Finite Element Linear Model Updating to the Sei Dareh Cable-Stayed Bridge with Load Testing Result

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ABSTRACT
The earthquake load gives a susceptible to the cable stayed bridge, because the cable bridge become lighter, slender and more sensitive to dynamic loads. As a case study, there was a Sei Dareh Cable-Stayed bridge that located in a relatively high level of susceptibility based on 2017 earthquake map. The paper presents a finite element (FE) linear model updating procedure for FE model of Sei Dareh cable-stayed bridge based on static and dynamic load measurements. Several parameters that will be updated by sensitivity analysis using FEMtools software were the natural frequency of mode shape, material properties such as modulus of elasticity and geometric properties such as radius of gyration and cross section of inertia are also considered in the study.

Keywords: *Cable stayed bridge, linear model updating, Sei Dareh, FEMtools.*

1. INTRODUCTION

The earthquake load gives a susceptible to the cable stayed bridge, because the cable bridge become lighter, slender and more sensitive to dynamic loads [1]. As a case study is the Sei Dareh cable-stayed bridge which is located in West Sumatera that has a relatively high level of vulnerability to earthquake. Therefore, it was important to analyze and simulate the behaviour of the bridge under seismic load with three dimentional Finite Element Model (3D-FEM) that reffer to as built drawing.

Even though, the generated 3D FEM models often behave differently from the real bridges in the field. This caused by simplification of assumptions made in modeling complex structures and error parameters due to material uncertainty and geometric properties and boundary conditions [2]. Therefore, a method to provide a match between the results of dynamic testing and the results of numerical modeling which is called the updating model was established in 1990.

Finite element model updating is a procedure to determine uncertain parameters in the initial model based on experimental results to achieve a model of the structure that better matches the experimental result [3]. Based on the Regulation of the Director General of Highways No. 4 of 2020, model calibration is carried out to determine the material properties and cross-sectional properties of the bridge structural elements that are reviewed such as the modulus of elasticity of the bridge material, the density of each material used, the stiffness of the bearings, the cross-sectional area of the components. structure, moment of inertia of the member cross-section and others.

Based on the reason, the paper presents a finite element (FE) linear model updating procedure for FE model of Sei Dareh cable-stayed bridge based on static and dynamic load measurements. Several parameters that will be updated by sensitivity analysis using FEMtools software were the natural frequency of mode shape, material properties such as modulus of elasticity and geometric properties such as radius of gyration and cross section of inertia are also considered in the study.

2. LITERATURE REVIEW

In the present, FE model updating become a key method to obtain the high accuracy FE model that matches as closely as possible with the existing bridge in the field. Some researchers have been study about the FE modeling on the Cable Stayed bridge. As an example was the paper assess the application of sensitivity based model updating technology to Safti Link Bridge, a curved cable-stayed bridge in Singapore [2]. The simulated dynamic properties obtained by finite element analysis have been significantly improved by modification of uncertain structural parameters such as young’s modulus of concrete and structural geometry. The similar studies were also established to Qingzhou cable-stayed bridge in Fuzhou [4], Sutong and Runyang cable-stayed bridge in Yangtze River [5], Stonecutters cable-stayed bridge in Hongkong [6], Seohae cable-stayed bridge in South Korea [7], and 12-span of Newmarket Viaduct in Auckland [8]. These studies carried out the finite element model updating based on dynamic load test and ambient vibration test.

The model updating was also used to identify the structural failure on several element of bridge like on the slabs and the cable. [9] discussed a new static-based method for failure detection of cable-stayed bridges using the changes in cable tension forces. The verification of the method was simulation by 3D-FEM studies failure detection of Sutong cable-stayed bridge. The result shows that the proposed method correctly identifies the failure location and failure magnitude in bridge girder when using noise-free cable forces. Similarly to the slabs, [10] studied a behavior of flat cantilever steel plate under excited with an impulse hammer to measure the vibration responses. By the experiment, the resonant frequencies and mode shapes of the structure at undamaged and damaged condition was obtained. After that, the experimental test specimen was numerically modelled using 3D-FEM which was interfaced with the FE model updating method. At the end, it found that the update finite element model shows a significant improvement on FEM-testing correlation of the modal parameter.

To obtain the high accuracy data when the finite element model updating carried out, the scaled model of cable stayed bridge was established. The 1:12 scaled reinforced concrete pedestrian cable stayed bridge was excited with shaking table test. Then, a fiber frame element-based nonlinear model and a new nonlinear model updating was built in OpenSees. From the research, this proposed method was tested and matched well when comparing updated RC bridge model and scaled model [11]. A scaled structure of the Sutong cable-stayed bridge in China was adopted as a case study. The simulated response time histories and the measured response time histories for the scaled bridge under medium and strong ground motions was observed. The result showed the proposed nonlinear 3D-FE model updating method was feasible and accurate for updating a long span cable stayed bridge. By the similar bridge and method, the author [12] discussed a collapse prognosis of a long-span cable-stayed bridge. From the research, the predicted structural responses and final failure mechanisms were compared with the measured responses and experimental observations with good agreement. It was indicated that the proposed method was suitable and accurate for evaluating the seismic performance and failure mechanisms of long-span cable-stayed bridges

2.1 Sensitivity Analysis

Determination of the parameters to be updated as in point (6) on methodology is the key to the success of the calibration of the structural model because it will determine whether the model made is closer to the real conditions in the field or not. The updated parameter has uncertainties in its value, for example the geometric structure, material properties of the structure. An example is the modulus of elasticity of the concrete material. It is possible that the value of the modulus of elasticity of the concrete material tested in the laboratory is as planned because the laboratory is a conditioned environment. Unlike the case when laying fresh concrete in the field, several factors such as changes in temperature, humidity, errors in laying and curing process affect the quality of the resulting concrete. This causes the uncertainty of one of the many parameters that exist. Because each parameter has its own level of probability of uncertainty, it is necessary to determine in advance the most dominant parameter by means of sensitivity analysis.

Although sensitivity analysis can automatically be done with FEMtools, in general the equation model that describes the sensitivity analysis for this updating model is as stated by Friswell and Motteershead (1995):

$$\{R_e\} = \{R_a\} + [S](\{P_u\} - \{P_0\}) \quad (1)$$

$$\{\Delta R\} = [S]\{\Delta P\} \quad (2)$$

$$[S]_{ij} = \frac{\partial R_i}{\partial P_j} \quad (3)$$

$\{\Delta R\}$ is a vector that shows the difference between the field test vector $\{R_e\}$ and the finite element modeling vector $\{R_a\}$. $\{\Delta P\}$ indicates the difference between the updated parameter vector $\{P_u\}$ and the vector of the pre-updated initial parameter $\{P_0\}$. [S] is a sensitivity matrix consisting of eigen sensitivities for different modes where R_i and P_j denote the i-th modal vector component and the j-th updated parameter vector component.

2.2 Correlation Analysis

In order to correlate the results of the finite element model and field testing measurement it was important to carried out the Modal Assurance Criterion (MAC) as shown in equation (4). MAC is a value in the form of an index that states how close the finite element model is to the measurement results in the field. The differences between both of them were not allowed exceeding 10%.

$$MAC\ (\phi_a, \phi_e) = \frac{\left|\phi_a^{\ T} \phi_e^{\ T}\right|^2}{(\phi_a^{\ T} \phi_a)(\phi_e^{\ T} \phi_e)} \tag{4}$$

where ϕ_a and ϕ_e = analytical and experimental mode shape vectors, respectively. The superscript *T* denotes the vector transpose.

3. METHODOLOGY

The research was initiate by make the initial 3D-FEM of the bridge structure. Then, the model updating was carried out in order to obtain the 3D-FEM that as closely as to existing bridge. Model updating was done by exporting the initial 3D-FEM and then inputting them into the FEMtools software to automatically. The model updating steps are carried out as follows [13] :

1. Creating an initial 3D-FEM with SAP2000 software
2. Exporting the initial model from sap2000 software to model updating software as known FEMtools
3. Importing the measurement test data to FEMtools software
4. Comparing the field load test data and initial model
5. Determining an allowable bonds ranges of changes parameter
6. Selecting the parameter that will be to be update
7. Performing sensitivity analysis to select the most dominant parameter to the overall structural model
8. Performing the iteration automatically or manually until the convergence criteria are met
9. After the iteration process was complete, the updated finite element model was obtained (updated model).

Based on point number 3 before, to update the model it needed the load test data for input to FEMtools software. Therefore, the static and dynamic load test that have been done on 2019 would use in this case. Load test data that would be use was natural frequency, deflection of the beam, the tilt of pylon, and strain on the steel box beam. As an example, **Table 1** show the natural frequency of bridge under dynamic load test.

Table 1. Natural frequency

Te-st	**Span (P1-P2)**	**Vertical Frequency (Hz)**		**Te-st**	**Span (P2-P3)**	**Vertical Frequency (Hz)**	
	Sche-me	**Pe-ak 1**	**Pe-ak 2**		**Sche-me**	**Pe-ak 1**	**Pe-ak2**
1	1A	1.18	1.87	1	2A	1.21	1.88
	1B	1.18	1.88		2B	1.18	1.88
	1C	1.17	1.85		2C	1.21	1.88
2	1A	1.17	1.88	2	2A	1.21	1.88
	1B	1.16	1.87		2B	1.18	1.88
	1C	1.20	1.88		2C	1.21	1.88
3	1A	1.18	1.86	3	2A	1.18	1.88
	1B	1.18	1.86		2B	1.18	1.85
	1C	1.18	1.86		2C	1.18	1.88

Among the parameters that are planned to be carried out for model model updating in this study are as shown in **Table 2** below. The selection of the parameters was based on the uncertainties like described on sub 2.1.

Table 2. Parameter to be updated

Element	**Parameter**
Cable	Elasticiy modulus
	Stressing cable force
Steel Box Girder	Elasticiy modulus
	Mass density
	Sectional area
	Section inertia (vertikal)
	Section inertia (lateral)
Stringer Girder	Elasticiy modulus
	Mass density
	Sectional area
	Section inertia (vertikal)
	Section inertia (lateral)
Cross Girder	Elasticity modulus
	Mass density
	Sectional area
	Section inertia (vertikal)
	Section inertia (lateral)
Pylon	Elasticity modulus
	Sectional area kaki *pylon*
	Sectional area *cross bottom pylon*
	Section inertia (z-z) *cross bottom pylon*
Connections and boundary conditions	Support at pylon legs
	Constrain between *cross bottom* girder and steel box girder

AUTHORS' CONTRIBUTIONS

This work lead by Afdhal, he modeled the structure, analyzed amd wrote the manuscript of extended abstract. Riawan was reviewed and evaluated the written manuscript and conceptual

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