STRUCTURAL HEALTH DIAGNOSIS USING SOFT COMPUTING TECHNIQUE FOR CABLE-STAYED BRIDGE AFTER EARTHQUAKE

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ABSTRACT :

The cable-stayed bridge is generally a highly statically indeterminate structure. The structural performance of the cable-stayed bridge is highly sensitive to the load distribution among major components such as the pylon, the stayed cables and the girders of the bridge. Therefore, the stayed cables of the cable–stayed bridge should be monitored to prevent bridge damage due to earthquake, strong wind, differential settlement, fatigue/defect of the material or loose of tension within the cables. Since the cable-stayed bridge with long span is usually on the critical path of transportation net and plays very important role on hazard mitigation. To assure the cable-stayed bridge remains functional after the moderate earthquake become increasing important. That makes the rapid structure health diagnosis of the cable-stayed bridge very necessary in a maintenance procedure. This study proposes a fast structural health diagnosis method for cable-stayed bridges using soft computing techniques (i.e. Neural Networks, Genetic Algorithm, etc.) and field measurement data. The neural networks were used to determine the type and degree of the damaged bridge with ease and efficiency. Based on the cable force evaluated, the structural behavior including the deformation and stress state of the bridge can be traced successfully. Also, the damage state of the cable-stayed bridge can be identified using neural networks through the measured cable forces within stayed-cables. The validity of the proposed method is confirmed by the numerical studies using SAP2000 on several bridge models. A few cases were studied and the results obtained could benefit the rapid structural health diagnosis of the cable-stayed bridges after earthquake.

KEYWORDS: neural network, structural health diagnosis, cable-stayed bridge, earthquake

1. INTRODUCTION

The cable-stayed bridge is one of the engineers' favorite because of its special style and long span feature. Since the progress of the design ability due to better performance of the computer as well as the break-through of the construction technology and the invention of the new material, the record for span length of the cable-stayed bridge was extended recently. In addition, the structural performance of the cable-stayed bridge is very sensitive to the load distribution among major components of the bridge such as pylons, stayed cables and the girders due to its highly statically indeterminate structure. Therefore, the structural health monitoring/diagnosis (SHM/D) system should focus on the cables of the cable–stayed bridge to prevent bridge damage due to earthquake (EQ), strong wind, differential settlement, fatigue or defect of the material as well as loose of tension within the cables. Besides, the bridge authority in Taiwan works very hard in monitoring, maintaining, and retrofitting of the bridges to prevent any defects from the bridges and to assure the robustness and safety of the bridges since most of the cable-stayed bridges play very important roles in the transportation network. Traditionally, the monitoring and maintenance jobs cost a lot of money and manpower. Therefore, the SHM/D of the post-tensioning cable forces for the optimum structural performance becomes very important in the maintenance procedure for cable-stayed bridges. Besides, an automatic monitoring system is required to reduce the maintenance cost. New technologies such as soft computing tools and new monitoring targets were used and feasibility of such application was studied. The robust SHD system should include four important factors, which are: 1. the instrumentation and data collection, 2. transfer method of the signal, 3. data analysis and recognition of the data characteristics, and 4. element damage diagnosis and bridge safety assessment. The American Society of Civil Engineers (ASCE) and International Association for Structural Control (IASC) have developed several methods for SHM/D. For SHD of structural damage, Rytter (1993) from Denmark proposed that five items should be evaluated: 1. the damage occurrence, 2. location, 3. type, 4. scope, and 5. its influence to structure safety.

It has been a common approach to use the vibration-based method to detect the damage of bridges. The developed methods are mainly based on the premise that modal parameters (i.e. natural frequency and mode shape) will change when the damage occurs. Generally speaking, the modal parameters are not always sensitive to the damages, and sometimes temperature change could induce remarkable frequency shift in case of the analyzed data coming form girder vibration in reality. In addition, when damage forms the major change of modal parameters often takes place in higher modes, which needs very precise measurement. Hence, another vibration-base method, which is developed on the basis of cable vibration, is proposed to detect the damage of cable-stayed bridge. The dynamic characteristics such as mode, frequency and damping ratio of the structure can be recognized, if the structure is suffered from damage, its natural frequency and stiffness matrix will change so the structural damage can be diagnosed. The previous researches on recognition of structural dynamic characteristics for bridges using measured micro-vibration data including Farrar et al (1997), Qin et al (2001), Lee et al (2006), indicates the success of the micro-vibration method.

In this paper, the applications of neural networks (NNs) on SHM/D of cable-stayed bridges are introduced. Combined with micro-vibration field measurement data, this study demonstrates a SHM/D case for cable-stayed bridges using grouped NNs after EQ. The damage state (type, location and scope) of the cable-stayed bridge can be identified using data (cable forces within stayed-cables) measured from Chi-Lu cable-stayed bridge and NNs easily and efficiently. The validity of the proposed method is confirmed by the numerical studies using SAP2000 and in-situ measured information. The results obtained help to prove the feasibility of SHM/D of the cable-stayed bridges using soft computing techniques.

2. DAMAGE DETECTION WITH AMBIENT VRIBRATION

2.1. Analysis and Measurement of Ambient Cable Vibration

The stay cable can be modeled as a simple one-dimensional structure since its large slender ratio. The in-plane transverse motion of stay cables is simple but more or less affected by its flexural rigidity and sag effect. The string theory has been often used to demonstrate the transverse vibration, generally for longer cables. For the purpose of parametric identification of stay cables, the measurement of ambient cable vibration can be the types of displacement, velocity or acceleration. In general, accelerometer, velocimeter and displacement sensor are utilized to collect the vibration signals. Recently, fiber Bragg grating (FBG) sensor and photometry technique are being developed to measure ambient cable displacement. Three stay cables of Chi-Lu cable-stayed bridge, L01, R17 and R34, were selected to be studied for their behaviors. These cables represent the short, medium and long stay cables of the bridge. The recorded ambient vibration signals were transformed into frequency domain by Fourier Transform technique. The natural frequencies of the cable R34 shown in Fig.1 can be identified up to twenty-third modes, which match the string's behavior, except the fundamental frequency affected by sag effect. The Fourier amplitude shown in Fig.2 for the cable L01 is not as clear as for the cables R34. However, it is still no problem to identify the first five natural frequencies from the clear peak responses of second and third modes, because they still remain approximately uniform distribution. In contrast, it is always a sophisticate process to identify the natural frequencies of bridge by measuring the ambient vibration of girder, especially for higher modes. That is one of the reasons why the ambient vibration of cable system is chose for performing damage diagnosis. In order to perform the damage diagnosis of the bridge in this study, it is also required to have the force data of the stay cables besides their natural frequencies. Hence, an iteratively search process, based on a finite-element cable model, was proposed to obtain the cable force and the exact values of EI and l simultaneously on the basis of the identified modal parameters of stay cable (Lee et al., 2006).

2.2. Force Variations of Cable System

A preliminary study was performed to provide the information about the force variation of the cable system of Chi-Lu cable-stayed bridge subjected to unusual loading conditions. Based on the consideration of the location of the bridge, it was presumed that possible unusual loads are EQ, differential settlement, abnormal overloading, wind, etc. and the types of the bridge damages are on girder, pylon and cable breakages. The finite-element model of the bridge was constructed to analyze the force variation of the cable system to different unusual loading conditions. Fig. 3 displays the force variation of each stay cable for the settlement analysis, in which major change of the force occurs at outer cables near the end piers and almost symmetrically in relation to the pylon. It is not difficult to realize that the force variation of the cable system should be also symmetrical for any possible differential settlement of the piers. In considering the case of static overloading, one ton/m uniform load was placed on the girder, and the corresponding force variation of the cable system is shown in Fig. 4. The result indicates that the major change of the cable forces symmetrically distributes on the central part of the cable system. In considering the load case after EQ, it focused on the redistribution of cable force associated with the structural damage of the bridge caused by seismic force. The damage condition of Chi-Lu cable-stayed bridge in the 921 EQ is taken into account in the analysis. From a series of structural analysis, it can be concluded that the major change of the cable forces concentrates on the stay cables near the damage locations, except the damage occurring at middle pier. Fig. 5 demonstrates the force variation of the stay cables caused by the simulated damage at girder near the cable No. 24 with different magnitudes. By comparing the variation condition of cable forces shown from Fig. 3 to Fig. 10, it can be roughly concluded that each unusual loading condition can be distinguished from the individual variation of cable force from the analysis. Accordingly, a NN with the input data from measured ambient cable vibration was trained to recognize the type of the unusual loading conditions.

3. SOFT COMPUTING TECHNIQUE

Different from the traditional hard computing method, the soft computing method are a collection of computational techniques in computer science, machine learning and some engineering disciplines, which study, model, and analyze complex phenomena. The features of soft computing techniques includes imprecision tolerant, adaptation and evolution of the system within the ever changing environment so they can handle situations with uncertainty, lack of sufficient information, and scatter in data (background noise). Known as a biologically inspired soft computing tool, neural networks (NNs) possess a massively parallel structure and provide their learning capabilities. It is the learning ability which differ the NN from other mathematically formulated methods, and allows the development of NN based methods for certain mathematically intractable problems. The neurons of the NN were able to process the signals from the neurons of the previous layer and send signals to the neurons at next layers. The knowledge learned from the training data was stored in the connected weights among the neurons. The whole NN works as a highly nonlinear system capable of dealing problems with imprecise data as well as acceptable prediction ability (generalization). Therefore, the NN is very suitable for SHM/D applications. Since 1989, Venkatasubramanian and Chan successfully applied NNs on structure health diagnosis. In 1995, Pandey and Barai proposed a method of damage prediction for truss bridge structures using multilayer perceptron. Later, Barai and Pandey (1997) use NNs to monitor the damage of the element on a truss bridge of railway while receiving the vibration signals. At the same year, Liu and Sun use NNs to analyze the structural health for the elements of a three-span single-supported bridge, the training data were generated using finite element model. Chan et al (1999) use NNs to diagnosis the damage degree of Tsing-Ma Bridge by monitoring the variation of cable forces. In 2001, Huang and Loh proposed a NN approach to identify the nonlinear dynamic system under strong EQs, and verified this method by a numerical model with a real bridge structure. More recently, Lee et al (2003) were concentrating on the research using NNs on SHM/D for cable-stayed bridges and obtained good results, and Zhu and Qian (2005) proposed a SHD method using NNs and indicated that the more input parameters (frequency plus mode shape), the more accurate results can be obtained.

The authors used a bunch of NNs to monitor the structural health of cable-stayed bridge for different abnormal loading change and to diagnosis the safety. The method is applied using the field measurement and analysis result from Chi-Lu cable-stayed bridge. Five feed forward back-propagation NNs trained by different types of inputs constituted the grouped NNs. The architecture of each NN among the group is set to be different. Among them, one NN is trained for distinguishing the damage type with temperature effect (noise), while another four NNs were trained for recognizing damage scope/degree and location with different causes (such as EQ, over design uniform loading, differential settlement, wind, cable breakage, etc.). The methodology can be extended to include fuzzy logic for warning or action thresholds to form a robust cable-stayed bridge SHM/D system.

4. CASE STUDY – CHI-LU CABLE-STAYED BRIDGE

The proposed methodology is applied on the Chi-Lu cable-stayed bridge, which is a single-pylon symmetric structure with two 120 m main spans. During the re-tensioning stage of the whole cable system in a nearly completed main structure, the bridge was stricken by a Ms 7.3 strong EQ that occurred about 3 kilometers north of the bridge in 1999 (Chang, 2004). It was observed that most of the major structural components were severely damaged after the EQ. In late 2004, the bridge was officially opened when its safety was confirmed experimentally. In order to make sure its long-term structural safety in service phase, the monitoring system is being constructed to diagnose the health condition of the bridge.

4.1. Methodology

Since the stayed-cable is the main path for load distribution on cable-stayed bridges, the changing stress condition of the bridge after the EQ can be detected from the stayed-cables. The NNs were used to distinguish the cause and the scope of the abnormal loading condition on the bridge including EQ, strong wind, differential settlement, distributed loading (over layered AC, overweight truck, and traffic jam, etc.) from in-situ measured cable forces even with noisy data. The influence of temperature on measurement data is also considered and discussed. The cause (type) and scope of the un-usual loading condition was recognized through the cable forces of the stayed-cables using NN. With the bridge safety index and alert or action level described in the bridge maintenance guideline, the safety of the cable-stayed bridge can be assured and the maintenance cost can be reduced.

4.2. Training of the Grouped Neural Networks

From analysis result, when the pylon or the pier of the bridge is suffered from damage, the variation of the cable force is not as obvious as the variation of the modal frequency. However, if the girder suffered from the damage, the variation of the cable force is much more obvious than the modal frequency. Therefore, the monitoring of the cable force plus modal frequency is very helpful for us to discover the damaged elements as well as the type and the scope of the damage to the cable-stayed bridge. The NNs were divided into several groups for different type of loading. One NN is trained to distinguish the type (NN-T), while other NNs are trained to monitor the damage caused by the EQ (NN-D), the strong wind (NN-C) and the differential settlement (NN-S) as well as uniform over-loading (NN-U). Figure 3 shows the variation of the cable force caused by differential settlement on left pier and figure 4 the variation of cable force caused by uniform loading. As for the influence of EQ, the main concern is the re-distribution of the cable force and the change of the modal frequency of the bridge. The damages on the pylon, the girder, and the pier with different location and scope were considered. Figure 5 shows the variation of cable force caused by the breakage of L-3 cable (single) due to earthquake. Figure 6 shows the variation of cable force caused by breakages of L-24 and R-24 (two cables) due to earthquake. Figures 7-10 show the variation of cable force caused by damages on main girder due to earthquake. Figure 7 shows the distribution of cable force variation when damage happened on main girder between cables 29 and 31. Figure 8 shows distribution when damage happened between cables 3 and 5 while figure 9 and 10 show the distributions due to damage between cables 14, 16 and 32, 34.

The architecture of the NNs for Chi-Lu cable-stayed bridge include 4 layers, which are one input layer with 35 neurons, 2 hidden layers, and one output layer with various neurons. The training data were prepared by SAP 2000 with models of Chi-Lu cable-stayed bridge (Table 1). Several groups of simulated data for damaged structure with earthquake, differential settlements, and uniform over-loading are created using analytical model of Chi-Lu cable-stayed bridge. There are 1200 sets of data in each group. 80% of the data sets were used for training the NN and the rest of the data were then used to test the generalization ability of the trained NN. The input data for the NN is the cable forces within 34 stayed-cables of the Chi-Lu cable-stayed bridge plus noise. The output of the NN indicates the type of the abnormal loading or damage (NN-T), and the location and the scope (degree) of the damage (NN-D, NN-C, NN-S, NN-U). For example, 0-0-1 in the first 3 neurons indicates differential settlement was happened and 0-0.01-0.03 in neurons means there are 1 cm settlement at the pylon and 3 cm settlement at the right pier (end of bridge). 1-0-0 in the first 3 neurons indicates the damage of main girder by EQ was happened and 0-0-1-0-0-1-0-1 indicates the location of the damage while 0.1 means the scope of the damage. The NNs were trained using the numerical data first and then the measured field data lately for calibration. The analysis on the cases of insufficient input data for the NNs based SHM/D method is also performed. The results of the trained NNs can distinguish the damage type, location and scope from the measured cable force successfully, even with insufficient measurement or error within 20%. Thus, the SHD using soft computing technique for cable-stayed bridge after EQ did improve the efficiency of the maintenance procedure.

5. SUMMARY

The SHD of cable-stayed bridge becomes very important recently. Ambient vibration and soft computing technique such as NN are applied to build a more robust SHD system. The precise natural frequencies of the measured cable can be obtained without difficulties since the development of the measuring equipments and parametric identification methods of cable vibration. Thereafter, an accurate cable force is calculated by using the empirical formula or finite-element method. At last, the trained NN are used for the recognition of the type and degree for the damages (the cause and the scope of the abnormal loading conditions) including differential settlement, EQ, strong wind, distributed loading, and then the health condition of Chi-Lu cable-stayed bridge is assessed to make sure the structural safety in service phase. The field engineers will be assisted with the proposed methodology to conduct SHD for cable-stayed bridges practically and save time on the procedure of bridge maintenance tasks. Meanwhile, the applications of grouped NN on SHM/D for cable-stayed bridges show high potential and the feasibility to solving inverse problem without unique answers for other similar bridges.

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Table 1 The samples of training data for neural networks (include different types of damages)

		1	3	4	1	4	6
INPUT（CABLE FORCE VARIATION）	Cable-01	0.00290	0.04701	37.6023	-0.4841	-89.4064	-28.3709
	Cable-02	-0.00472	0.04701	-3.451	-0.551	-10.5704	28.3709
	Cable-03	0.00152	0.05345	37.1188	-2.6523	-57.8824	-16.6556
	Cable-04	-0.00336	0.05345	-2.3246	-0.3803	-6.4696	16.6556
	Cable-05	0.00083	0.06607	19.768	-5.6517	-44.232	-11.8595
	Cable-06	-0.00289	0.06607	-1.9661	-0.3313	-4.7992	11.8595
	Cable-07	0.00029	0.06498	29.3828	-7.9669	-28.1248	-7.1113
	Cable-08	-0.00205	0.06498	-1.2485	-0.2502	-3.0024	7.1112
	Cable-09	0.00003	0.06995	23.6053	-11.3575	-20.0712	-4.8336
	Cable-10	-0.00166	0.06995	-0.8734	-0.216	-2.1424	4.8335
	Cable-11	-0.00010	0.08379	21.0376	-8.2428	-16.1216	-3.7632
	Cable-12	-0.00147	0.08378	-0.6683	-0.2089	-1.7752	3.7631
	Cable-13	-0.00010	0.08466	15.8103	-3.194	-10.9136	-2.5683
	Cable-14	-0.00088	0.08465	-0.4116	-0.1695	-1.3232	2.5681
	Cable-15	0.00004	0.08355	11.6089	-0.2561	-7.0904	-1.831
	Cable-16	-0.00018	0.08353	-0.2203	-0.135	-1.0736	1.8308
	Cable-17	0.00029	0.08060	8.33	1.3455	-4.2856	-1.4289
	Cable-18	0.00064	0.08058	-0.0784	-0.1078	-0.9928	1.4286
	Cable-19	0.00065	0.07593	5.8241	2.108	-2.208	-1.2707
	Cable-20	0.00162	0.07590	0.0276	-0.0892	-1.0568	1.2705
	Cable-21	0.00109	0.06966	3.9437	2.3515	-0.6424	-1.2876
	Cable-22	0.00274	0.06963	0.1086	-0.0792	-1.2448	1.2874
	Cable-23	0.00202	0.07950	3.2811	2.9306	0.7368	-1.8321
	Cable-24	0.00498	0.07946	0.2217	-0.0998	-1.9776	1.8318
	Cable-25	0.00223	0.05301	1.5548	2.0398	1.56	-1.6501
	Cable-26	0.00542	0.05297	0.2258	-0.0844	-1.932	1.65
	Cable-27	0.00360	0.05521	1.0841	2.1857	3.0752	-2.462
	Cable-28	0.00862	0.05515	0.3495	-0.1249	-3.0808	2.4619
	Cable-29	0.00447	0.04122	0.451	1.701	4.0448	-2.8397
	Cable-30	0.01062	0.04134	0.4044	-0.1479	-3.76	2.8256
	Cable-31	0.00536	0.02696	0.0336	1.2177	4.9168	-3.175
	Cable-32	0.01267	0.02697	0.4564	-0.1748	-4.4912	3.1697
	Cable-33	0.00503	0.00970	-0.1843	0.5838	4.4768	-2.7001
	Cable-34	0.01184	0.00978	0.3938	-0.1579	-4.0824	2.6918
OUTPUT	Type	0	0	0	1	1	1
		0	1	1	0	0	0
		1	0	1	0	0	0
	Damage Scope, Location	0	0.086	0	0	1	0
		0.01	0.086	0	0	0	0
		0.03	0.086	0	1	0	0
				0	0	0	0
				0	0	1	0
				1	1	1	0
				0	0	0	1
				0	1	1	1
				1	0.1	0.8	0.65
				1			
				1			
				1			
				1			
				1			

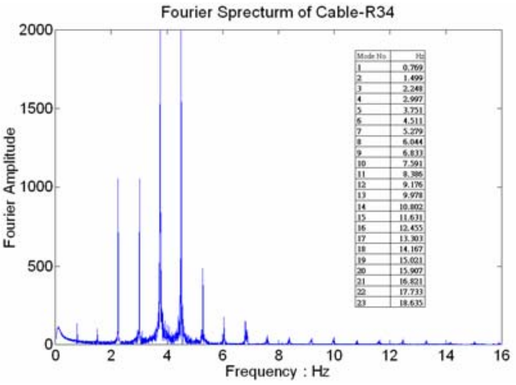

Figure 1 Fourier spectrum of cable R-34

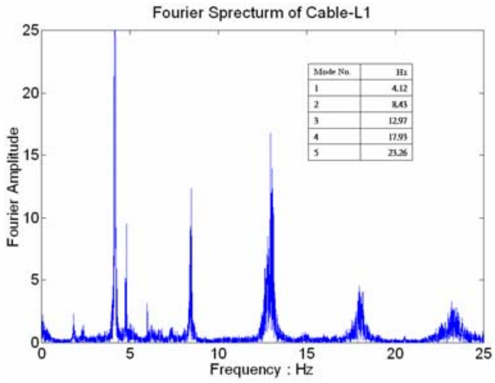

Figure 2 Fourier spectrum of cable L-01

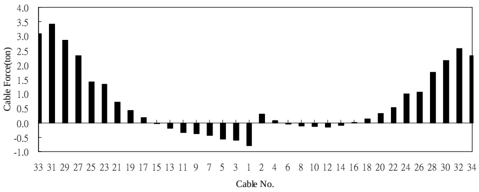

Figure 3 Variation of cable force caused by differential settlement on left pier

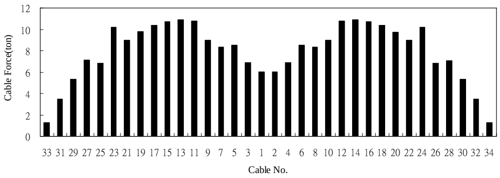

Figure 4 Variation of cable force caused by uniform loading

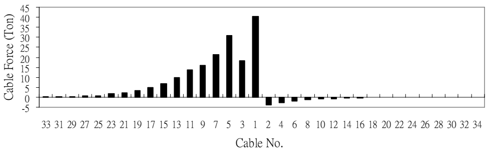

Figure 5 Variation of cable force caused by single cable breakage (L-3)

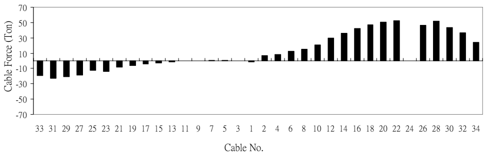

Figure 6 Variation of cable force caused by two cable breakages (L-24 and R-24)

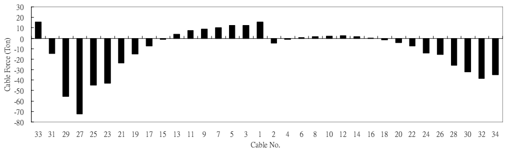

Figure 7 Variation of cable force caused by EQ (damage on main girder between cables 29, 31)

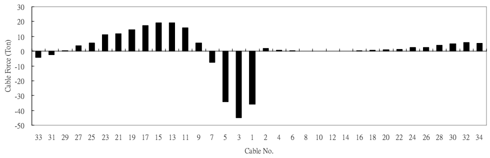

Figure 8 Variation of cable force caused by EQ (damage on main girder between cables 3, 5)

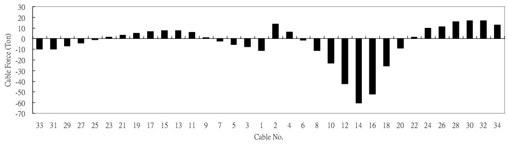

Figure 9 Variation of cable force caused by EQ (damage on main girder between cables 14, 16)

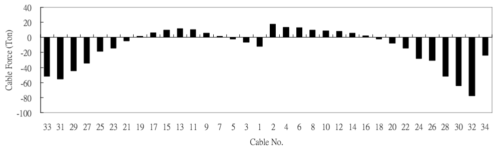

Figure 10 Variation of cable force caused by EQ (damage on main girder between #32, 34)