary	Risk rank	Rank value
<L/1550	<65mm	[0,0.325]	Optimal	A
(L/1550, L/1000)	65~100mm	(0.325,0.5]	Good	B
(L/1000, L/600)	100~166mm	(0.5,0.83]	Appropriate	C
(L/600, L/500)	166~200mm	(0.83,1]	Poor	D
>L/500	>200mm	1.0	Inferior	E

$$\mu_A(x_1,\varpi,\theta)\approx 0.0$$

$$\mu_A(x_2,\varpi,\theta)\approx 1.0$$

Therefore, strain of main span is normalized to [0, 1] by the following Sigmoid distribution functions:

Rank A: $$\mu_A(x)=\frac{1}{1+e^{-(-0.131x+3.943)}}\qquad 0<x\le 65$$ (2)

Rank B: $$\mu_{B/A}(x)=\begin{cases}\dfrac{1}{1+e^{-(0.13x-4.641)}} & 0<x\le 65\\[2ex] \dfrac{1}{1+e^{-(-0.243x+19.729)}} & 65<x\le 100\end{cases}$$ (3)

Rank C: $$\mu_{C/B}(x)=\begin{cases}\dfrac{1}{1+e^{-(0.241x-20.338)}} & 65<x\le 100\\[2ex] \dfrac{1}{1+e^{-(-0.129x+16.822)}} & 100<x\le 166\end{cases}$$ (4)

Rank D: $$\mu_{D/C}(x)=\begin{cases}\dfrac{1}{1+e^{-(0.128x-17.447)}} & 100<x\le 166\\[2ex] \dfrac{1}{1+e^{-(-0.25x-45.443)}} & 166<x\le 200\end{cases}$$ (5)

Rank E: $$\mu_{E/D}(x)=\begin{cases}\dfrac{1}{1+e^{-(0.249x-45.907)}} & 166<x\le 200\\[2ex] 1 & x>200\end{cases}$$ (6)

Similarly, the values of rest parameters can be normalized with Sigmoid function.

h. Fuzzy synthetic assessment

1) Component risk assessment: a part could be composed of many components, for example, cable as a part has the number of cables. Each component will be in fuzzy and normalized to a five dimensional vector with fuzzy membership in [0,1]. According to the principle of maximum degree of membership, the highest value among the degrees of membership in same type of component is its results of risk assessment.
2) Part risk assessment: expression for its risk assessment is:

   Matrix of part: $V_i = W_{ij} * R_i \quad i=1,2...,n, j=1,2...,m$ (7)

   Weight set of part: $W_{ij} =\{w_{i1}, w_{i2}, ..., w_{im}\}$ and satisfy: $\sum_{j=1}^{m} w_{ij}=1$

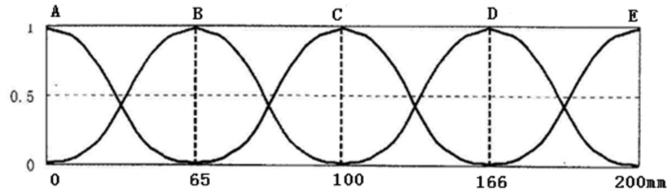

Fig. 5 Sigmoid distribution function draft of strain of main span

   Where W_{ij} is weight matrix, R_i is a m×5 matrix of risk assessment results in all the m components of the i-the part, V_i is the assessment matrix of the i-the part.
3) Position risk assessment: expression for the risk assessment is:

   Matrix of position: $V=W_i *\{V_i\} \quad i=1...n$ (8)

   Position weight set: $W_i =\{w_{i1}, w_{i2}, ..., w_{ij}\}$, and satisfy: $\sum_{i=1}^{n} W_i=1$

   Where W_i is weight vector with n dimension, $\{V_i\}$ is a n×5 matrix of risk assessment results of the i-the position, V is the n×5 matrix of risk assessment.
4) Entire bridge risk assessment: expression for bridge risk assessment is:

   Matrix of bridge: $V=W *\{V_i\} \quad i=1...n$ (9)

   Bridge weight set: $W =\{w_1, w_2, ..., w_n\}$, and satisfy: $\sum_{i=1}^{n} W_i=1$

   Where W_i is weight vector with n dimension, $\{V_i\}$ is a n×5 matrix of risk assessment results of the i-the position, V is the five dimensional vector, i.e. vector of risk assessment for the entire bridge.

According to the principle of maximum degree of membership, the highest value among the degrees of membership in the vector is final result of risk assessment for the entire bridge.

V. SAFETY ASSESSMENT EXAMPLE

Beijing six loop is a highway connecting to new towns in suburb as well as the part of national highway network. A pre-stressed concrete, curve cable-stayed bridge on the loop consists of four continuous spans and two towers, overpass Foncha railway. Overall length is 263 meter, 100 meter of main span, 70 meter for sub span[2][3].

Over seventy sensors have been deployed on the bridge to collect its structure information in real time, to preprocess them, to transmit them to a remote data center located on the south west of Beijing, China.

There is an integrated software installed on a server in the data center, which can normalize the input data, fuzzy them by Sigmoid function (shown in the fifth column on Tabs. VIII and IX); then, the output vector of each element in position hierarchy can be derived by the calculation of the weights and fuzzy input (in the last column on Tab. VIII); As the same as, the output vector of the entire bridge can be got (in the last column on Tab. IX). All the procedures are completed by the software automatically.

TABLE VIII

SAFETY ASSESSMENT RESULTS OF POSITIONS

Parts	2nd level index	Weight value	Fuzzy and normalization	Rank of position
Cable system	Cable-stayed tension	0.579	(0.898, 0.100, 0.002, 0, 0)	The rank result of super structure is (0.907, 0.089, 0.004, 0, 0)
Main span system	Strain of 1/2 main span	0.080	(0.981, 0.011, 0.009, 0, 0)	
	Deflection of 1/2 main span	0.048	(0.616.0.384, 0, 0, 0)	
	Crack of main span	0.031	(0.721, 0.279, 0, 0, 0)	
Tower system	Tile of towers	0.262	(0.981, 0.012, 0.007, 0, 0)	
Pier	Tower pier sink	0.50	(0.993, 0.007, 0, 0, 0)	The rank of low structure is (0.872, 0.097, 0.031, 0, 0)
Abutments	Displacement	0.35	(0.782, 0.152, 0.066, 0, 0)	
	Crack of pier body	0.15	(0.823, 0.121, 0.056, 0, 0)	
Deck Pavement	Deck Crack	0.692	(0.912, 0.063, 0.025, 0, 0)	The rank of deck system is (0.884, 0.084, 0.032, 0, 0)
Expansion joint	Height difference	0.308	(0.821, 0.129, 0.050, 0, 0)	

The results in tables shows that all the positions, super structure, low structure, and deck system are Optimal condition. According to the principle of maximum degree of membership, the highest value for vector (0.887, 0.092, 0.021, 0, 0) is 0.887, therefore the status of the entire bridge is Optimal condition, as well. In the near future, the set of input/output pairs obtained by fuzzy synthetic assessment approach will been as sample pair to train the fuzzy neural network to get stable set of weights and thresholds of the network. In final, the fuzzy network will be able to give risk evaluation ranks of each hierarchy for the bridges, in real time.

VI. CONCLUSIONS

In this paper, a fuzzy synthetic assessment approach is applied to automatically analyze the risk rank of bridge structure safety The traditional AHP method is adapted to establish the hierarchical structure model of bridge risk evaluation; The major factors are identified in every hierarchy, which could impact to the structure safety of the bridge; Sigmoid contribution functions in Fuzzy theory is combined with the AHP to fuzzy the input of the system as well as the normalization, the weight values of elements between any two hierarchies are given. In final, the risk rank matrices or a vector will be calculated automatically. According to the principle of maximum degree of membership, the highest value among the degrees of membership in same type of components and position are their results of risk assessment. Based on the principle, the rank of safety assessment for the entire bridge will be obtained. All the analysis results will be displayed on a huge LED screen dynamically.

In future, the set of input and output pairs derived by the fuzzy hierarchical assessment approach will be provided fuzzy artificial neural network algorithm with the set of samples that will train the fuzzy network, adjust the weight values and thresholds of elements among the levels, and classify the clusters of output. As soon as the study process of the network

TABLE IX

SAFETY ASSESSMENT RESULTS OF ENTIRE BRIDGE

Position	1st level index	Weight value	Result from levels	Rank of entire bridge
Super structure	Cable-stayed tension	0.35	(0.907, 0.089, 0.004, 0, 0)	(0.887, 0.092, 0.021, 0, 0)
Low structure	Tile of towers	0.55	(0.872, 0.097, 0.031, 0, 0)	
Deck system	Height difference	0.10	(0.884, 0.084, 0.032, 0, 0)	

tends to stable state, the membership matrices or vectors and the ranks of safety risk assessment for the bridge will be calculated out by the trained fuzzy network, automatically.The more data the system obtains, the more stable results it gets. The intelligent expert database will be established for the the safety assessment of bridge structure, the bridge health status will be evaluated in real time, the scientific strategy to maintain bridge will be provided for safety travel.

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