Chapter 26
Finite Element Model Updating of the UCF Grid Benchmark Connections Using Experimental Modal Data

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Abstract Structural connections are a crucial component of any structural system. The connection stiffness can impact the static and especially the dynamic behavior of a structure. Therefore, reliable finite element modeling of the structural systems involves accurate estimation of their connections stiffness parameters. Accurate representation of connection stiffness parameter is one of the most challenging steps in model verification as connections are physically small parts of a structure and some parameter estimation procedures may lack the sensitivity to change in connection behavior to capture the stiffness parameter of connection elements. One of the most well-known experimental structures which has been extensively used in the model updating research field in recent years is a structural frame set up in the University of Central Florida which is known as the UCF Grid. This experimental structure is an instrumented planar grid comprised of several steel members interconnected by gusset plates. The grid is instrumented by eight uniaxial accelerometers to capture the accelerations of the specific nodes of the structure when the grid vibrates due to an excitation. In this paper, the modal data of the grid obtained experimentally by an impact test are used for estimation of the stiffness parameters of the grid joints. A modal based error function method is employed to update the finite element model of the grid built in SAP2000® environment. For the model updating computations, an optimization MATLAB® code is linked to the SAP2000® Open Application Programming Interface to facilitate the parameter estimation procedure. The updated finite element model of the grid based on new estimations for its joints' stiffness parameters could represent the structural behavior of the grid in a more reliable scheme.

Keywords Model updating · Parameter estimation · Joint stiffness · Modal data · UCF Grid

26.1 Introduction

The interface of mechanical and structural members relay on structural connections transmit demands throughout the structure. There are various types of connections that can provide appropriate rigidity for structural joints. The stiffness of connections plays a critical role, particularly in the mechanical behavior and vibration characteristics of complicated systems. Therefore, it is essential to evaluate the rigidity of mechanical systems connections and estimate their stiffness parameters. While most of the connections in the mechanical or structural systems are semi-rigid, they are usually considered as pinned or fixed in the design calculations. From the stiffness viewpoint, a pinned joint assumes no rotational rigidity while a fixed joint assumes an infinite rotational rigidity. This simplification is mainly due to the complexities of modeling semi-rigid connections in analytical models or lack of knowledge about the stiffness parameters of the semi-rigid joints. The former case is no longer common due to computational enhancements; however, the latter is still valid and complicated. Introducing numerous stiffness parameters for modeling of sophisticated connections may mitigate the challenges of finding a stiffness protocol which can represent the realistic mechanical behavior of the joint. However, although simulation of such detailed connections is applicable it may not be practical. Hence, for modeling of complex joints, a trade-off between simplicity and accuracy is required.

The effect of the rigidity of connections on the behavior of mechanical or structural systems has been investigated by many researchers [1]. Li presented a model updating method with emphasis on identification of joint stiffnesses [2]. He defined a reduced-order characteristic polynomial in terms of the measured natural frequency, the partial modal properties predicted from a flawed FEM model. Bayo et al. proposed an approach to model internal and external semi-rigid connections

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for the global analysis of steel and composite frames [3]. This method is based on a finite dimensioned elastic-plastic four-node joint element that considers the panel zone deformations and all the internal forces that concur at the joint. Cunha et al. applied a model updating technique with static and dynamic data to identify the stiffness of bolted joints for pultruded frame structural systems used in civil construction [4]. In the automotive industry, finite element models which are used for estimation of the body structure performance are classified into two groups. In the first group, a shell model is developed in which the details of each individual part of a structure, including connections are simulated. The second group includes concept models in which all major load-carrying members are simulated with beam elements, while shear panels are simulated with coarse shell elements. In these models, joints are simulated with different parametric representations. There are various techniques for concept modeling of joints, however, two of them are more common. The first method uses an elastic finite element superelement representation with element coefficients determined through optimization routines correlating analysis response with the actual performance of the local joint or overall body. The second method considers a tri-spring representation with parameters simulating certain joint behavior. Shahhosseini et al. discussed these two primary methods for modeling major compliance joints in concept models [5]. Also, structural optimization techniques have been employed for improving the design of complex mechanical systems in which the size, shape and other geometrical properties of the joints are modified to yield an efficient sketch for connections configuration. Kiani et al. presented an approach for evaluating the structural performance of a vehicle model in terms of the joint stiffness. Also, they utilized a material-based technique for joint stiffness modeling by considering changes in the elastic modulus of the material at the designated joint regions. In their research, it was shown that the evaluation of a car body structure based on the optimum joint stiffness could have a superior performance relative to the baseline model without a weight penalty [6].

In this paper, the finite element model of an instrumented experimental frame is developed in SAP2000® software [7]. In the preliminary model, all connections are modeled as either simple or fixed. The measured frequency response functions of the frame are used for modal extraction. Then the modal parameters are employed to update the joints stiffness values. It is assumed that the connections of the structure are semi-rigid. Their semi-rigidity is modeled by incorporating partial fixities at the connection zones. The rotational stiffness values of the connections are estimated through an optimization algorithm by an in-house parameter estimation MATLAB®-based program [8], developed at University of New Hampshire which takes advantage of SAP2000® OAPI. It is shown how the rigidity of connections can affect the modal behavior of the structure. Moreover, the robustness and limitations of the modal stiffness parameter estimation technique are discussed.

26.2 Model Updating

Inherent uncertainty existing in structural modeling, demands an effort to make the mathematical models more representative of the reality by model updating techniques. In general, for updating the finite element models, particularly estimating the joints structural parameters, there are a couple of classes. In the first category which is called direct methods, a set of characteristic equations are solved to determine the joint parameters. These equations include analytical mass and stiffness matrices and experimentally measured modal or FRF data. The other class contains penalty techniques in which some kind of error norms are minimized to reduce the differences between the finite element model and the measurements. Various error functions have been introduced for structural parameter estimation purposes [9]. One of the most robust and common penalty methods of model updating is based on using modal parameters of the structure. In this technique, modal parameters of the structural or mechanical system, including natural frequencies and mode shapes are obtained experimentally and used as the input to the optimization procedure. On the other hand, the mass and stiffness matrices of the system are constructed by the analytical model based on as-built drawings of the structure. The equation of modal stiffness-based error function which is utilized in this research is given by Eq. (26.1) [10],

$$\{E(p)\}_i = [K(p)]\{\Phi\}_i - \omega_j^2 [M(p)]\{\Phi\}_i \tag{26.1}$$

where $\{E(p)\}$ is the modal stiffness-based error function vector, $[K(p)]$ and $[M(p)]$ are analytical stiffness and mass matrices, respectively, $\{\Phi\}$ and ω are the mode shape vector and natural frequency extracted from a non-destructive test, p is the structural parameter to be estimated and i is the vibration mode number. If only some of the degrees of freedom of the structural system are measured in a non-destructive test, which is a common case, the experimental modal data are incomplete. In such conditions, the modal data incompleteness needs to be resolved in some way. One of the suitable methods for removing this issue is partitioning the mass and stiffness matrices and using only the measured DOFs by Guyan reduction technique [11]. Therefore, the mentioned error function can be expressed as [10],

$$\{E(p)\}_i = \left(\left([K_{aa}] - \omega_i^2 [M_{aa}]\right) - \left([K_{ab}] - \omega_i^2 [M_{ab}]\right).\left([K_{bb}] - \omega_i^2 [M_{bb}]\right)^{-1}\left([K_{ba}] - \omega_i^2 [M_{ba}]\right)\right)\{\Phi_a\}_i \qquad (26.2)$$

where the subscripts a and b indicate measured and unmeasured degrees of freedom, respectively and the partitioned mass and stiffness matrices and mode shape vector are shown as

$$[M] = \begin{bmatrix} M_{aa} & \vdots & M_{ab} \\ \ldots & \vdots & \ldots \\ M_{ba} & \vdots & M_{bb} \end{bmatrix}, \qquad [K] = \begin{bmatrix} K_{aa} & \vdots & K_{ab} \\ \ldots & \vdots & \ldots \\ K_{ba} & \vdots & K_{bb} \end{bmatrix}, \qquad \{\Phi\} = \begin{Bmatrix} \Phi_a \\ \cdots \\ \Phi_b \end{Bmatrix} \qquad (26.3)$$

If it is assumed that the uncertainties are limited to the stiffness parameters of the structure, only the stiffness matrix is updated in each iteration of the optimization procedure. The parameter estimation is implemented by minimizing the error function through the following objective function,

$$J(p) = \sum_i \sum_j E(p)_{ij}^2 \qquad (26.4)$$

where J is the objective function and j denotes the parameter number. The iterative updating continues until a defined convergence criterion is satisfied.

26.3 Modal Extraction and System Identification

As mentioned previously, for the modal parameter estimation method, experimental natural frequencies and mode shapes are required. However, the accelerometers can measure the acceleration of structural nodes. Therefore, the experimentally obtained time histories of accelerations need to be processed to provide information about the modal properties of the structure. When the excitation source is known, such as an impact test in a lab, the peak picking method could be a practical technique for extraction of modal parameters of the structure [12]. This method employs signal processing techniques, in which initially using discrete Fourier transform (or power spectral density functions), the frequency spectra of input (impact) and output (acceleration) signals are obtained and then the FRF plots are drawn. The frequencies corresponding to the peaks of the FRF plots give the natural frequencies of the structure and the imaginary parts of the peaks yield the mode shape components of each mode. This technique is based on the fact that in the vicinity of a resonance, contribution of the vibrating mode dominates the FRF, while the effect of other modes is limited.

26.4 UCF Grid and Impact Test

The University of Central Florida (UCF) Grid is an experimental frame at the UCF which is used for model updating tests. This experimental structure was designed and fabricated to simulate the behavior of the deck-on-beam bridges [13]. The UCF Grid has two longitudinal girders, 5.48 long, covering two spans. It also has seven transverse beams connecting the two girders which are 1.83 long with transverse bracing at 0.91 m intervals. All longitudinal and transverse beams are S3 $\times$ 5.7 profiles, while the columns of the frame are W12 $\times$ 26 profiles. All Girders, beams and columns are made of A36 steel with Young's modulus $E = 200\ GPa$ and mass density $\rho = 7850\ \ kg/m^3$. The length of the columns is 1.07 m and their connection to the base is fixed but to the girders can be considered as pinned. This is because the column-girder connection is made of a cylinder located between two curved bearing plates. The connection of the transverse beams to the girders is comprised of two angle clips and two cover plates so that can transfer shear and moments. Therefore, these joints may behave as semi-rigid connections. Figure 26.1 shows the UCF Grid and its connections. The UCF Grid was instrumented by eight unidirectional PCB 393C accelerometers placed vertically and excited by an IPC 086D20 impact hammer at four locations. The location of accelerometers and impacts are shown in Fig. 26.2 [14].

Nondestructive impact tests were conducted on the UCF Grid by Gul and Catbas to determine its modal parameters [13]. In this paper, the response of the system to impact at node 10 is considered, i.e., the vertical acceleration time histories of

Fig. 26.1 Laboratory setup of the UCF Grid (left) and beam to girder connections (right) [15]

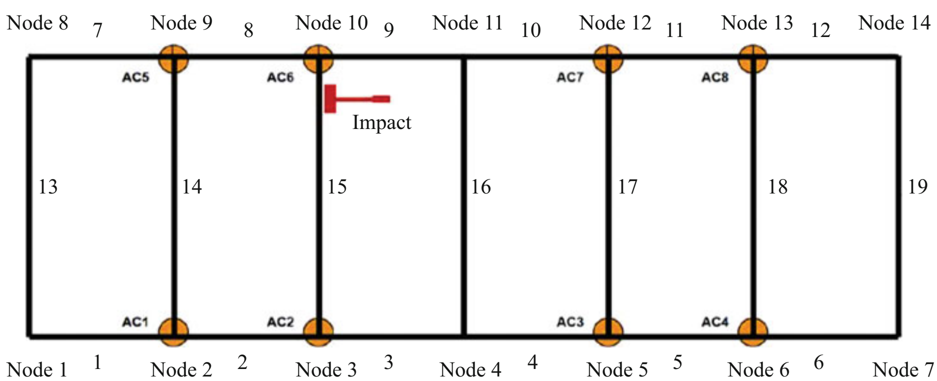

Fig. 26.2 Accelerometer and impact locations [14]

the eight accelerometers are recorded upon the impact hammer excites the frame at the location of the sixth acceleration. Frequency response function of the first accelerometer (AC1) is shown in Fig. 26.3.

26.5 Finite Element Modeling of the UCF Grid

A beam model of the UCF Grid is developed by SAP2000® version 19.1.1. All beam and girder connections are modeled as fixed joints and columns are connected to girders by pinned joints. Also, the connection of columns to the base is fixed. Each of the girder or beam members of the grid need to be divided into some smaller members to ensure that there is not any mode mismatch between the analytical and experimental vibrations. The SAP2000® model of the UCF Grid is depicted in Fig. 26.4. Considering the first 12 modes, a modal analysis is performed. The analytical and experimental natural frequencies of the UCF Grid are given in Table 26.1. In addition, the corresponding mode shapes are shown in Fig. 26.5. In the mode shapes figure, the columns were replaced by pinned supports to save space as this replacement does not affect the mode shapes. Further, it should be noted that the 7th, 8th and 9th analytical modes cannot be captured by the instrumentation layout used because the mentioned modes relate to the local vibration of beams 13, 16 and 19 as denoted in Fig. 26.2.

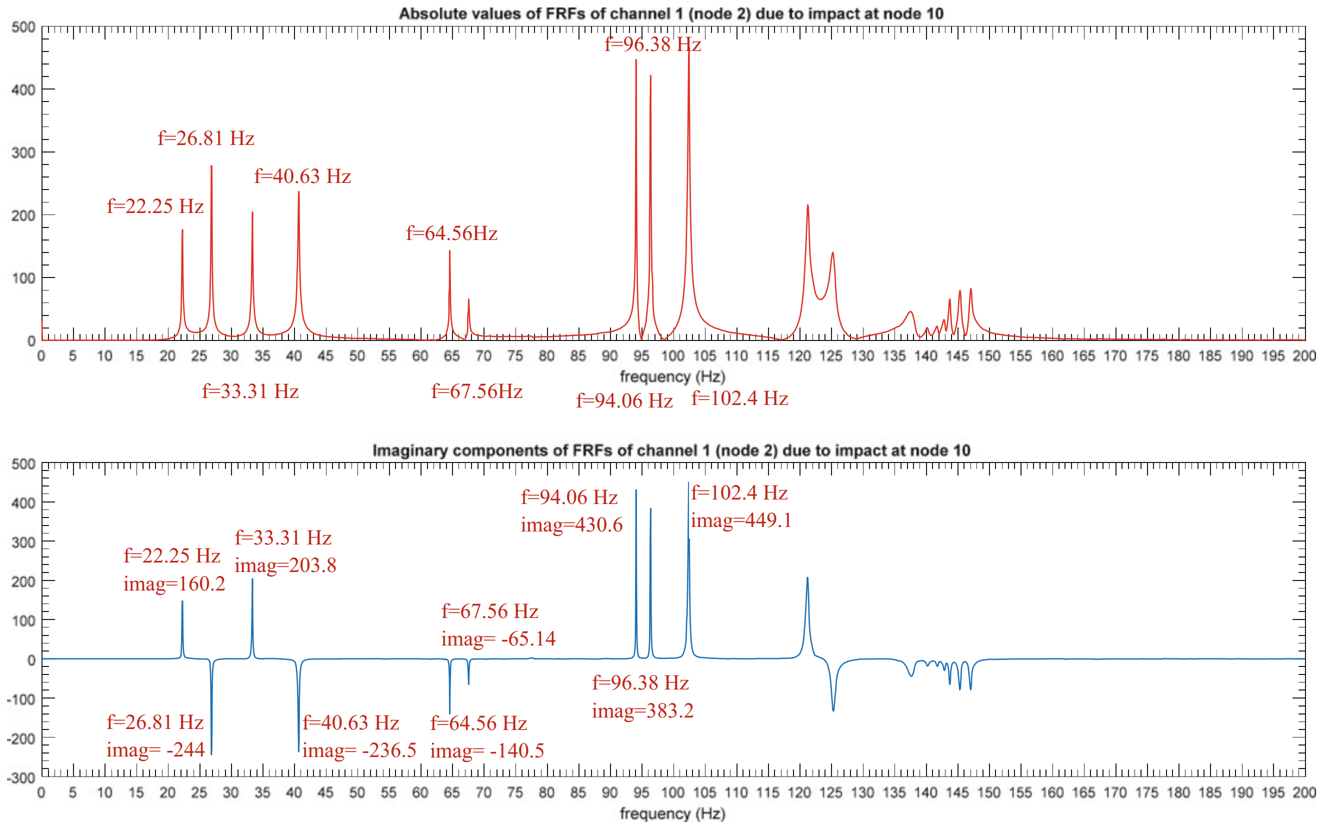

Fig. 26.3 FRF of the first accelerometer due to impact at node 10; absolute values (top), imaginary values (down)

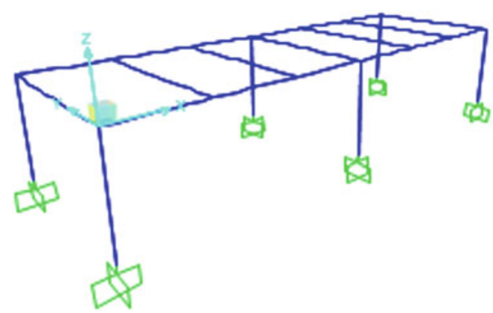

Fig. 26.4 SAP2000® model of the UCF Grid

Table 26.1 Analytical and experimental natural frequencies of the UCF Grid

Mode number	Analytical natural frequencies (Hz)	Experimental natural frequencies (Hz)
1	22.63	22.25
2	28.44	26.81
3	33.87	33.31
4	43.76	40.63
5	62.38	64.56
6	65.63	67.56
7	73.20	–
8	73.20	–
9	73.38	–
10	96.33	94.06
11	99.50	96.38
12	109.62	102.40

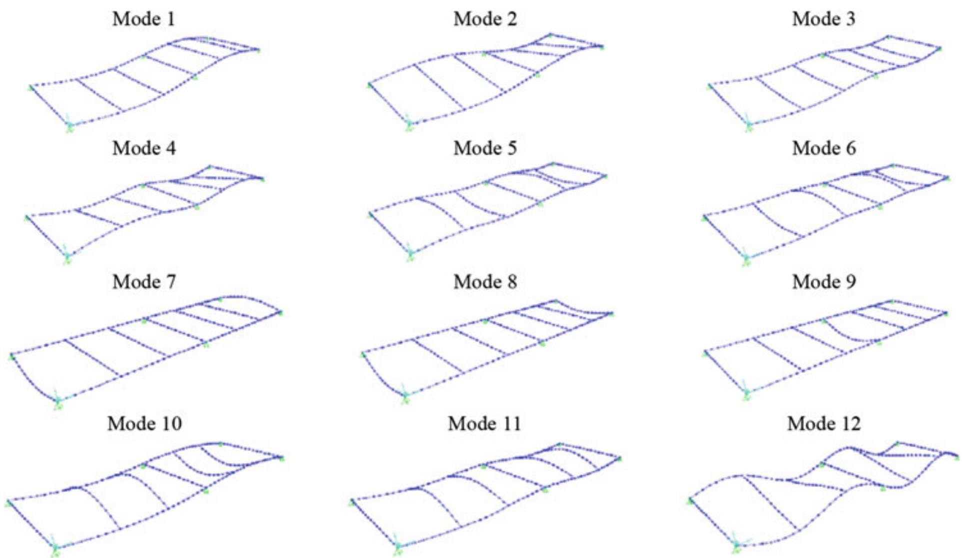

Fig. 26.5 The first 12 analytical mode shapes of the UCF Grid

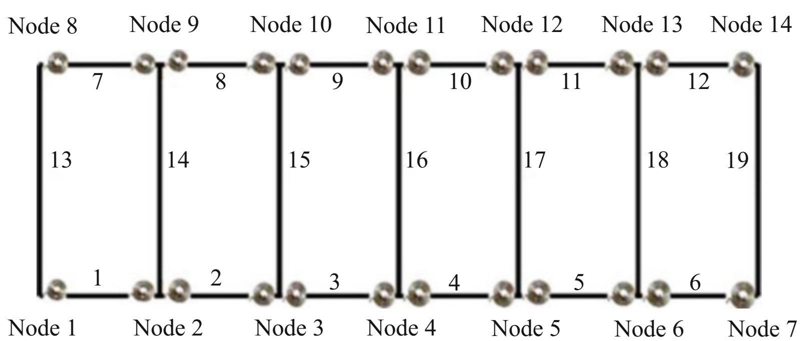

Fig. 26.6 The UCF Grid with partial fixity springs

26.6 Parameter Estimation Analysis

The finite element model of the UCF Grid has been updated by several researchers. Sanayei et al. updated the stiffness and mass of the UCF Grid at the element level, simultaneously using three static and dynamic error functions [14]. Also, Garcia-Palencia and Santini-Bell applied their two-step model updating algorithm for updating mass, stiffness and damping matrices of the UCF Grid using FRF method [16]. They also compared modal and FRF methods for updating the UCF Grid [17].

In this research, it is assumed that the uncertainties are limited to only the rigidity of connections. Therefore, multiple cases are investigated in which the rotational stiffness of the connections are estimated by updating the partial fixities at the ends of members. For the model updating, an in-house MATLAB®-based parameter estimation program linked to the finite element model of the UCF Grid through SAP2000® Open Application Programming Interface (OAPI) is used. For the minimization of the objective function, *fmincon* from the MATLAB® Optimization Toolbox™ is employed. First, we need to know the initial values which should be assigned to the partial fixity springs at the end of members. Since in a fixed connection, the two connected members do not have any relative rotation, theoretically the stiffness of a partial fixity spring is infinite. However, practically if the magnitude of the stiffness of partial fixities is large enough, the connections behave as fixed joints. In Fig. 26.6, the partial fixity springs have been considered at the connections of beams to girders to simulate the semi-rigid joints. Although the two girders of the UCF Grid are continuous in the longitudinal direction of the grid, the holes of the bolts at the connection zones may have weakened those regions, so semi-rigidity for those joints could be likely. The variations of the UCF Grid natural frequencies with the rotational stiffness of the partial fixity springs are shown in Fig. 26.7. Therefore, this plot could be helpful for selecting the initial values for the partial fixity springs from a reasonable range.

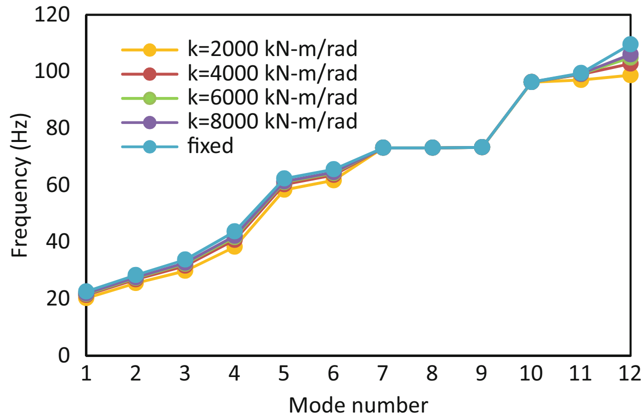

Fig. 26.7 Variations of the natural frequencies of the UCF Grid with the rotational rigidity of beam to girder connections

Table 26.2 Mode selection for parameter estimation and the corresponding estimated partial fixities

Case no.	Considered modes	Estimated k (kN m/rad)
1	1, 2, 3, 4, 5, 6, 10, 11, 12	10,277
2	1, 2, 3, 4, 10, 11, 12	3573
3	1, 2, 3, 4, 5, 6, 12	11,307
4	1, 2, 3, 4, 12	3741

Table 26.3 Analytical, experimental and updated natural frequencies of the UCF Grid

Mode no.	Anal. freq. (Hz)	Case 1 freq. (Hz)	Case 2 freq. (Hz)	Case 3 freq. (Hz)	Case 4 freq. (Hz)	Exper. freq. (Hz)
1	22.63	22.12	21.25	22.17	21.31	22.25
2	28.44	27.81	26.73	27.86	26.80	26.81
3	33.87	32.97	31.46	33.05	31.56	33.31
4	43.76	42.54	40.49	42.64	40.62	40.63
5	62.38	61.57	60.11	61.65	60.21	64.56
6	65.63	64.84	63.41	64.92	63.51	67.56
7	73.20	73.20	73.20	73.20	73.20	–
8	73.20	73.20	73.20	73.20	73.20	–
9	73.38	73.38	73.38	73.38	73.38	–
10	96.33	96.33	96.32	96.33	96.32	94.06
11	99.50	99.32	99.03	99.34	99.05	96.38
12	109.62	106.82	102.07	107.07	102.38	102.40

26.6.1 One-Parameter Estimation Analysis

For the first stiffness parameter estimation procedure, the semi-rigid connections layout of Fig. 26.6 is considered. In this analysis, it is assumed that there is only one parameter to be estimated. Hence, all the partial fixity springs shown in Fig. 26.6 are put in a group, i.e., at the end of model updating, all the springs would have the same updated value. Based on the selection of modes which contribute to the optimization algorithm, four cases are investigated as given in Table 26.2. In none of the four cases, local modes 7, 8 and 9 are considered. The estimated stiffness values of the partial fixity springs are provided in this table as well, while the updated natural frequencies of these four cases are given in Table 26.3. Modal Assurance Criterion (MAC) analysis is done for mode tracking to ensure that the frequencies are correctly assigned to the specific vibration modes. The objective function plots and MAC value graphs of the four cases are shown in Figs. 26.8 and 26.9, respectively. MAC plots ensure that there would be no mode switch due to the change in parameters.

It is observed that the estimated stiffness value highly depends on the selection of modes. In all four cases, the program could find a local minimum for the objective function, however the difference between estimated value of cases 1 and 3 and cases 2 and 4 is significant. The reason for such a considerable difference is the contribution of modes 5 and 6, as in cases 1

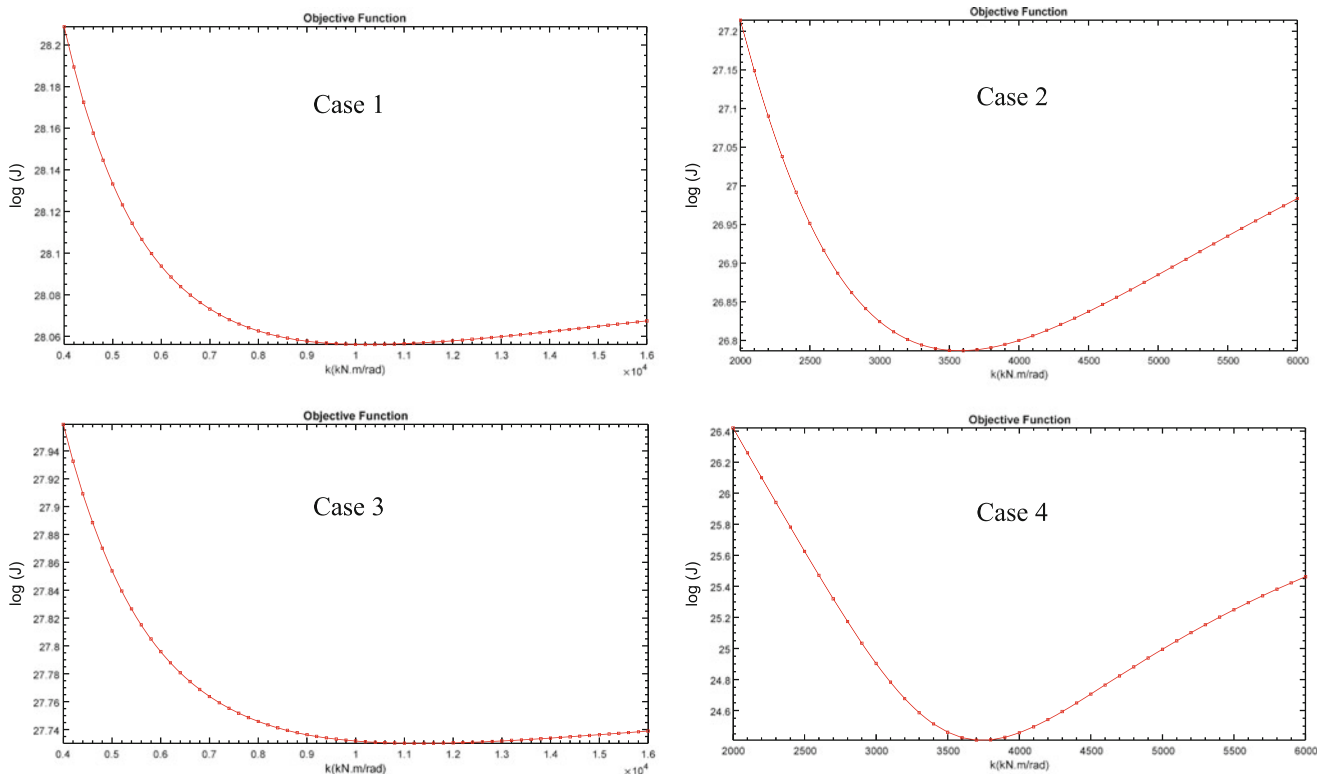

Fig. 26.8 Objective functions of the four cases defined in Table 26.2

and 3, modes 5 and 6 are contributed while in cases 2 and 4, the two mentioned modes are ignored. Comparing MAC plots of cases 3 and 4 with cases 1 and 2 demonstrates that the instrumentation used for this test, is not sufficient for capturing modes 10 and 11. This can be verified as in the MAC plots of cases 1 and 2 (which includes modes 10 and 11), large non-diagonal bars can be seen for modes 10 and 11. An interesting point is the role of modes 5 and 6 in the estimation of stiffness parameter. In these two modes, the vibration of beams 14, 15, 17 and 18 (see Fig. 26.6) is considerable. Therefore, it might be required to update the rotational rigidity of these four members too. Therefore, in the next section, the model updating is performed by considering this additional group of stiffness parameters.

26.6.2 Two-Parameter Estimation Analysis

In this section, as shown in Fig. 26.10, the connections of beams 14, 15, 17 and 18 to the girders are modeled as semi-rigid joints in addition to the previously introduced partial fixities. The previously defined rotational fixities are considered as group 1 and the new spring constants are put in group 2. Hence, in this analysis there are two unknown stiffness parameters. In Fig. 26.10, the group 1 is shown by red boxes and the group 2 is specified by blue boxes. The contributed modes are the same as the ones in case 3 of the previous section, i.e., modes 1 to 6 and mode 12 are contributed. The analytical, experimental and updated natural frequencies for this analysis are given in Table 26.4. Also, the corresponding MAC plot is shown in Fig. 26.11. Further, the updated values for the two partial fixities are given in Table 26.5.

The results of the two-parameter estimation analysis show that considering partial fixities for beam to girder connections does not improve the estimation procedure. In this case, the partial fixity of the parameter 1 converges to the same value of case 3 in one-parameter estimation, while the stiffness of group 2 parameters reaches the upper defined bound. Considering the graphs of Fig. 26.7, this boundary value represents a fixed connection, which was the condition in the one-parameter estimation. Therefore, introducing partial fixities for the beam to girder connections does not provide any information about the semi-rigidity of these joints. Hence, the two-parameter estimation procedure does not show much advantage over the one-parameter estimation.

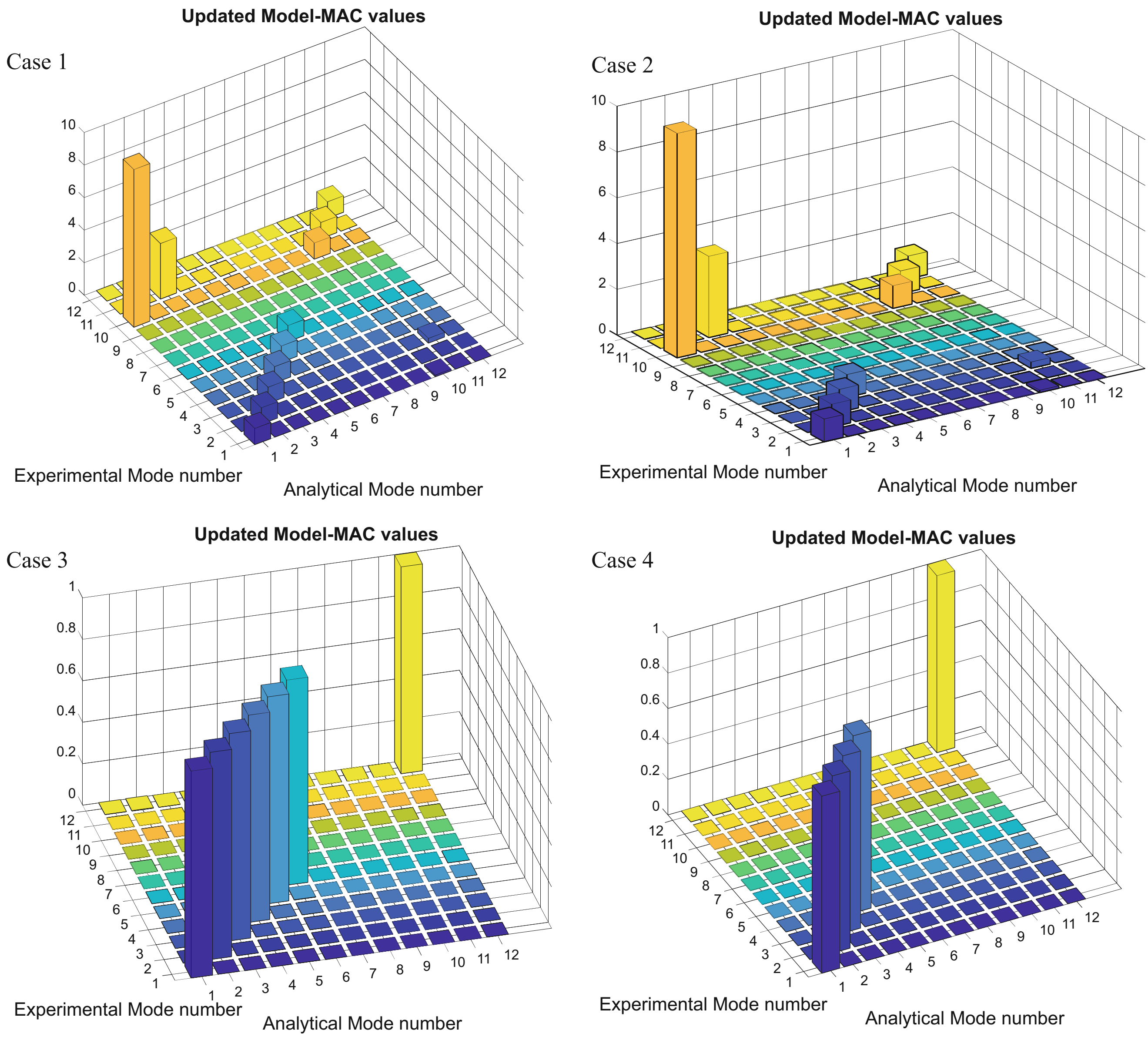

Fig. 26.9 MAC value plots of the four cases defined in Table 26.2

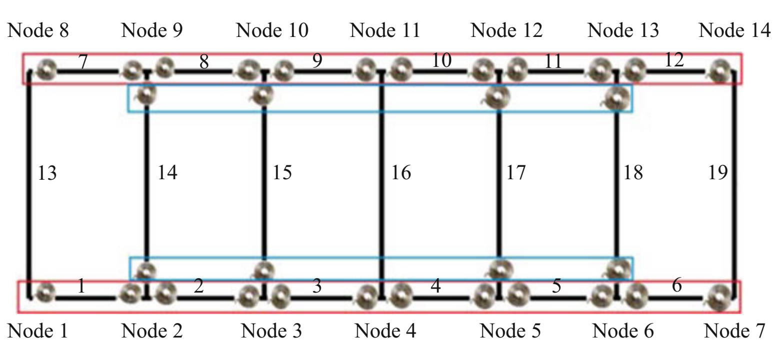

Fig. 26.10 The UCF Grid with partial fixity springs for two groups of connections

Table 26.4 Analytical, experimental and updated frequencies obtained by two-parameter estimation

Mode no.	Anal. freq. (Hz)	Updated freq. (Hz)	Exper. freq. (Hz)
1	22.63	22.17	22.25
2	28.44	27.86	26.81
3	33.87	33.05	33.31
4	43.76	42.64	40.63
5	62.38	61.65	64.56
6	65.63	64.92	67.56
7	73.20	73.20	–
8	73.20	73.20	–
9	73.38	73.38	–
10	96.33	96.33	94.06
11	99.50	99.34	96.38
12	109.62	107.07	102.40

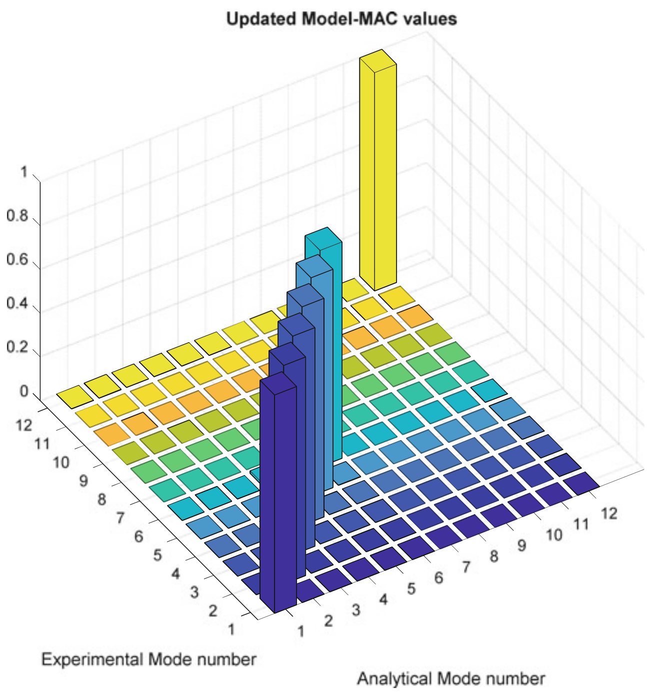

Fig. 26.11 MAC value plot of the two-parameter estimation analysis

Table 26.5 Initial and updated values of two-parameter estimation

Stiffness parameter	Initial stiffness value (kN m/rad)	Updated value (kN m/rad)	Lower bound (kN m/rad)	Upper bound (kN m/rad)
Group 1	8000	11,307	4000	16,000
Group 2	8000	16,000	4000	16,000

26.7 Conclusion

In this paper, the stiffness parameters of the joints of an experimental structure were verified with respect to laboratory collected model response data. The capability of SAP2000® software package for incorporating partial fixities at the connection regions as well as the OAPI was employed. It was shown how the joints stiffness of the experimental structure could affect its modal behavior. The parameter estimation operation presented in this paper was limited to updating the rigidity of the joints. Obviously, there are some uncertainties in terms of stiffness, mass and damping of the structure members. In a more comprehensive model updating procedure, those uncertain structural parameters need to be incorporated in the parameter estimation and model updating protocol. Also, it was demonstrated that updating the partial fixity springs through an automated parameter estimation program which takes advantage of the OAPI algorithms and MATLAB® Optimization Toolbox™ options could facilitate the structural model updating procedure. Using this protocol can play an important role in model-based condition assessment and improvement of analytical representation of the modal and dynamic behavior of structural and dynamic systems.

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