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Updating of Existing Structures' Models Based on Modal Testing

Optimalisation de modèles de structure basée sur des essais modaux

Optimierung von Tragwerksmodellen auf der Basis von modalen Versuchen

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SUMMARY

Strengthening or rehabilitation of existing structures are common tasks of the civil engineer today. Successful planning of the related work has to be based on a sound knowledge of the structure's actual properties. First, a modern method combining analytical and experimental investigations is described. A preliminary Finite Element Model is updated based on the results of Modal Testing. This updated model can be assumed to be as close to reality as possible. Two examples of the method's application are then discussed: Investigation of the effects of strengthening measures for the bridge on the Aare River at Aarburg and the Westend Bridge, Berlin.

RÉSUMÉ

Le renforcement et l'assainissement des ouvrages d'art font aujourd'hui partie des tâches courantes de l'ingénieur civil. Le succès de la planification des travaux exige une connaissance approfondie des caractéristiques actuelles de l'ouvrage. L'article décrit une méthode moderne qui associe les résultats d'études analytiques et expérimentales: optimalisation d'un modèle de structure porteuse obtenu par la méthode des éléments finis au moyen des résultats d'une analyse modale expérimentale. Cette méthode est illustré à l'aide de deux exemples: ponts sur l'Aar à Aarburg et de Westend à Berlin.

ZUSAMMENFASSUNG

Verstärkung und Sanierung von Bauwerken gehören heute zu den täglichen Aufgaben des Bauingenieurs. Um diese Aufgabe zweckmäßig lösen zu können, muss ein möglichst wirklichkeitsnahes Bauwerksmodell erarbeitet werden. Zunächst wird eine moderne Methode beschrieben, die zu diesem Zweck die Resultate analytischer und experimenteller Untersuchungen kombiniert: Optimierung eines Finite Element Modells des Tragwerkes aufgrund der Resultate einer experimentellen Modalanalyse. Die Anwendung der Methode wird dann anhand zweier Beispiele illustriert: Untersuchung der Auswirkung von Verstärkungen der Aarebrücke Aarburg und der Westend-Brücke Berlin.

1. INTRODUCTION

Establishing a proper model of an existing structure is not always an easy task. Drawings and design calculations may no longer exist, the actual static and kinematic boundary conditions as well as the effective structural mass and stiffness may be uncertain. However, the first step of the method to determine a realistic structural model described in this paper is always generating of a preliminary Finite Element (FE) model based on all the information available. As a second step, a modal test is performed on the structure. The results of this modal test are then used to update the preliminary FE model. This updating procedure (also referred to as LINK) yields an FE model being as close to reality as possible. Within the boundaries of linearity, this model can then be used to perform analytical studies of any type like e.g. determining of the structural response to a static or dynamic input function or, as will be the case here, to calculate the effects of possible strengthening or rehabilitation measures.

2. MODAL TESTING

2.1 General

Modal Testing means determination of a structure's modal parameters, e.g. natural frequencies as well as associated mode shapes and damping coefficients, from its Frequency Response Matrix. This matrix is derived from tests where the structure's response to controlled dynamic excitation is measured. The time signals simultaneously acquired for input force $x_i(t)$ and response $y_k(t)$ are transformed into the frequency spectra $x_i(\omega)$ and $y_k(\omega)$ by applying the Fast Fourier Transformation. From this, the Frequency Response Function (FRF) between points i and k, $H_{ik}(i\omega)$, and the Frequency Response Matrix $H(i\omega)$ for the whole structure can be determined.

Two items are important here:

- The larger the number of response measurement points the better the information on the structure's modal parameters especially the mode shapes.
- Dealing with linear structures means that $H(i\omega)$ is symmetric to its diagonal. This is of considerable practical importance because it is then possible to keep the point of excitation k constant and to hover the measurement points i over the structure.

2.2 Excitation

From the several possibilities to efficiently excite a structure like a bridge, bandlimited burst random excitation making use of a servohydraulic actuator has proven to be the most suitable one. Impulse-type excitation using some hammer-like instrument may be much cheaper to apply but experience shows that the quality of the results is not sufficient for large structures. Narrow-band excitation using e.g. mechanical actuators with unbalanced masses is very time-consuming since only one frequency can be investigated at a time.

The heart of the servohydraulic actuator used in the tests described later is a 10 kN cylinder with a 100 mm stroke. A 500 kg mass is fixed to the tip of its piston rod so that the cylinder produces a maximum force amplitude of 5 kN. To drive the cylinder a suitable electronic circuitry, an air-cooled hydraulic power pack (40 l/min, 280 bar) and a diesel generator (45 kW) are necessary. The driving signal is provided by the Modal Analysis System described later on. To allow measurement of the force introduced into the structure the actuator is placed on three load cells (Fig. 1).

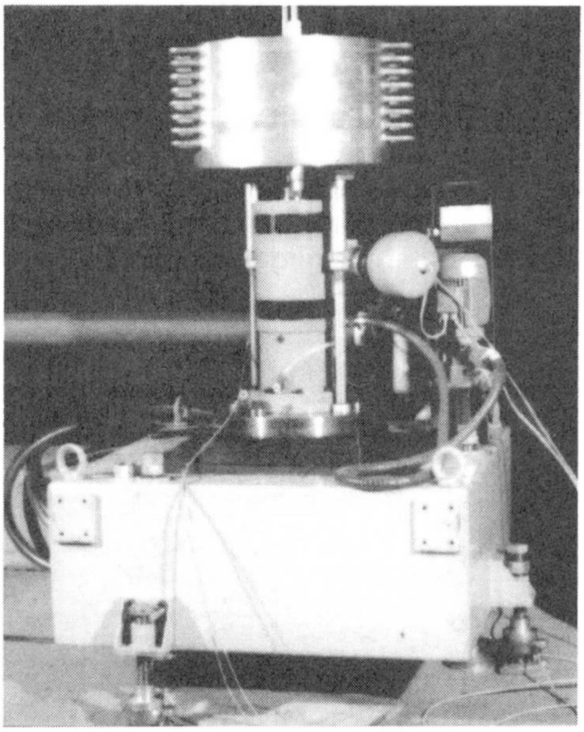

Fig. 1 The vibration generator.

2.3 Response Measurement

The standard instruments used with Modal Testing at EMPA are accelerometers Brüel & Kjær 8306. These have a measurement range of ±1 g, a sensitivity of 10 V/g and a resolution of 10^{-6} m/s^2. Usually, the structural response is determined in every measurement point in three directions. Hence, three of these accelerometers are orthogonally fixed to a supporting device. Stiffness of the connection between structure and transducers is ensured by firmly screwing the supports to the bridge pavement or concrete. Depending on the equipment and time available, EMPA uses two to four of these three-dimensional set-ups simultaneously. Testing of a bridge typically requires five to ten minutes per measurement cycle or up to two working days for 150 to 250 measurement points.

2.4 Signal Acquisition and Processing

The measured force and acceleration signals are passed through a front end where they are filtered, amplified and digitized. Signal processing requires a computer and Modal Analysis software packages. The time signals are first transformed into the frequency domain. All Frequency Response Functions response/force are then calculated, averaged over a reasonable number of FRF's and stored on hard disk. Depending on the quality of the signals acquired, "reasonable" may be a number between 5 and 15.

Calculation of the modal parameters from the FRF's is the second processing step. Determination, or, as the process is of an iterative and therefore not of a mathematically exact nature, estimation of the modal parameters is a two-stage procedure. With the CADA-X software package used by EMPA pole values (damped natural frequencies, damping ratios) and modal participation factors are firstly calculated using the Least Squares Complex Exponential Algorithm. In the second stage the modal vectors or mode shapes are calculated using the Least Squares Frequency Domain Technique.

3. FINITE ELEMENT MODELING, MODEL UPDATING

Application of the LMS Link model updating software based on CADA-X modal test results is possible for MSC/NASTRAN FE-models only. To later allow model updating, the modal test measurement point grid has to be a sub-quantity of the grid used for the FE-model. The crucial part of the Link-software is the Sensitivity Analysis routine which gives indications where mass and/or structural stiffness should be changed to optimally adapt the FE-model to the experimental results. However, the engineer can fortunately enough not be fully replaced by the computer: His judgement is very much sought after here. The result of the updating efforts is presented graphically in form of the so-called MAC-Matrix (Modal Assurance Criterion).

4. EXAMPLES

4.1 Bridge on the Aare River at Aarburg

The Bridge on the Aare River at Aarburg was built by Robert Maillart in 1911/12. It consists of a clamped-in concrete arch with a 72 m span, a bridge deck and originally a significant number of columns between the two. The latter two elements mentioned having been subject to severe deterioration, they were removed and replaced by a prestressed concrete bridge deck slab with two longitudinal main girders but without any columns between deck and arch in 1969 (Fig. 2).

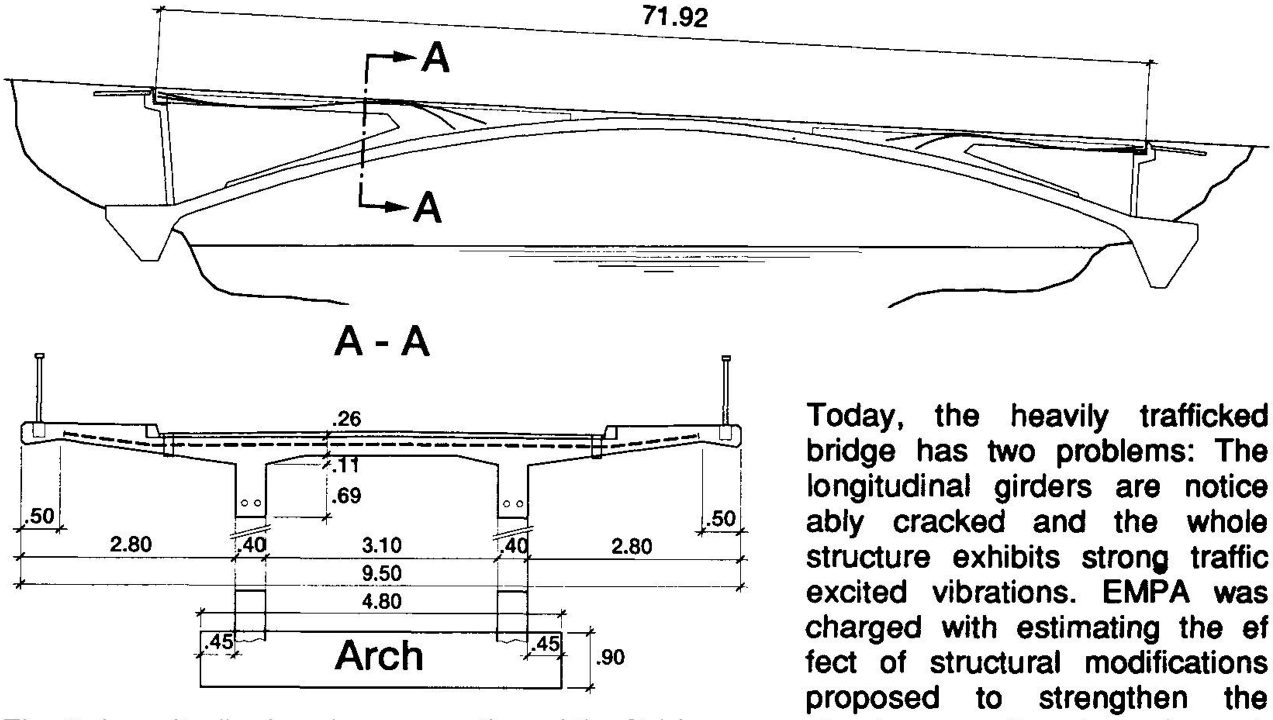

Fig. 2 Longitudinal and cross section of the Bridge on the Aare River at Aarburg (dimensions in m).

Today, the heavily trafficked bridge has two problems: The longitudinal girders are noticeably cracked and the whole structure exhibits strong traffic excited vibrations. EMPA was charged with estimating the effect of structural modifications proposed to strengthen the structure on the dynamic and, subsequently also on the static bridge behavior.

A modal test was performed on the bridge in April 1992. The structure was excited using the abovementioned servohydraulic vibration generator. The bridge response was acquired in a total of 142 measurement points in three directions each, 106 and 36 of them distributed over the bridge deck and arch respectively. The initial FE-model of the bridge consisted of roughly 200 CQUAD4 quadrilateral plate elements. It was refined after having performed the modal test finally consisted of 304 plate and beam elements. Figure 3 gives the comparison of frequency and mode shape as determined experimentally and analytically for the first three of the total of seven natural vibrations identified in the range f = 3...9 Hz. Coincidence can be described as being good.

Subsequent investigations using the updated FE-model showed that strengthening of the longitudinal bridge deck girders solves the static problems. The dynamic problem of shifting the fundamental frequencies out of the critical range of heavy vehicles dynamic wheel loads, $f \approx 3$ Hz, can however be achieved through fixing of the horizontal longitudinal mobility of the bridge at one bridge deck abutment only. This suppresses the first two natural modes of the bridge and yields a fundamental frequency of f = 4.54 Hz. Studies are now performed to develop shock absorbers suppressing the vibrations but ensuring the mobility for longterm deformations due to e.g. temperature effects.

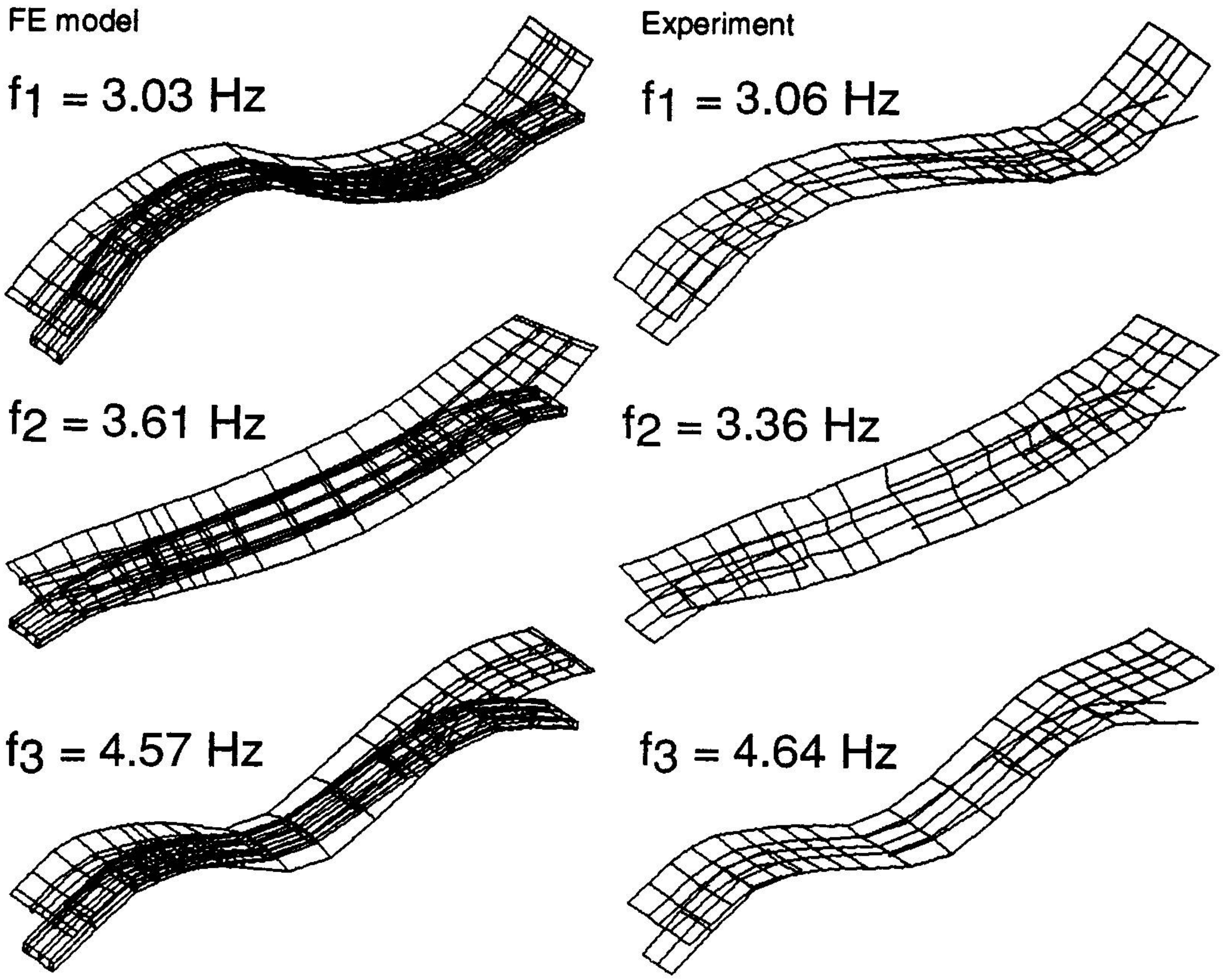

Fig. 3: Aare Bridge: Frequencies and mode shapes: Updated FE-model vs. experiment.

4.2 Westend Bridge Berlin

The Westend Bridge is a part of the Berlin City Highway Belt where it connects downtown Berlin and Tegel Airport. This 242 m long and roughly 30 years old bridge is a prestressed concrete girder continuous over eight spans with lengths between 5 m and 38 m. The cross section is a 14 m wide three-cell box. The bridge is exposed to relatively dense heavy commercial traffic and does no longer match today's requirements. It has therefore been strengthened by means of of longitudinal prestressed steel plates being added externally to the box girder bottom flange in 1993. To assess the effectiveness of the structural modifications, two test series have been planned, one before and one after strengthening. This report covers the test performed in autumn 1993. The project is a joint venture encompassing EMPA and BAM (Bundesamt für Materialprüfung- und -Forschung, Berlin, Germany) and is also financially supported by the Berlin Senate.

The modal test measurement point grid consisted of 215 points on the bridge deck and 18 points on piers and abutment walls. The modal test's results were not of same high quality as for the Aare Bridge. This is on the one hand due to the vibraton generator's energy being limited for $f < 2$ Hz, on the other hand to the relatively short middle span which cuts the bridge into two dynamically rather weakly coupled parts and makes it hence very difficult to identify all bridge modes with using one exciter only. Attempts will be made to use two shakers simultaneously for the second test in 1995 (Multiple Input Method).

The FE-model of the bridge was built up from 1000 CQUAD4 quadrilateral plate elements and 28 CBEAM beam elements (Fig. 4). Comparison of the experimental and analytical results is given in Figure 5 for the first four of the total of 25 identified modes between f = 1.7 Hz and f = 16 Hz.

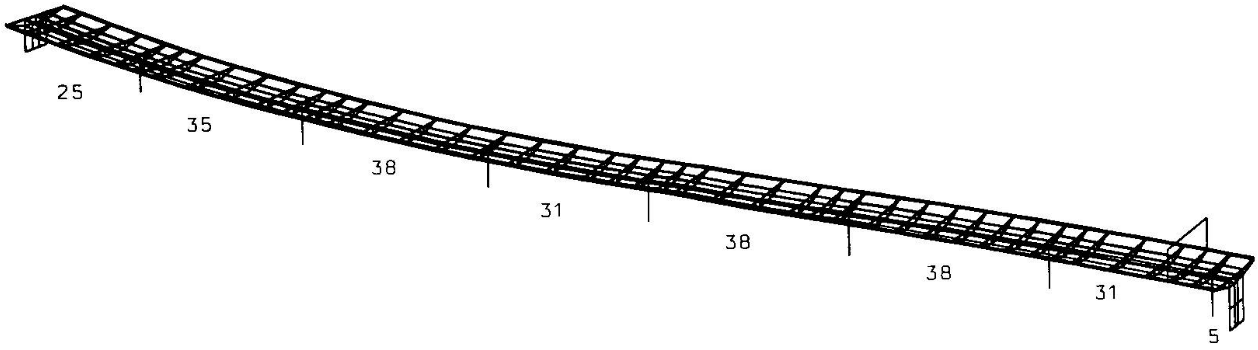

Fig. 4 Westend Bridge: Finite Element model. Span lengths are indicated in m.

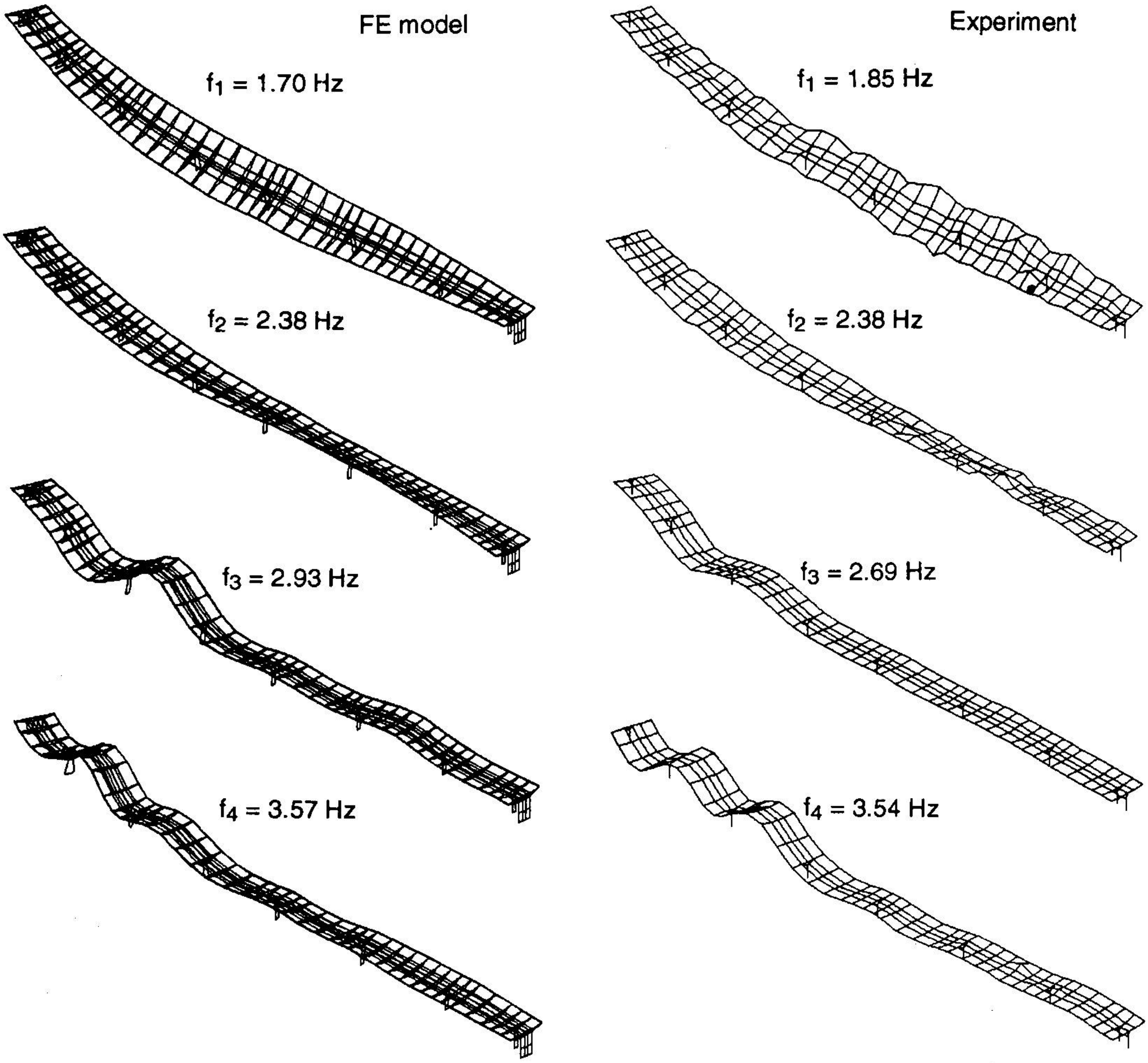

Fig. 5 Westend Bridge: Frequencies and mode shapes: FE-model vs. experiment.