Dynamic characterization, modelling and model updating of a lively footbridge

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ABSTRACT

This paper presents finite element analyses, experimental measurements and finite element model updating of a lively footbridge consisting on an arched main span 40m long and several shorter access spans. Firstly, a finite element model of the bridge is created in a commercial CAE software and static and modal response are numerically estimated. Then, experimental measurements using static loading test and ambient vibration tests are performed. Initial finite element model is adjusted to match with the static response by fitting some selected parameters. Modal parameters (natural frequencies, mode shapes and modal damping) are extracted and after that the current finite element model is updated. Among the selected parameters, semi-rigid connections in some joints, concrete Young's modulus and mass density of the concrete deck (to account on pavement mass) are selected to minimize the differences between numerical and experimental structural response. Sensitivity of the modal response to these parameters is also shown. At the end of the study, good agreement between analytical and experimental results is achieved, revealing the suitability of the entire process.

Keywords: Operational Modal Analysis, Static Loading Test, Vibration, Civil Structures.

1. INTRODUCTION

Although in the past, civil engineering sector made extensive use of approximate models to estimate the dynamic response of bridge type structures, nowadays is usual to model the structure using current CAE abilities. Simple discrete models have proved insufficient for the accurate modelling of slender footbridge structures as they cannot represent some effects as the closely spaced modes of vibration which frequently occur in practice. Additionally, modern footbridges become increasingly slender and prone to oscillate under pedestrian loading, so there is a much greater need for vibrations to be considered at the design stage. Having the FE methods the capability for the accurate modelling of the dynamic behaviour, and becoming CAE software more affordable, civil engineering practitioners do not hesitate in their use. However, with regard to lively structural design, there is a lack of expertise in FE modelling, particularly with regard to their vibration serviceability performance, being not rare that the model does not match with the real structure.

The way forward for developing such expertise is by linking modal testing and FE analysis by the updating of the models of representative structures and extract general design guidelines. This type of

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approach is the usual in, for example, the aerospace engineering sectors [1-6], but it is only recently that the civil engineering community has begun to adopt this advanced technology [7-11].

The aim of the paper is to describe a procedure for the use of test data in the manual and automatic updating of FE models. The exercise is done using the ANSYS FE code [12] in conjunction with FEMTools [13], a state-of-the-art updating software.

2. STRUCTURE DESCRIPTION

The footbridge is an urban link with several minor access spans and one main 40m long arched central lively span. Most of the structural members are constructed using tubular steel profiles. An aerial photograph of the footbridge and 3D isometric view of its FE model is depicted in Figure 1. More information about the structure can be found in [14].

Figure 1. Footbridge under study: photograph and numerical FE model.

3. FE MODELLING

The initial FE model, comprising over 600 beam 3D elements for the steel members and 120 shell elements for the deck, modelled in ANSYS [12] is suitable, after minor changes, for importation to the FEMtools [13] software. Several cross section types are considered for the steel skeleton but for the deck just one constant thickness element (200mm) is used. The handrails on the bridge, although are rigidly attached to the deck, are considered non-structural and then not modelled. However, additional mass for their consideration can be taken into account and distributed over the deck.

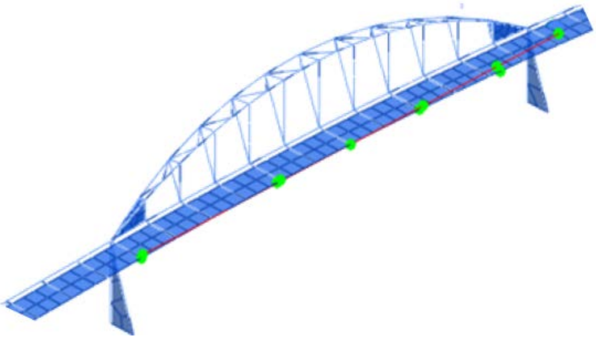

Figure 2. FEM mesh and signal acquisition points.

The FE mesh is given in Figure 2 together with the experimental test grid (green points). Note that, when the model is going to be correlated with the results from test data, it is important to ensure that the nodes of the FE mesh are coincident with the locations of the test points [15, 16].

Using this initial model, maximum deflection for the nominal static loading case was 24.17mm and the first three vibration modes and natural frequencies are shown in Figure 3 . Note than in the first mode, torsional effects are predominant, in the second one the main effect is vertical bending while the third one is mainly transversal bending (as shown in the additional Figure 3c).

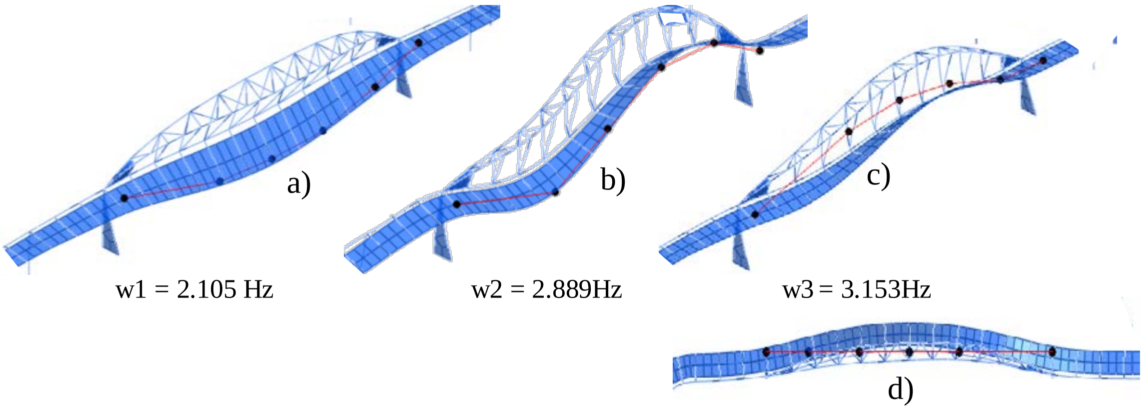

Figure 3. First three natural mode shapes.

4. TESTING

A simple static loading test is carried out to determine the central deflection when a load of 20 tonnes is placed on the central span deck, resulting in 32mm. Also a simple modal ambient testing programme is conducted. Ten minutes recordings for vertical acceleration in the 4 selected central points (Figure 2) are registered at 200Hz. Figure 4 shows the data and, after postprocesing using SSI method (using MATHLAB), estimated frequencies and dampings are shown in Table 1. Similar results can be obtained using FEMTools routines, based on a global poly-reference Least Squares Complex Frequency (pLSCF) method. The damping values reported in Table 1 are not used in the following updating exercise, they are included to realise how low they are. Corresponding mode shapes are over-displayed in Figure 3 (black polygonal line).

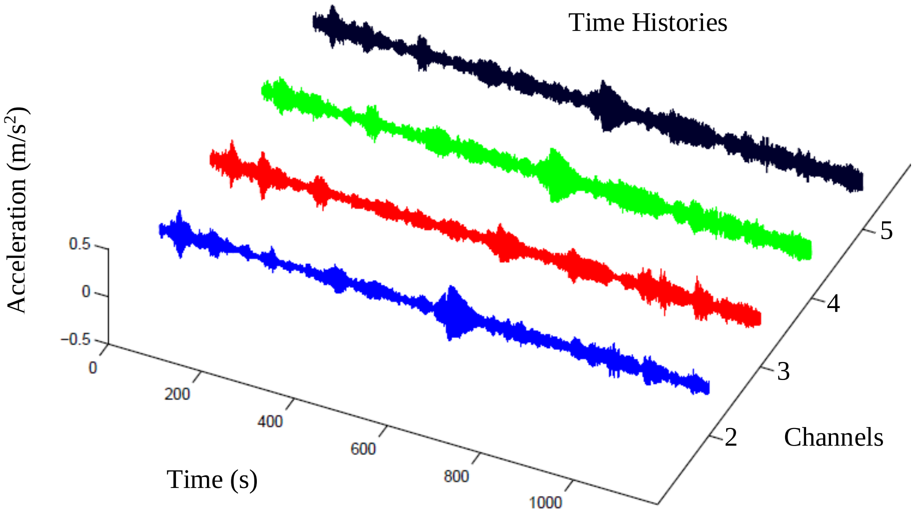

Figure 4. 10 minutes ambient vibration records corresponding to the testing points shown Figure 2.

Table 1. Modal frequencies and dampings estimated using operational modal analysis.

Mode	Frecuency (Hz)	Damping (%)
w1	2.081	0.31
w2	2.502	0.75
w3	2.877	0.60

5. CORRELATION BETWEEN MODELS AND MANUAL UPDATING

Table 2 shows the comparison of natural frequencies of experimental (OMA) and FE vertical modes. Obviously, although MAC values are high, updating is needed for the frequency values, but before proceed with the selection of the parameters to be changed, static considerations are going to be taken into account. Note that the third mode is include just for checking purposes (it is maily a horizontal mode and only vertical accelerations are recorded)

Table 2. Experimental and initial numerical (FE model #0) frequencies.

Mode	OMA	FEM#0	MAC
w1	2.081	2.105	99.1
w2	2.502	2.889	98.7
w3	2.877	3.153	

Prior to attempting to update the FE model in FEMtools in an automatic way, it is recommended to experiment with selected input parameters by hand. The initial FEM is not accounting for the inherent flexibility of the steel joints and other effects. It is because of that the experimental static deflection was 33% larger than the numerical one. Once identified that most of the flexibility were concentrated in the connections between the lower chord of the arch and the transverse beams that support the deck, a semi-rigid joint was defined and their value manually adjusted to match with the measured deflection, resulting in a bending lost of about F=83% (considering that a perfect rigid joint has a value of 0% and an hinge one is 100%). After introducing this effect, the static deflection is the expected one (32mm) and the numerical modal response turned, has shown in Table 3.

Table 3. Experimental and numerical (FE model #1) frequencies. Semi-rigid joints.

Mode	OMA	FEM#1	MAC
w1	2.081	1.988	99.4
w2	2.502	2.689	99.1
w3	2.877	2.939	

This reduction in the bending capacity of the connections is considered too large to be consistent with the joint design and welding procedure, so other sources of discrepancies should be searched. In this case, after having a look to the deformed configuration under the static loading and realizing about the significant rigidity of the deck (that was acting like an arch itself), it is decided to decrease the Young´s modulus of elasticity used to simulate the concrete of the deck (Ec). In doing so, several pairs of values for F and Ec can be found. After a detail modelling of the referred steel connection, value for F was adjusted to 21%. With this value for F, the corresponding value for Ec is 0.9 1010N/m^2. Note that this finding suppose a 70% decrement (initial value vas Ec=3 1010N/m^2). In nominal conditions it is not consistent such a big reduction but after knowing the on-site construction procedure carried through in pouring the concrete, in more than one layer, and the self-supporting formwork used (generating about 50% reduction in the concrete thickness in about 50% of the plant surface), the results obtained was assumed to make sense. Note that the structural effect is similar to reduce the thickness of the shell elements used for modelling the concrete. In this new assumption, modal estimations are shown in Table 4. Although the adjusted FE model is closed enough to the real structure, additional improvement are possible, as presented in the next section.

Table 4. Experimental and numerical (FE model #2) frequencies.

Semi-rigid joints and reduced concrete modulus.

Mode	OMA	FEM#2	MAC
w1	2.081	1.939	99.3
w2	2.502	2.583	99.3
w3	2.877	2.680	

6. AUTOMATIC UPDATING

At this point, for conducting the automatic updating exercise it is necessary to choose additional parameters to change. It is recommended to act over the parameters with more indeterminacy. At this stage, the mass distribution along the deck (including steel formwork, reinforcement bars, concrete, pavement and hand railing) is chosen as a local parameter for each of the 120 shell elements considered in the central span.

Initial density for the shell elements was ρc = 2300kg/m^3 and final values after the automatic modal updating are shown (in a chart way showing percentage of change) in Figure 5. Changes in the range of +50% and -75% are accepted. Final values for the density of the 120 shell elements cover all the range. The resulting mean value for the 70 elements in the central span is 2168kg/m^3. Note that this value is a bit low for any reinforced concrete slab. This result, together with the low Ec found in the previous section (70% reduction), suggests that if the deck thickness had been reduced (from 200mm to, for example, 150mm), both parameters (Ec and mean density) had been not change that much (but that exercise is out of the scope of this paper). Besides, the tendency is to remove mass from the middle and to add it near the supports in the central span. This tendency is consistent with the existence of a big manhole cover in the central part of the deck.

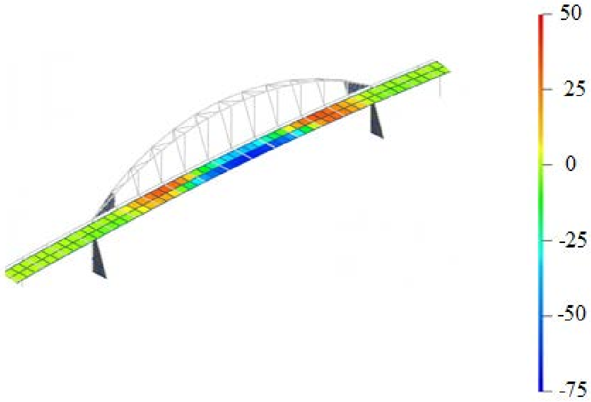

Figure 5. Percentage changes for the mass distribution on the deck elements.

Table 5. Experimental and numerical (FE model #2u) frequencies.

Semi-rigid joints, reduced concrete modulus and unequal mass distribution.

Mode	OMA	FEM#2u	MAC
w1	2.081	2.0809	99.4
w2	2.502	2.5022	99.6
w3	2.877	2.680	

For the referred values, modal response is presented in Table 5, that shows the best agreement after the manual and automated updating. For the automatic procedure, MAC values of the analytical and measured mode shape pairs together with natural frequencies values were used as an updating criterion. FEMtools updating software uses well-proven iterative, parametric, modal and FRF-based updating algorithms using sensitivity coefficients and weighting values (Bayesian estimation). The procedure can be configurated with different confidence level for the different targets (natural frequencies, mode shapes, etc). It is also recommended to physically examine the mode shapes and assign lower confidence factors if the shapes appear to be erratic or even not pairing them (as has been done for mode 3) if they are weakly correlated The following Table 6 shows the best-fitted values that the automatic updating procedure can achieve for the models #0 and #1 when unequal mass distribution is allowed and confidence level for mode 1 is set to 99% and for mode 2 to 95%.

Table 6. Experimental and best numerical frequencies for models #0 and #1 with unequal mass distribution.

Mode	OMA	FEM#0u	FEM#1u
w1	2.081	2.0789	2.0798
w2	2.502	2.5858	2.5761

7. SENSITIVITY ANALYSIS

As former described, manual updating is important, as it enables the analyst to quantify the possible effect that each selected parameter may have on the static and modal response of the structure. This is extremely important as it provides a basis for judging whether the results obtained from the automatic procedure are suitable. Besides, unless reasonable starting values of the updating parameters are given, the FEMtools software may have difficulty in improving the correlation between the experiments and the analysis. The software has the possibility to know, through a sensitivity analysis, if the selected parameters are worthy to change or not. Besides, note that without additional information (static deflection, connection flexibility, ...), automatic updating would not have been able to adjust the model in the way done manually. In this work, automatic updating is reserved for final adjustment to match with the modal response without affect to the static deflection. This highlights one of the potential problems of the blind application of automatic updating procedures.

Figure 6 shows the sensitivity of the selected parameters to the first, second and third modes. Note that when concrete density ρc is considered global, it affect in the same direction to all the considered modes, so, to move up the first frequency and down the second one (as required in model #0, #1 and #2) is not possible simultaneously.

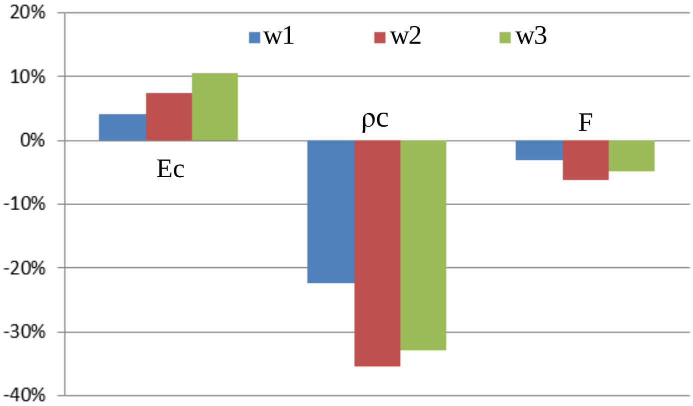

Figure 6. Concrete flexibility (Ec), concrete density (ρc) and semi-rigid joints (F) sensitibity.

When concrete density is considered local, the corresponding sensitivity chart is the one presented in Figure 7a (for mode 1) and Figure 7b (for mode 2)

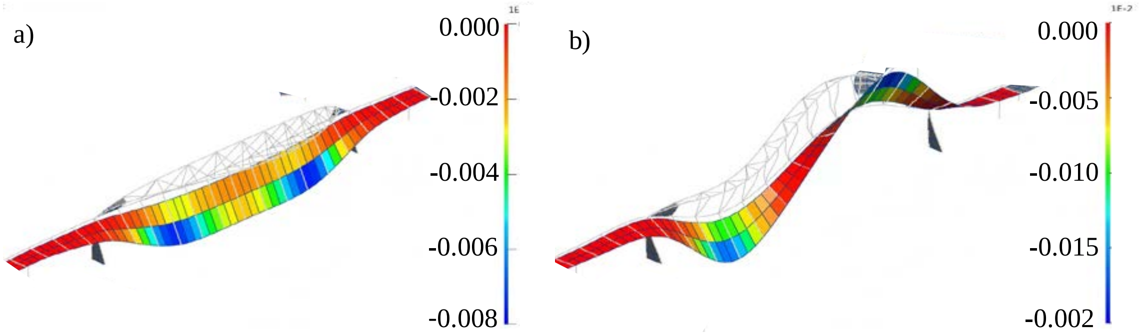

Figure 7. Local concrete density sensitivity for mode 1 (a) and mode 2 (b).

8. DYNAMIC RESPONSE

The structural damping has been introduced using the Rayleigh damping procedure. The damping coefficients alpha and beta have been set to achieve an approximate damping of 0.35% for all the considered modes. This damping ratio has been obtained adjusting the exponential free-decay curve in the structural response shown in Figure 8 in the range 32 to 60 seconds. Figure 8 shows the dynamic test consisting in a controlled input force (via electrodynamic shaker) in the middle of the footbridge from second 4 to second 32 just at the first frequency of the structure. After that, the shaker is turned off (although some force is recorded, as the moving mass of the shaker is moving together with the structure).

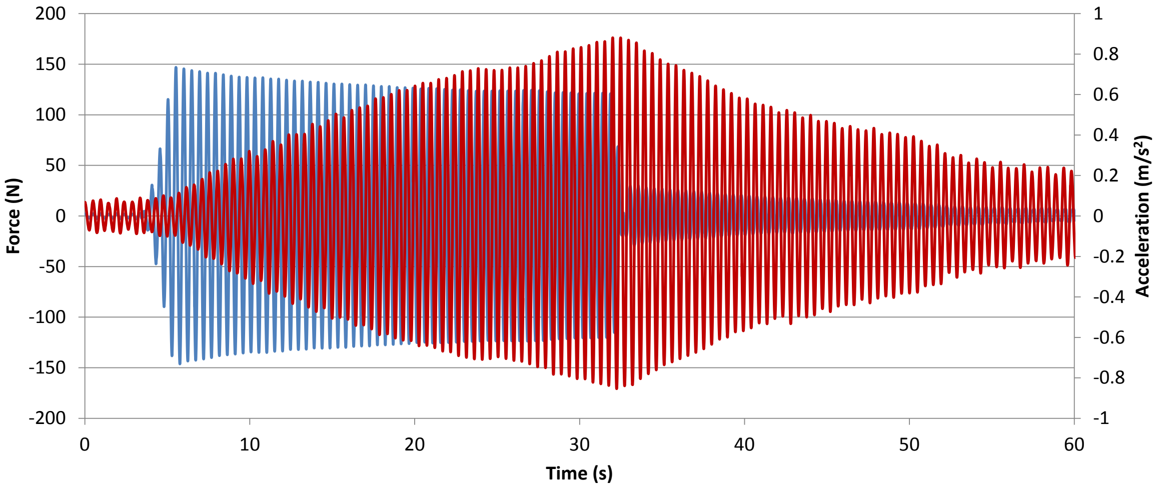

Figure 8. Experimental input force and corresponding response.

In order to check that the updated model is able to estimate the measured forced response, to simulations are performed. For that, a theoretical sinusoidal input force (from 4 s to 32 s, amplitude 130N, at resonance) is applied, equivalent to the experimental one, as shown in Figure 9.

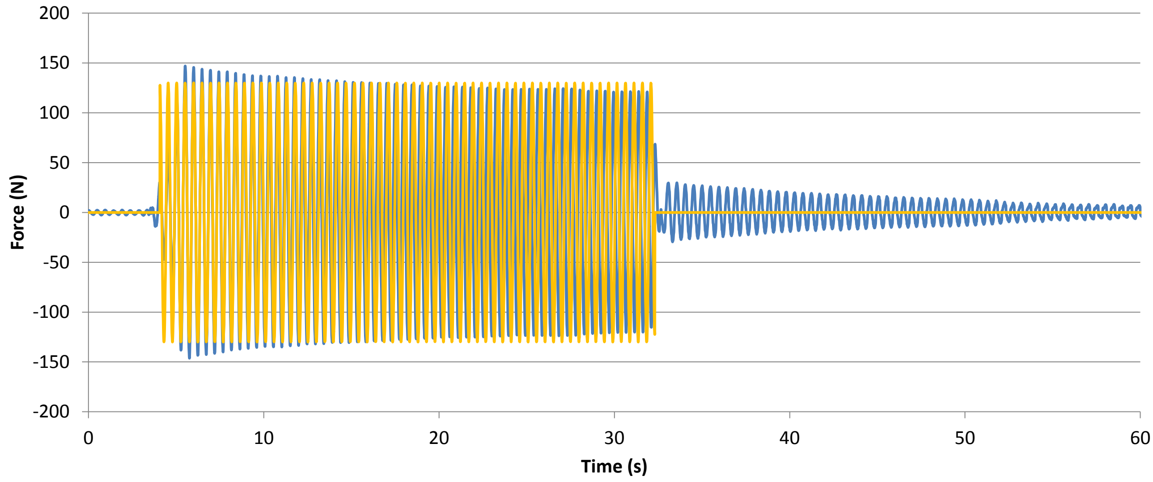

Figure 9. Real and theoretical input forces

The simulated responses are shown in Figure 10. Note the good agreement to the real one.

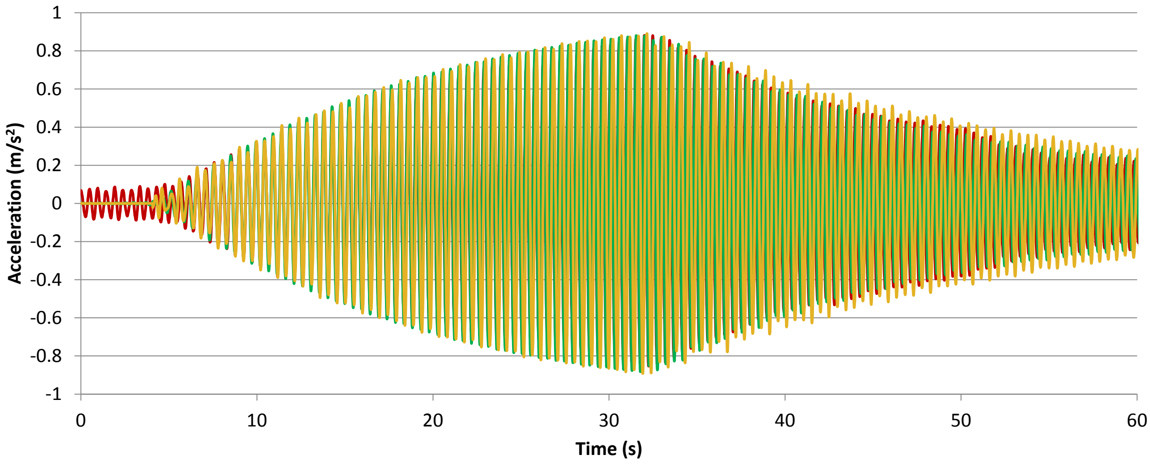

Figure 10. Simulated responses compared with the real one

9. CONCLUSIONS

The procedure of FE model updating using static test data and modal test data of full-scale structures has be applied successfully to a particular lively footbridge. Progressive updating steps are shown in Figure 11. Three based steps (FEM#1, FEM#2 and FEM#2u) are enough to get a FE model matching with the static and modal test data.

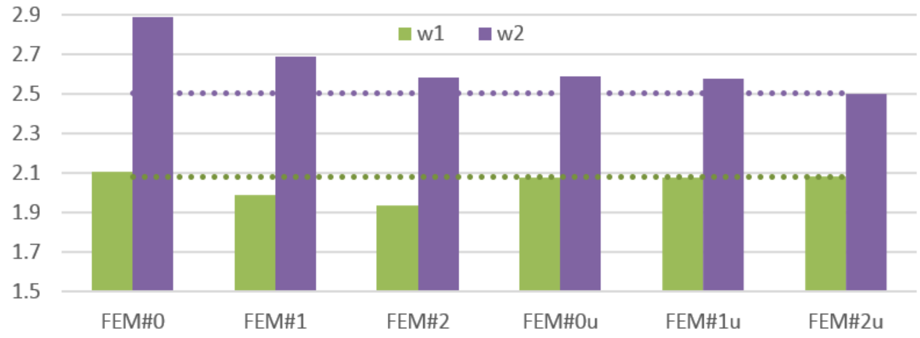

Figure 11. Successive adjustments.

Unlike aerospace or automotive engineering, the designs for most civil engineering structures are one-off. This requires designers to ensure, first time, that the structure performs satisfactorily. Hence, the immediate benefit of updating models of existing civil structures, which are already designed and built, is not as obvious as, for example, in other engineering design industrial sectors. It is important to stress here that the main advantage of this exercise for students and civil engineers is not in the improvements of existing prototypes and their numerical models. The principal benefit is a more reliable modelling to assist in future designs of similar structures. Consequently, increased knowledge, from the updating of FE models, based upon prototype [17] or full scaling testing could be extremely valuable to designers in the future.

The blind application of the automatic updating procedures built in purposely developed software can easily produce meaningless results. It is critical the practitioner assistance over the complete process.

Unless the initial input parameters are sufficiently close to the final values, any highly sensitive updating software may not find a good solution. In addition, if only natural frequencies are used for updating, then unrealistic values for the selected parameters may be predicted.

Once the model is properly updated, it can be used to estimate the dynamic response of the structure.

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