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# Ambient vibration testing and finite element model updating of a concrete footbridge

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**ABSTRACT**: The paper aims to present finite element (FE) model updating process of a concrete footbridge using output-only measurement. The FE model of the structure under investigation was developed by ABAQUS before to proceed with ambient vibration testing. The natural frequencies and their associated mode shapes of the structure were identified by analyzing ambient vibrations data using frequency domain decomposition technique in ARTeMIS. Applying design of experiment technique (DOE) on selected structural parameters and manual tuning by trial and error resulted in better correlation between FE and measured modes. Subsequently, automatic updating using FEMtools based on prototype testing improved the simulated dynamic properties obtained from initial FE analysis in a meaningful way. In updating procedure, the most uncertain structural parameters i.e. stiffness values of spring supports were modified so as to acquire the best possible match between test and FE data.

## 1 INTRODUCTION

The technology of finite element model updating has been widely applied to the civil engineering structures and particularly to the bridges in recent decade. The exercise were carried out for the purposes such as model updating of bridges (Cantieni, 2009, Cantieni et al., 2008), (Turek et al., 2010), (Caetano and Cunha, 2002) and dynamic assessment (Brownjohn and Xia, 2000) using modal testing approach. The aim of this paper is to describe the use of modal test data in the manual and automatic updating of FE model of a concrete footbridge.

## 2 DESCRIPTION OF TEST STRUCTURE

The test structure is a 37m reinforced concrete footbridge, comprises of three spans fixed differently at two end abutments, one side is sticking in the mood and the other side cutting from the pavement. There are four structural parts which connect the footbridge to the ground; two cross beams at end abutments and two cross frames at intermediate supports. Also, there is a longitudinal I-beam stiffener at mid span underneath the surface of footbridge. The depth of concrete slab is 0.09m with a curve shape in elevation view of structure. Further details about the cross section, plan and elevation views are given in Figure 1.

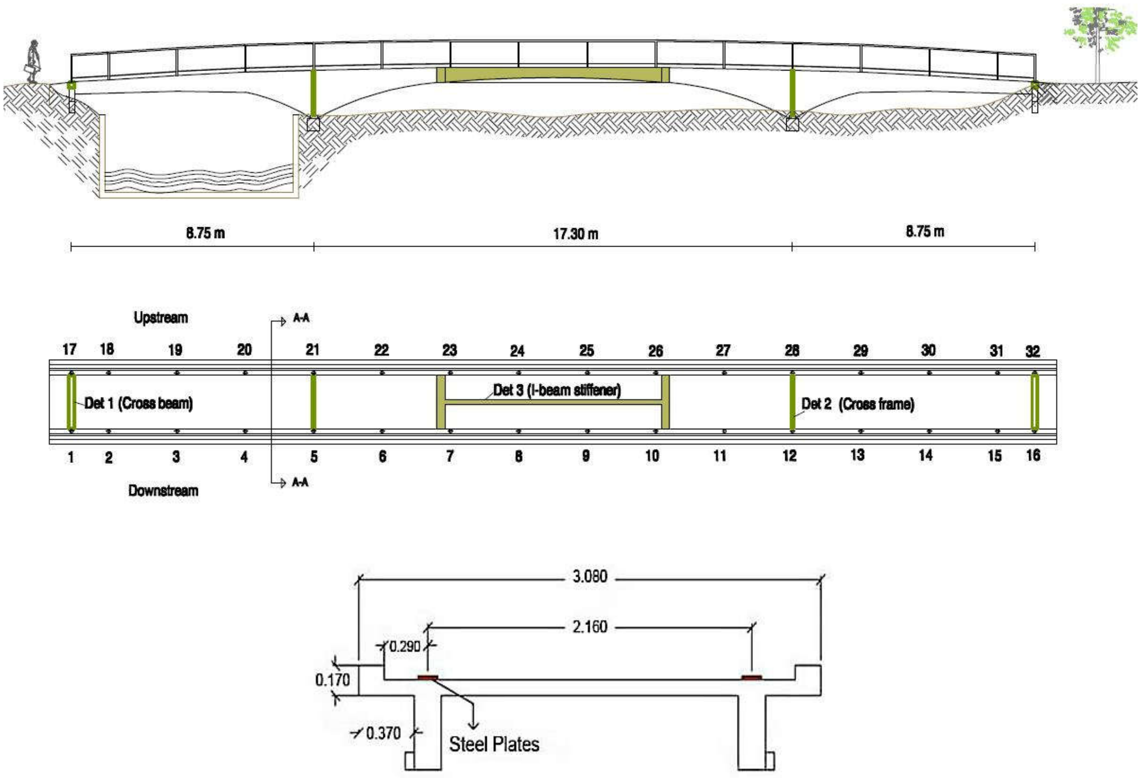


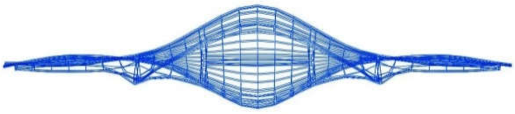
Figure 1: Elevation, plan views and cross section of the footbridge

## 3 FINITE ELEMEN MODELLING

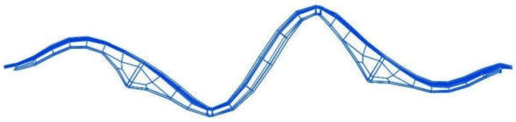
A 3-D FE model was constructed using C3D8 and SPRING1 elements of ABAQUS 6.7-1 (ABAQUS, 2010). The C3D8 is an 8-node linear brick which was used to model the surface, side walls, cross beams, cross frames and I-shaped stiffener beam of the footbridge. In order to model the elastic supports, SPRING1 which is an element between a node and ground, acting in a fixed direction was chosen for all supports of structure at three directions. The justification to choose spring elements can be stated as the soil surrounded the footbridge has produced a flexible behaviour for the structure at end and intermediate supports. The stiffness values for springs in X and Y directions are 1E+8 N/m and in Z direction 1E+7 N/m. The values of 2500 kg/m$^3$, 2.1E+10 N/m$^2$ and 0.2 were used for mass density, Young's modulus of elasticity and Poisson's ratio respectively. A free vibration analysis was performed to extract natural frequencies and mode shapes of the footbridge. The six FE mode shapes were estimated from 7.58 to 20.88Hz which is displayed in Figure 2. Information provided by initial finite element model was applied to plan the test strategy for 1-D and 2-D ambient vibration measurements.

Lateral mode at 7.58 Hz

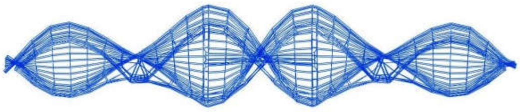
1st Bending mode at 8.66 Hz



1st torsion mode at 12.09 Hz



2nd bending mode at 14.85 Hz



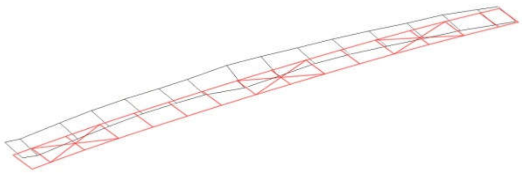
2nd torsion mode at 20.88 Hz

3rd bending mode at 20.53 Hz

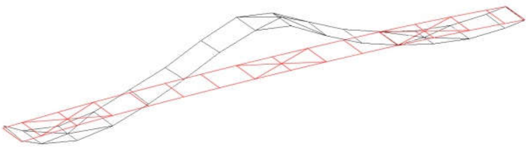
Figure 2: Modes of vibration calculated from the initial FE model

## 4 AMBIENT VIBRATION TESTING (AVT)

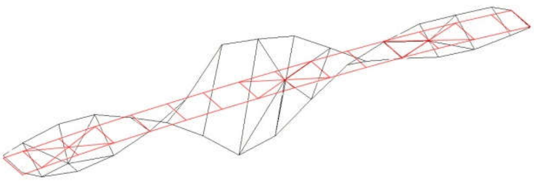
In order to identify the footbridge, two sets of tests were conducted. The first one scanned the structure using four rovers while three 1-D sensors were placed as references at test points 9, 19 and 29. The data was analyzed using enhance frequency domain decomposition (EFDD) technique of ARTeMIS (ARTEMIS, 1999-2002). The five bending and torsion mode shapes of the structure were identified. The results of 1-D measurement are shown in Figure 3. The second ambient vibration test was planned so as a 3-D reference sensor measured the response of structure at test point 26 and the four roving accelerometers were used to record the data in two dimensions; vertically and longitudinally/laterally. Analyzing test data using EFDD method revealed an additional lateral mode at 6.58Hz (Figure 3).



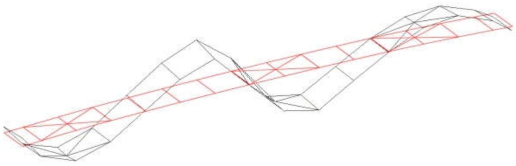
EFDD lateral mode at 6.85 Hz



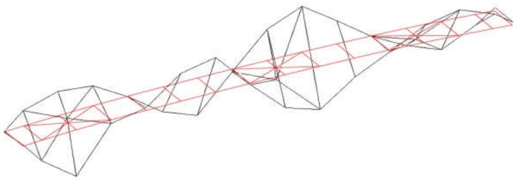
EFDD 1st bending mode 2 at 7.55 Hz



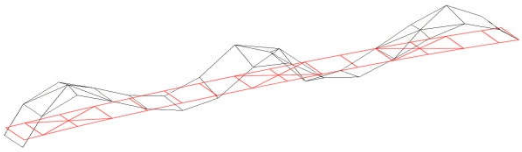
EFDD 1st torsion mode at 10.53 Hz



EFDD 2nd bending mode at 13.37 Hz



EFDD 2nd torsion mode at 17.61 Hz



EFDD 3rd bending mode at 20.43 Hz

Figure 3: EFDD mode shapes of 1-D and 2-D AVT

## 5 UPDATING PROCEDURE

Calibration and updating the primary finite element model based on test data was performed in four steps using FEMtools 3.4 (FEMtools, 1994-2009). The three criteria of updating procedure, i.e. natural frequencies, modal assurance criteria (MAC) and mode shapes were taken into account. To create a complete set of test data, the number of five mode shapes from 1-D AVT was selected and one lateral mode identified from 2-D AVT was added to test data to be used for updating process.

### *5.1 FE model tuning*

There were FE mode counterparts for all six modes identified experimentally. However, the sequence of 3rd bending mode and 2nd torsion was reversed compared to their test mode shape pairs. Also, natural frequencies of all experimental modes were overestimated. The maximum frequency error was %18.52 which is quite large and displays the difference between FE-test pairing identified as 2nd torsion mode. All mode shapes were correlated with the MAC values higher than %75.4. Checking the identified mode shapes and comparing them with initial FE model found that the mid span is too stiff and the lower stiffness values are required to be introduced for intermediate supports. In order to find better starting values for spring stiffness and also improve the correlation of analytical and experimental mode shape counterparts, a design of experiment (DOE) procedure was applied. To conduct this analysis, each four springs which represented one support at end abutments and intermediate supports were grouped as one. That means there were a total number of thirty sets of $K_x$, $K_y$ and $K_z$ chosen as DOE parameters. Consecutively, the six test frequencies and six test MAC values were selected as responses. The results obtained from DOE analysis modified the order of FE mode shapes and also decreased the frequency error to %11.65, though the MAC values were being reduced to %58 and %47 unexpectedly for lateral and 3rd bending modes respectively. The 2nd and 3rd mode shapes did not represent good correlation at end supports. The COMAC was used to assess the amount of movement that should be allowed at the end supports. COMAC for DOF UZ is displayed in Figure 4 as an example.

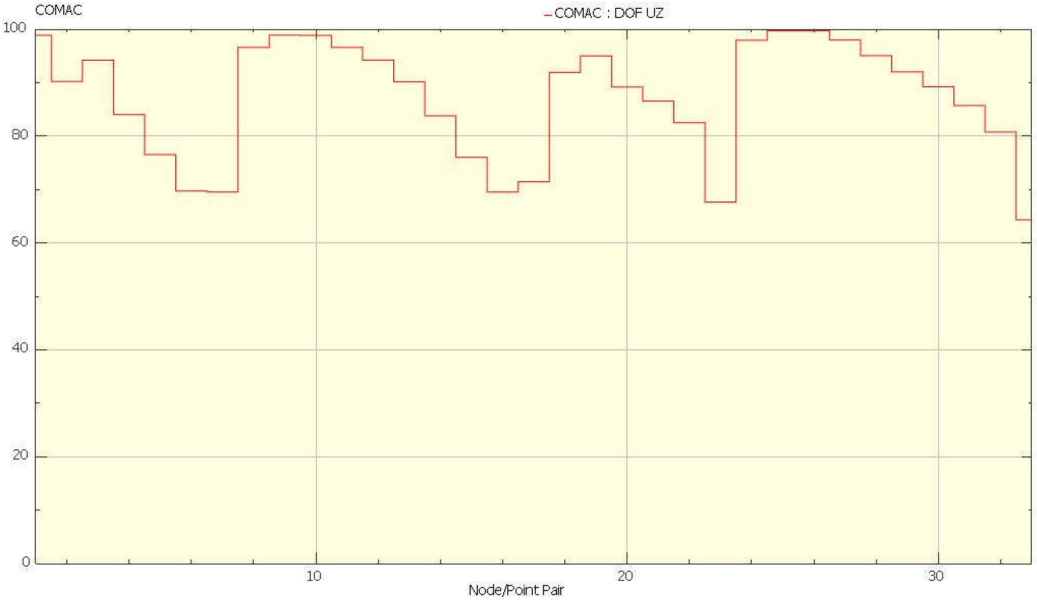


Figure 4: COMAC for DOF UZ

### *5.2 Parameter and target response selection*

Having reduced the maximum frequency error in manually tuned model from %18.52 to %11.65 and matching the sequence of experimental and FE modes made the automatic updating process being conducted more efficiently. The most uncertain parameters which contributed to build the initial FE model of this footbridge were spring stiffness values of supports. This is because of the dynamic behaviour of supports provided by test data. The settlement of about 0.05m of structure at one side and the soil surrounded it which is not enough rigid, as well as the condition of two abutments which one is totally free and the other one is sticking in the mud had made a significant uncertainty about boundary conditions. Sensitivity analysis revealed that the Young's modulus of elasticity and mass density are not that much effective on updating process, therefore, they were not considered as updating parameters.

All six measured modes of vibration were selected for automatic updating task. Therefore, the total number of 34 responses consists of all test natural frequencies, MAC values and mode shapes were included. Considering the results of manual tuning and DOE it was found that if natural frequencies were the only updating criterion selected, the updating procedure does not produce successful results. As a result, the MAC values and mode shape of the FE and test results were added as target selections too. However, the level of confidence in natural frequencies is a factor of ten higher than that assigned to the mode shapes (FEMtools, 1994-2009) and (Pavic et al., 1998).

### *5.3 Updating process and results*

The updating procedure was conducted by setting up the values of EPS1 to 0.1, EPS2 to 0.01 and limiting DP/P value to %5. The process was stopped after fifteen iterations. The lowest MAC value was increased to %77.3 for 2nd torsion mode. Checking the sensitivity matrix and focusing on more sensitive parameters led to choose only 19 parameters out of total 30 stiffness values. Also the target responses were limited to only two test frequency and test MAC of 2nd torsion mode shape. The process was converged after seven iterations. The updated frequencies, frequency differences and mode shape correlation MAC values between updated and measured models are given in Table 1. These show the maximum frequency errors of only %6.75 and high MAC values all being above %84.2. Figure 5 represents the MAC matrix with high values on its diagonal corresponding to paired modes. The mode shapes of updated footbridge model are displayed in Figure 6 and are closed to the measured mode shapes. All of these comparisons between updated and measured data illustrated that the model updating was successful.

Table 1: Correlation between experimental and updated FE models

| No. | Measured frequency $f_m$ (Hz) | Initial FEM $f_i(Hz)$ | Difference $\frac{(f_i - f_m)}{f_m}$ (%) | Updated FEM $f_u(Hz)$ | Difference $\frac{(f_u - f_m)}{f_m}$ (%) | MAC (%) |
|---|---|---|---|---|---|---|
| 1 | 6.85 | 7.58 | 10.71 | 6.83 | -0.28 | 84.2 |
| 2 | 7.55 | 8.66 | 14.76 | 7.19 | -4.72 | 99.0 |
| 3 | 10.53 | 12.09 | 14.82 | 10.78 | 2.38 | 94.3 |
| 4 | 13.37 | 14.85 | 11.05 | 13.60 | 1.75 | 94.0 |
| 5 | 17.61 | 20.88 | 18.52 | 17.69 | 0.44 | 84.2 |
| 6 | 20.43 | 20.53 | 0.52 | 19.05 | -6.75 | 87.6 |

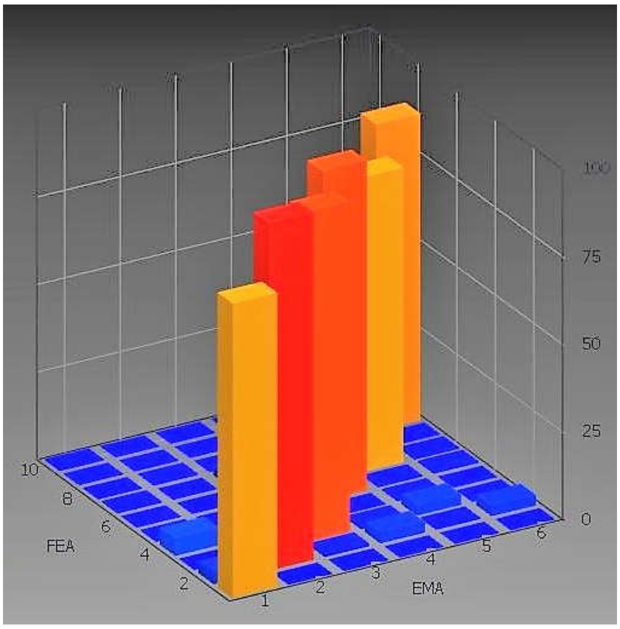
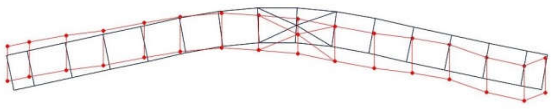
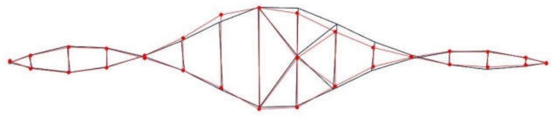


Figure 5: MAC matrix between updated and measured data



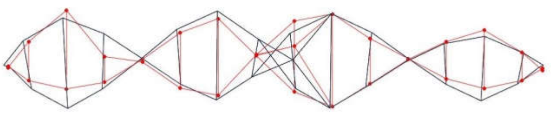
FE-test lateral mode shape pair

FE-test 1st bending mode shape pair

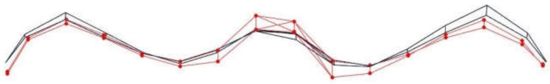


FE-test 1st torsion mode shape pair

FE-test 2nd bending mode shape pair



FE-test 2nd torsion mode shape pair



FE-test 3rd bending mode shape pair

Figure 6: Mode shapes of updated and measured models (updated FE-solid line; test-dotted line)

## 6 DISCUSSIONS

In order to do model tuning, it is essential to specify an appropriate starting value of a selected parameter to provide a good set of data. If the initial value is not in the correct order or too different from its true value, the iteration process cannot be converged. Therefore, the role of design of experiment (DOE) to find better starting values and manual updating steps could be highlighted here. The initial FE model is required to be tuned based on engineering judgement and suitable estimation before model updating. This case was specifically true for the uncertain boundary conditions of the footbridge under investigation. Also, in model updating procedure, parameter selection is a crucial step, as the FE model is affected by updating selected parameters. Those parameters chosen for updating purpose should be uncertain physically to produce meaningful results at the end of analysis. Additionally, parameters should be limited to only most sensitive and effective parameters, otherwise the updated FE model produced does not reflect the real image of structure. Thus, parameter selection should be based on the purpose of correcting uncertainties in the model built and the sensitivity of data set.

Conducting sensitivity analysis would help to determine sensitive and also low sensitive parameters which do not effect on the improvement of FE model. For this case study, performing a normalized sensitivity analysis and subsequently choosing the most sensitive parameters which could enhance the quality of correlation in two steps led to minimize the frequency error of FE-test mode pairs to %6.75 and correlate the mode shapes with MAC values all being above %84.2. Of 3o parameters which were considered as uncertain in the first step of automatic model updating, the number of 11 parameters was excluded from the updating process, since the target responses were not that much sensitive to them. Only two test frequency and MAC of 2nd torsion mode shape were targeted in second step, as the aim of updating in this level was to improve correlation between FE and measured of 2nd torsion mode shape. However, at the end of seventh iteration, MAC values of other four mode shapes were increased too.

The stiffness values of spring supports were free to increase and decrease. It was found that the supports at right side of the footbridge (fixed abutment side) were stiffer. The right cross beam which is close to fixed abutment is stiffer than left one close to free abutment. As it was expected the right side of structure sticking in the mud produces higher stiffness for supports. It is interesting here that the left cross frame represented more rigid behaviour compared to the one at right side. It could be justified as the lateral supports of the cross frame which is next to the drain wall at both up and down streams (US and DS) are 3 and 1.5 times more rigid than compared to the right side which the footbridge has a settlement of about 0.05m. It seems the interaction between soil and cross frames made a significant different between stiffness values of lateral spring ($K_y$) of left and right cross frames, while the differences between longitudinal ($K_x$) and vertical ($K_z$) spring stiffness values of both intermediate supports are smaller in amount. Furthermore, it was found that the stiffness values of vertical springs ($K_z$) do not change considerably along the footbridge while the values of $K_x$, $K_y$ varies up to 2 to 7 times along the footbridge's supports. The starting values which obtained from DOE analysis and updated values for 30 updating parameters are listed in Table 2.

Table 2: The values of starting and updated parameters

| Parameter No. | Type | Location | Starting value (N/m) | Updated parameter value (N/m) |
|---|---|---|---|---|
| 1 | $K_x$ | Cross beam(free end-DS) | 5.67E+7 | 4.75E+7 |
| 2 | $K_y$ | Cross beam(free end-DS) | 11.94E+7 | 11.20E+7 |
| 3 | $K_z$ | Cross beam(free end-DS) | 9.97E+6 | 7.87E+6 |
| 4 | $K_x$ | Cross beam(free end-US) | 4.83E+7 | 5.51E+7 |
| 5 | $K_y$ | Cross beam(free end-US) | 11.15E+7 | 11.90E+7 |
| 6 | $K_z$ | Cross beam(free end-US) | 7.86E+6 | 9.98E+6 |
| 7 | $K_x$ | Left cross frame(DS) | 2.61E+7 | 2.04E+7 |
| 8 | $K_y$ | Left cross frame(DS) | 17.51E+7 | 21.35E+7 |
| 9 | $K_z$ | Left cross frame(DS) | 6.44E+6 | 6.43E+6 |
| 10 | $K_x$ | Left cross frame(US) | 2.07E+7 | 2.30E+7 |
| 11 | $K_y$ | Left cross frame(US) | 21.40E+7 | 17.55E+7 |
| 12 | $K_z$ | Left cross frame(US) | 6.42E+6 | 6.44E+6 |
| 13 | $K_x$ | Right cross frame(DS) | 2.69E+7 | 3.94E+7 |
| 14 | $K_y$ | Right cross frame(DS) | 11.82E+7 | 6.81E+7 |
| 15 | $K_z$ | Right cross frame(DS) | 5.72E+6 | 5.66E+6 |
| 16 | $K_x$ | Right cross frame(US) | 4.63E+7 | 2.76E+7 |
| 17 | $K_y$ | Right cross frame(US) | 6.70E+7 | 11.75E+7 |
| 18 | $K_z$ | Right cross frame(US) | 5.72E+6 | 5.66E+6 |
| 19 | $K_x$ | Right cross frame(DS) | 16.06E+7 | 15.35E+7 |
| 20 | $K_y$ | Right cross frame(DS) | 1.38E+8 | 14.05E+7 |
| 21 | $K_z$ | Right cross frame(DS) | 9.70E+6 | 9.29E+6 |
| 22 | $K_x$ | Right cross frame(US) | 15.63E+7 | 16.40E+7 |
| 23 | $K_y$ | Right cross frame(US) | 14.22E+7 | 13.90E+7 |
| 24 | $K_z$ | Right cross frame(US) | 9.09E+6 | 5.36E+6 |
| 25 | $K_x$ | Cross beam(fixed end-DS) | 8.23E+7 | 9.35E+7 |
| 26 | $K_y$ | Cross beam(fixed end-DS) | 9.98E+7 | 10.20E+7 |
| 27 | $K_z$ | Cross beam(fixed end-DS) | 9.91E+6 | 9.97E+6 |
| 28 | $K_x$ | Cross beam(fixed end-US) | 9.35E+7 | 8.24E+7 |
| 29 | $K_y$ | Cross beam(fixed end-US) | 10.20E+7 | 9.99E+7 |
| 30 | $K_z$ | Cross beam(fixed end-US) | 9.96E+6 | 9.91E+6 |

## 7 CONCLUSIONS

To conduct a successful FE model updating based on available data and test analysis, following issues could be highlighted:

(1) The selection of updating parameters should be based on uncertainties exist to build the FE model. The parameters must be physically uncertain and should be sensitive to the targeted responses. Applying sensitivity analysis together with engineering judgement is a good way to select updating parameters.

(2) It is necessary to perform design of experiment (DOE) and manual tuning based on trial and error to obtain appropriate starting values of selected parameters for model updating.

(3) Applying only natural frequencies as target responses may not be sufficient for FE updating. Therefore, including MAC and mode shapes information could improve the quality and accuracy of correlation.

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