Localization of damages in concrete structures

L. Frýba, M. Pirner, S. Urushadze  
Institute of Theoretical and Applied Mechanics,  
Academy of Sciences of the Czech Republic, Prague

Abstract

Three methods for the localization of imperfections or damages in concrete structures were developed and applied in laboratory conditions: COMAC, CAMOSUC and SEM. They are based on hammer blow method, modal analysis and on the special evaluation methods. These non-destructive approaches enable us to estimate the position of imperfections in structures, like the failures due to repeated loads that appear in fatigue tests. Furthermore, they facilitate to determine the inspection intervals and to estimate the residual life of structures.

1 Introduction

The application of changes of the dynamic characteristics of structures, like natural frequencies, forms of natural vibrations, damping, etc., to the detection of imperfections and damage arose some years ago, see Natke [1]. A rapid progress in experimental and computational techniques, precise recorders and other test and evaluation equipment have supported the development of several methods in recent years.

The methods were verified for discrete as well as continuous systems and especially for linear ones. The present stage of investigation has taken place in laboratories although the first tests in situ were also performed, see Frýba, Pirner [2].

The paper shows three methods that are able to identify and localize the imperfections and/or damage in a structure. They were verified in the laboratory.
2 Test arrangement

17 reinforced concrete panels were used for experiments, see Figure 1. They were produced for the fatigue tests of the European Rail Research Institute as described in details in the report by Fryba, Pirner, Urushadze [3]. The panel is a slab $2 \times 1 \times 0.1$ m stiffened by two girders $2 \times 0.4 \times 0.15$ m at longer sites, supported near the corners and designed for the central static load of $50$ kN.

The following instrumentation was used:
- loading arrangement: hydraulic power supply MTS 510.30, actuator MTS, load capacity $100$ kN, stroke $150$ mm, electronic controller MTS 407,
- deflections: mechanical indicator LVDT,
- strain gauges: Hottinger Baldwin Messtechnik,
- hammer blow: Bruel & Kjaer,
- modal analysis: SIGNALYS, MATLAB 5.2 programmes, ONO SOKKI CF 350Z DUAL - CHANNEL FFT ANALYZER, ICATS version 68 B.

The values of material properties of both the components reinforcement and concrete, measured deflections, stresses, ultimate static and fatigue loads, natural frequencies after static and fatigue tests as well as the fatigue characteristics are published in [3] by Fryba, Pirner and Urushadze.

The research together with the French, Swedish and Swiss experiments served as a basis for the formulation of a new Leaflet of the International Union of Railways for the design and assessment of reinforced concrete railway bridges to fatigue, see Fryba, Bousquet, Brühwiler [4].

The panels (Figure 1) served also for the development of the identification and localization methods:
3 COMAC method

The method frequently used for the determination of conformity between natural frequency modes of two states of the structure is the Modal Assurance Criterion (MAC), [1], [2]. It is suitable in cases when natural frequencies of various vibration modes are very close each other, however, it does not take into account the local deviations of displacement.

Therefore, we have developed another criterion, the so-called COordinate Modal Assurance Criterion (COMAC): A numerical value $C_j$ is calculated from the response of the structure to the hammer blow according to the formula:

$$C_j = \left[ \frac{\sum v_{n}(j) \cdot v_{id}(j)}{\left( \sum v_{n}(j)^2 \right) \cdot \left( \sum v_{id}(j)^2 \right)} \right]$$

where:

- $v_{n}(j)$ is the displacement of the $i$-th vibration mode of the first (virgin) state of the structure at point $j$,
- $v_{id}(j)$ is the displacement of the $i$-th vibration mode of the second (damaged) state of the structure at point $j$,
- $N$ is the number of exciting vibration modes, $N$ should be greater or equal to 2.

Figure 2: The hammer blow test of hanging panel at dynamic tests.
The COMAC method compares two states: undamaged (virgin) state with the damaged state. If $C_j = 1$ an absolute agreement exists between two states while $C_j = 0$ means an absolute disagreement of the compared displacements at point $j$. If the COMAC value is between zero and one, i.e. $0 < C_j < 1$, it means that the second state differs from the first (virgin) state or in other words: a damage appeared at the point $j$ after the previous test. Thus, the point $j$ indicates the position of a failure. The method distinguishes an important failure at the time being.

The application of the COMAC method can be shown on the panel B 3. The hammer excites the frequencies $f_1 = 175.78$ Hz, $f_2 = 312.50$ Hz and $f_3 = 380.86$ Hz in the virgin state of the panel. The frequencies were measured and the COMAC values (1) calculated after 500 000 and 1 000 000 load cycles while the fatigue life was 1 024 714 cycles. The COMAC values are calculated in the Table 1 where the lowest $C_j$ values indicate the presence of the cracks at points C 6, C 7, D 7, E 7 and F 5 (the net is indicated in the Figures 2 and 3). They correspond well to cracks in the Figures 3 and 4.

Table 1: The frequencies and COMAC values for the panel B 3 after 500 000 and 1 000 000 load cycles

<table>
<thead>
<tr>
<th>$f_j$ (Hz)</th>
<th>Virgin state</th>
<th>after 500 000 cycles</th>
<th>after 1 000 000 cycles</th>
<th>net see Figures 2 and 3</th>
<th>COMAC values after 500 000 cycles</th>
<th>COMAC values after 1 000 000 cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_1$</td>
<td>175.78</td>
<td>166.02</td>
<td>138.67</td>
<td>B 7</td>
<td>0.9988</td>
<td>0.7386</td>
</tr>
<tr>
<td>$f_2$</td>
<td>312.50</td>
<td>296.88</td>
<td>269.88</td>
<td>C 7</td>
<td>0.6232</td>
<td>0.6458</td>
</tr>
<tr>
<td>$f_3$</td>
<td>380.86</td>
<td>367.19</td>
<td>328.13</td>
<td>D 7</td>
<td>0.8106</td>
<td>0.4175</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>E 7</td>
<td>0.8906</td>
<td>0.6846</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>F 7</td>
<td>0.9929</td>
<td>0.6846</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>B 6</td>
<td>0.9159</td>
<td>0.9546</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>C 6</td>
<td>0.9992</td>
<td>0.9451</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>D 6</td>
<td>0.7397</td>
<td>0.9546</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>E 6</td>
<td>0.9613</td>
<td>0.8233</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>F 6</td>
<td>0.9613</td>
<td>0.7163</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>B 5</td>
<td>0.9982</td>
<td>0.9399</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td>C 5</td>
<td>0.9451</td>
<td>0.6740</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>D 5</td>
<td>0.9546</td>
<td>0.8599</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td>E 5</td>
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<td>0.8614</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>F 5</td>
<td>0.9665</td>
<td>0.6959</td>
</tr>
</tbody>
</table>

4 CAMOSUC method

It was observed that the imperfections are expressed by local changes of the constructional stiffness. Therefore, the CAMOSUC method (ChAnge of MOde SUrface Curvature) compares the modes of natural vibration of a structure in the
Figure 3: The forms of the forced vibration of the panel B 3 after hammer blow test and modal analysis. Full thick lines = virgin state, dashed lines = damaged state after 1 024 714 load cycles; a) = first mode, b) = third mode of vibration.
virgin state with that one in the damaged state after absorbing a lot of load cycles. The changes in radii of curvatures indicate the failures in the structure.

The CAMOSUC value $M_i$ at the point $j$ is expressed as

$$M_i = \left| v_{i,v}'' - v_{i,d}'' \right| = \left| v_{i+1,v} - 2v_{i,v} + v_{i-1,v} \right| h^2 - \left| v_{i+1,d} - 2v_{i,d} + v_{i-1,d} \right| h^2$$

where $v$ are the natural modes of vibration, the indices $_v$ and $_d$ denote the virgin and damage state, respectively, and $h$ is the dimension in the direction of the investigated points $i+1$, $i$, $i-1$. It is supposed that the cracks are perpendicular to the place where the smallest radii of the curved natural mode occur. The assumption need not be valid for strongly unhomogenous materials or for structures with a complex stress state.

The experiments on the reinforced panels used an optimal number of transducers which correspond to the capacity of applied programmes for the modal analysis (SIGNALYS and MATLAB 2). This approach enables the clear visibility, comparison of modes of natural vibration and/or their animation. The transducers were placed in 7 cross sections, see Figures 2 and 3.

The Figure 3 shows an example of the CAMOSUC method applied to the panel B 3 and its slab. It depicts the modes of the forced vibration after the hammer blow in both the virgin state (full thick lines) and damaged state (dashed lines) for the first and third modes of vibration. The Figure 3 clearly explains the longitudinal (Figure 3 a) and transverse cracks (Figure 3 b) in the slab which are caused by the first and third mode of vibration, respectively. The position of cracks roughly corresponds to the Figure 4.

Figure 4: The cracks at the tensile side of the slab, panel B 3, after 1 024 714 load cycles.
5 SEM method

The following relation holds true between the orthonormal modes of natural vibration \([ v ]\) and the stiffness matrix \([ K ]\)

\[
[v]^T [K] [v] = [\omega^2]
\]  

(3)

where \([ \omega ]\) is a matrix of circular natural frequencies. The equation (3) may be rearranged as

\[
[K] = [v]^T [\omega^2] [v]\]

(4)

and can be written for both the virgin state (index \(v\))

\[
[K]_v = [v]^T_v [\omega^2]_v [v]_v^{-1}
\]

(5)

and the damaged state (index \(d\)).

Figure 5: System error matrix for the virgin state and damaged state after 1,000,000 load cycles.
The error matrix of stiffness is defined as

\[ [K]_d = ([v]_d^T [\alpha^2]_d [v]_d)^{-1} \]  

(6)

and it represents a theoretical basis of the System Error Matrix (SEM) method.

The software ICATS, version 68B, evaluates the system error matrix where the transfer frequency function \( H(i\omega) \) is applied to the modal analysis. An example in the Figure 5 shows the system error matrix \( k_{ik} \) (in percentage of stiffness error) for the virgin and the damaged state after 1 000 000 load cycles for the first and second modes of vibration. The greatest errors represented by the darkest fields in the Figure 5 indicate the places where the damages occur (the scale of the net in the Figure 5 differs from that one in the Figure 3).

6 Application of dynamic tests

The first natural frequencies \( f \) of all investigated panels measured after each 500 000 (approximately) load cycles \( n \) are reproduced in the Figure 6. They are related to the first natural frequency \( f_i \) of each panel in the virgin state. Besides, several symbols (right down) indicate the values \( f/f_i \) measured after the total collapse of some specimens under the static load.

The Figure 6 shows a general tendency of natural frequencies to diminish with the increasing number of load cycles. It is a consequence of appearance of failures in the panels during the fatigue tests.

The engineering analysis and experiences in that field indicate that for values \( f/f_i > 0.95 \) the structure is probably not damaged. On the other hand, the mean value \( f/f_i = 0.4 \) of the totally collapsed specimens imply a certainty of damages. The double safety gives the value \( f/f_i = 0.8 \) which can be assumed as a limit at which the structure is surely damaged. The values \( f/f_i = 0.95 \), 0.8 and 0.4 are depicted by dashed thick lines in the Figure 6.

As the great dispersions of fatigue results are characteristic for concrete the suggested limits may be stated only with certain probability. They should simply warn the Authorities that something happened since the last inspection or test. It is assumed that the important structures, like bridges, towers, etc., are tested in the virgin state before opening of the structure to the public or traffic.

The derived limits and the Figure 6 can be applied to the estimation of the residual life of a structure and to the calculation of inspection intervals.

Example 1

Let us assume that the measured first natural frequency of a bridge after 10 years of traffic is about 5% lower than that one in the virgin state. The today’s traffic is expected in the future. Then, the ultimate value \( f/f_i = 0.8 \) will be reached in about 14 years. Calculation using the Figure 6: \( f/f_i = 0.95 \) corresponds to \( 10^5 \) cycles while \( f/f_i = 0.8 \) to about \( 10^7 \) cycles. Thus: \( 14 = 10 \cdot \log 10^7 / \log 10^5 \).
Example 2

The example 1 warns the Authority that the next inspection must be performed in shorter intervals. When should be planned the next inspection not to cross the value \( f/f_1 = 0.9 \) which corresponds to \( 10^6 \) in the Figure 6? This value will be reached in 12 years \((12 = 10 \cdot \log 10^7 / \log 10^5)\) so that the inspection interval should be \( 2 = 12 - 10 \) years.
7 Conclusions

The identification and localization of imperfections or damages in structures is a very important problem for civil engineering. Especially the reinforced and prestressed concrete structures suffer from the impossibility to observe the damages in the first stage of their appearance.

The developed non-destructive methods could contribute to the solution of this problem. The complex dynamic investigations are supposed to be performed at the virgin state of the structure and then, say, in 10 years intervals. The investigations reflect the changes in natural frequencies, forms of natural vibrations, curvatures of deflections and error matrices after long-standing operation of the structure. The measured data enable to determine the inspection intervals and to estimate the residual life of structures.

The methods COMAC, CAMOSUC and SEM are non-destructive, illustrative and well tried in laboratory conditions. They need, of course, further development, field applications and verifications.

Acknowledgement

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References