Feasibility of dynamic test methods in classification of damaged bridges

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ABSTRACT

Bridges may need to be assessed and restored in military operations. The ability to make an assessment quickly without the use of a baseline data set is essential if a correct decision about the safety of the bridge is to be taken.

To acquire knowledge of the possibilities and limitations of detecting damage through dynamic measurements, a series of experiments was carried out consisting in static and dynamic tests of concrete slabs with different degrees of damage.

By carrying these tests it was possible to gain insight as to how the dynamic response changes at different damage levels. In the present article, the information which can be obtained from modal parameters relating to the presence and extent of damage and possibly the strength of the structure is discussed.

Introduction

The monitoring of structures to detect damage at the earliest possible stage is a subject which has been given much attention by civil, mechanical and aerospace engineers. Damage or fault detection, as determined by changes in the dynamic properties or response of structures, has been studied considerably. The basic idea is that modal parameters (notably frequencies, mode shapes, and modal damping) are functions of the physical properties of the structure (mass, damping and stiffness). Therefore, changes in the physical properties will cause changes in the modal properties.

In this study experiments were performed to investigate the dynamic behaviour of concrete bridges with different degrees of damage. The experiments comprised static and dynamic tests on three concrete slabs, considered as scale models of a single span concrete plate bridge. Two of these slabs were damaged, one using an explosive charge and the other by drilling a hole through it. The dynamic tests of the structure involve the measurement of the motion it undergoes at different locations due to excitation by an impact hammer. The tests were carried out for different loading levels.

The research is part of an on-going program to investigate the possibilities of damaged bridge classification.

Description of the experiment

In total, three slabs have been tested. The slabs have a dimension of 1.0 x 2.0 x 0.1 m and were tested in a three point bending configuration. The load was applied using a hydraulic jack connected to a transverse steel beam across the mid section of the slab, see Figure 1. With such a configuration it was possible to determine the load displacement curve for the slab in question. Table 1 provides an overview of the tested slabs and the types of tests carried out. Slab ‘M’ has been damaged using an explosive charge of 125 g plastic explosive (PETN). This created a hole of about 125 mm through the slab with damage extending a further 125 mm around this hole. Slab

‘H’ has been damaged by cutting a 250 mm hole through it. As a result of this, two of the six reinforcement bars the slab were cut. In order to avoid applying the load over the damaged area and because damage in the real situation is not likely to extend symmetrically over the structure, both damage types are offset from the middle of the plate by a distance of 250 mm in the longitudinal direction.

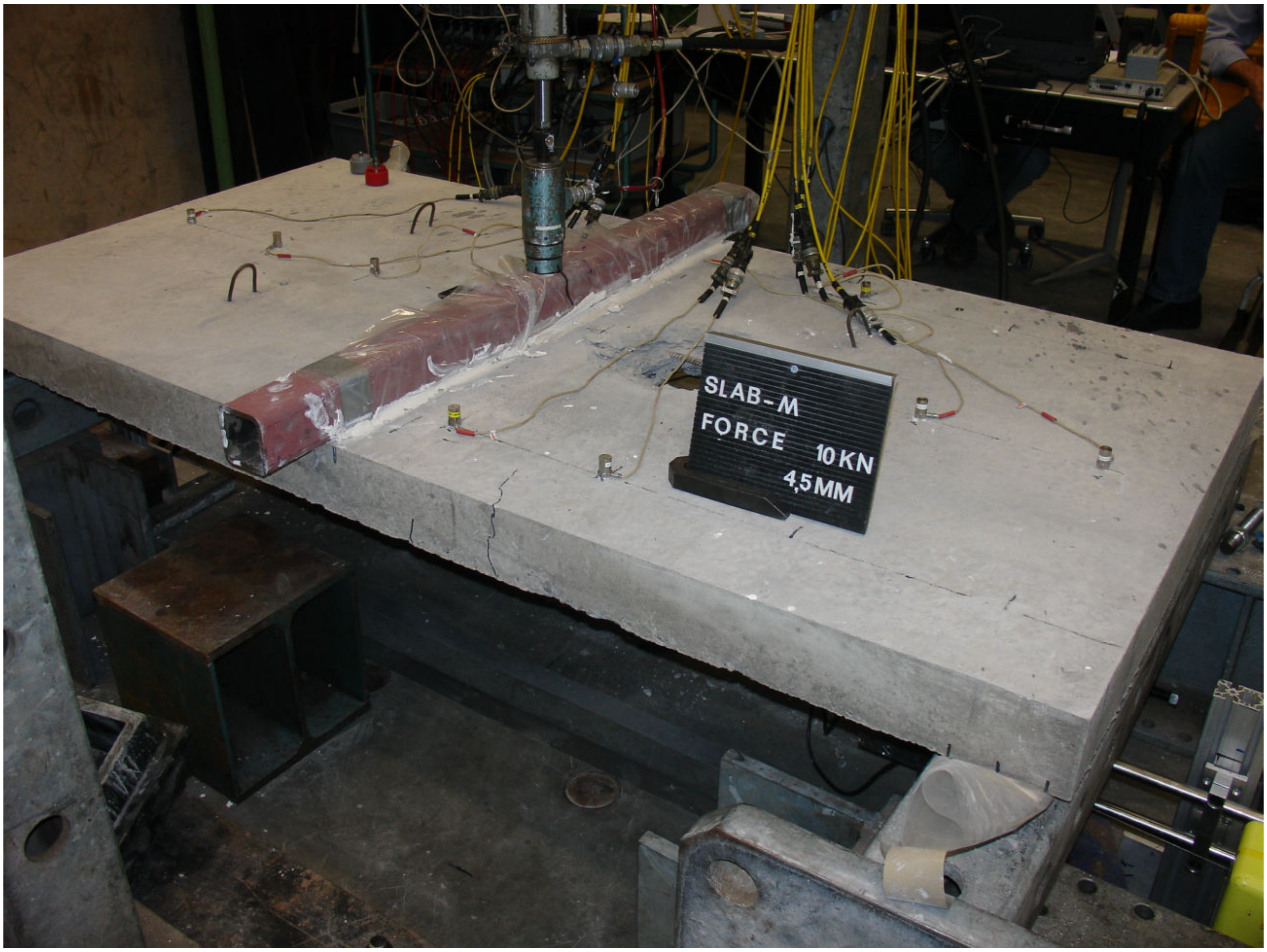


Figure 1: Test configuration for one of the slabs.

Table 1: Test slabs.

Test ID	Slab description
S	slab with standard reinforcement
H	slab with artificial damage (hole)
M	slab with mine damage

Each slab was tested in the same manner, applying alternatively a given load and then carrying out a dynamic impact test using a hammer. The load levels at which to do this was determined during the course of the experiment by monitoring the displacement in middle of the slab and the force applied by the hydraulic jack. Before increasing the load to the next level, the load was removed and the hydraulic jack was disconnected, in order to carry out another dynamic test with the slab in an unloaded state. The impact force was measured directly in the hammer. Using a set ten accelerometers placed at different points on the slab, the motion of the slab in the vertical direction was measured.

Among the various analyses that have been carried out is a modal analysis. This will be discussed in present paper. The analysis relates to the dynamic tests carried out on the slabs with the hydraulic jack disconnected (zero vertical load). Table 2 summarizes the various load levels obtained in the tests.

Table 2: Load levels at which dynamic testing was carried out. The impact file number refers to the file containing data from the impact tests with the slabs in *unloaded* state. F_{i-1} is the last load level (or preload) reached prior to dynamic testing.

Impact or file #	**Slab 'S' F_{i-1} [kN]**	**Slab 'M' F_{i-1} [kN]**	**Slab 'H' F_{i-1} [kN]**
1	0	0	0.0
3	11	14	11
5	23	25	23
7	32	30	27
9	35	34	28
11	28	36	24
13	7	28	11

Results

Comparison of theoretically and experimentally determined eigenfrequencies

The eigenfrequencies of a plate can be calculated analytically. The experimental modal frequencies are compared with those from a theoretical model of a plate which is simply supported on two opposite sides and free on the two other sides. Of course, this model corresponds in fact to plate S, the intact plate, without any prior loading. In order to compare frequencies at higher load levels, the theoretical frequencies are scaled so that the 1st natural frequency matches that obtained in the experiment. This assumes that the damage induced by the load is uniformly distributed, which is not entirely true since flexural cracks will be more extended in the middle of the slab.

Theoretical model

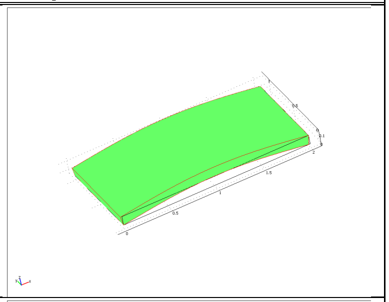
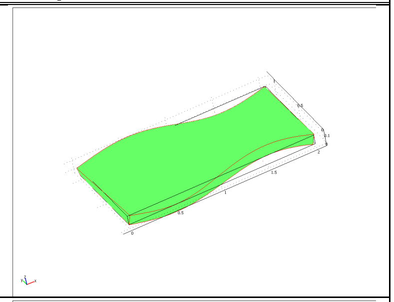
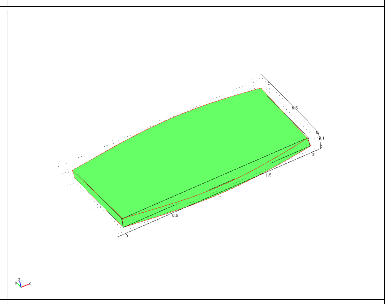
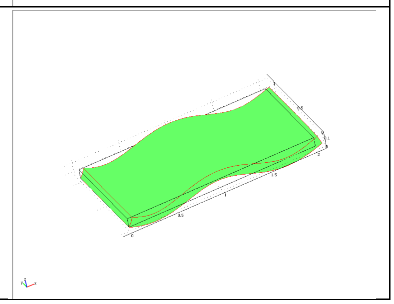
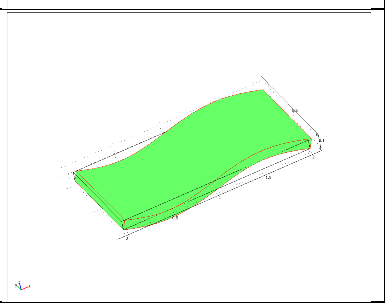
The theoretical model describes a rectangular plate as is shown in Figure 2. The dotted lines indicate the sides where the plate is simply supported. The eigenfrequencies can be calculated for a plate with different aspect ratio's a/b where b is the length of the supported side of the plate and a is the length of the free side.
The eigenfrequency can be calculated from:

(1) $$f = \frac{\lambda^2}{2\pi \cdot a^2}\sqrt{\frac{E \cdot h^3}{12 \cdot m \cdot \left(1-\nu^2\right)}}$$

With E = modulus of elasticity
v = poisons ratio
h = height of the plate

λ^2 depends on the mode shape and the aspect ratio a/b. Values of λ^2 for the first 5 modes and corresponding to an aspect ratio of 2 are in given in Table 3.

Table 3: Values of λ^2 corresponding to an aspect ratio of 2 and different mode shapes.

λ^2	Mode	Shape	λ^2	Mode	Shape
9.87	Ω_{11}		64.54	Ω_{22}	
27.52	Ω_{12}		88.83	Ω_{31}	
39.48	Ω_{21}				

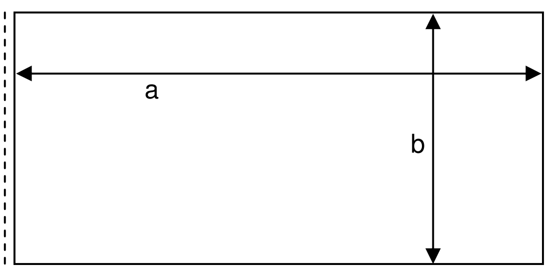


Figure 2: Rectangular plate which is simply supported on two opposite sides (indicated with the dotted line) and free on both other sides.

Slab S: comparison of the measured and theoretical eigenfrequencies.

The theoretical eigenfrequencies depend on the modulus of elasticity of the material and the geometry. If the plate is considered as a simply supported beam, these two properties can be reduced to a single one, that is, the bending stiffness of the plate, EI. Table 4 shows the theoretical mode shape frequencies obtained by selecting a value of EI such that the 1st frequency of vibration corresponds with that obtained from an analysis of the experimental frequency response spectra. The frequency for the first mode therefore is equivalent to that of the experiment.

File 1 corresponds to the undamaged situation. File 2, 4, 6 etc are loaded situations and are not considered in this analysis. File 3 indicates the situation where the plate is slightly damaged, in file 5 the plate is somewhat more severely damaged etc.

Table 4: Theoretical eigenfrequencies for slab S.

Frequency [Hz]		**File 1**	**File 3**	**File 5**	**File 7**	**File 9**	**File 11**	**File 13**
	EI [kNm^2]	1558	1292	1083	875	667	592	192
Mode no.								
1	Ω_{11}	38	35	32	28	25	23	13
2	Ω_{12}	106	96	88	79	69	65	37
3	Ω_{21}	152	138	127	114	99	94	53
4	Ω_{22}	248	226	207	186	162	153	87
5	Ω_{31}	342	311	285	256	224	211	120
6	Ω_{13}	406	370	338	304	266	250	142

In Figure 3 the measured response spectra of slab S are shown. The first, second, fourth and fifth measured eigenfrequencies of the undamaged plate match well with the calculated eigenfrequencies. The theoretical model describes the behaviour of an isotropic plate and is a relatively good approximation of slab S in the undamaged situation. The observation that the calculated and measured eigenfrequencies correspond is expected. The third eigenfrequency corresponds to the “second” bending. Since the impact is applied relatively close to the middle of the slab, this mode is hardly visible in the measured data.

When the plate is damaged, the theoretical eigenfrequencies do not match with the measured higher modes. The eigenfrequencies that correspond to the higher modes seem to change less than the frequency of the first mode. This is probably due to the uneven distribution of the cracks over the plate. Most of the cracks are concentrated in the middle of the plate where the plate is loaded. Hence, only the first mode is most affected by this local decrease in stiffness.

An interesting effect is the increase in the amplitude of the first mode and the decrease in amplitude of the higher modes for increasing load levels. Because the first mode is more easily excited due to the decreased stiffness, this mode will be more prominent.

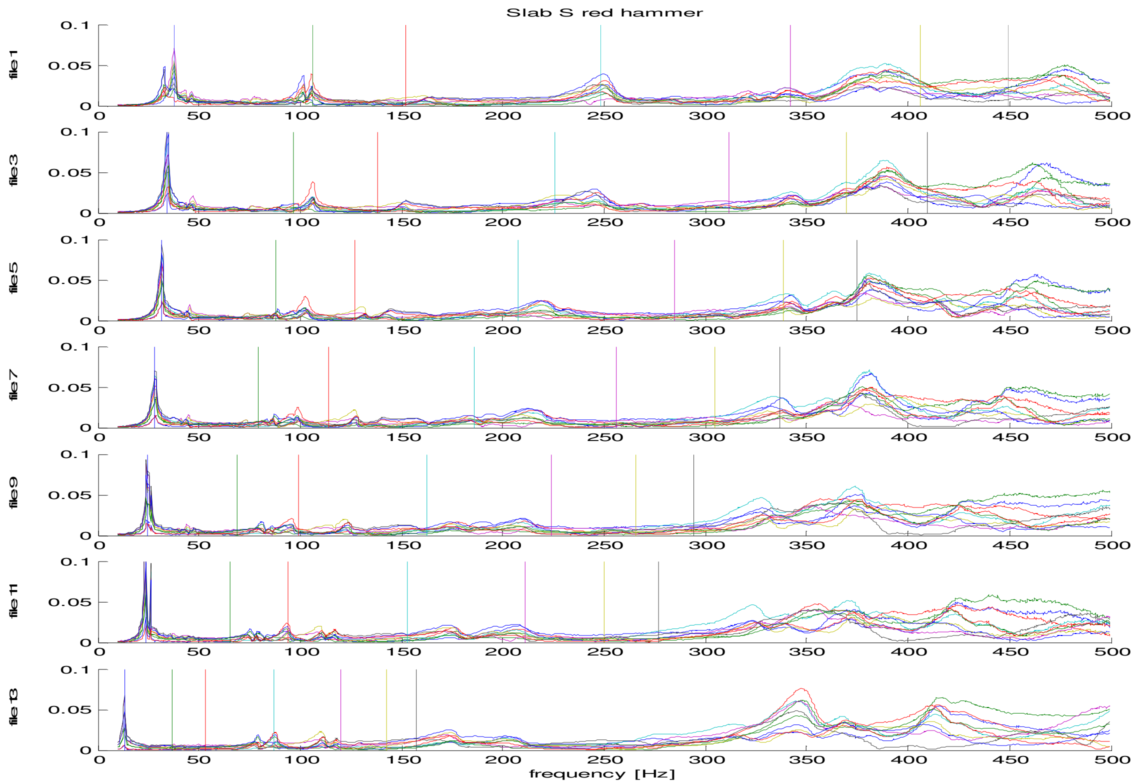


Figure 3: Measured frequency response functions for slab S. File 1 is the undamaged situation. File3, 5 etc represent the slab with an increasing degree of damage (or preloading). The vertical lines indicate the theoretical frequencies of vibration from Table 4.

Slab M: comparison of the measured and theoretical eigenfrequencies.

The theoretical eigenfrequencies for slab M are given in Table 5. As with slab S, the bending stiffness, EI, was "tuned" to the first experimental eigenfrequency.

Table 5: Theoretical eigenfrequencies of slab M.

Frequency [Hz]		**File 1**	**File 3**	**File 5**	**File 7**	**File 9**	**File 11**	**File 13**
	EI [kNm^2]	792	725	721	696	592	525	500
Mode no.								
1	Ω_{11}	27	26	26	25	23	22	22
2	Ω_{12}	75	72	72	71	65	61	60
3	Ω_{21}	108	104	103	102	94	88	86
4	Ω_{22}	177	169	169	166	153	144	141
5	Ω_{31}	244	233	233	228	211	198	194
6	Ω_{13}	289	277	276	271	250	236	230

In Figure 4 the experimental response spectra of slab M are shown. Compared to the frequency response spectra of slab S, the first eigenfrequency seems to be much more dominant than other frequencies. The higher eigenfrequencies are much less distinct. In case of slab M, the first file does not represent an undamaged plate.

The measured eigenfrequencies of slab M were compared with those of slab S. Comparing the eigenfrequencies of slab S with those of slab M, it is clear that there is an initial damage in slab M. In fact, this initial damage could be compared to the damage in slab S from to the application the ultimate load (see Table 2). From the results of the slab H (with the drilled hole), it will be clear that the low initial natural frequency is not the result of damage due to the presence of a hole, but the result of flexural cracks which were created due to the blast load.

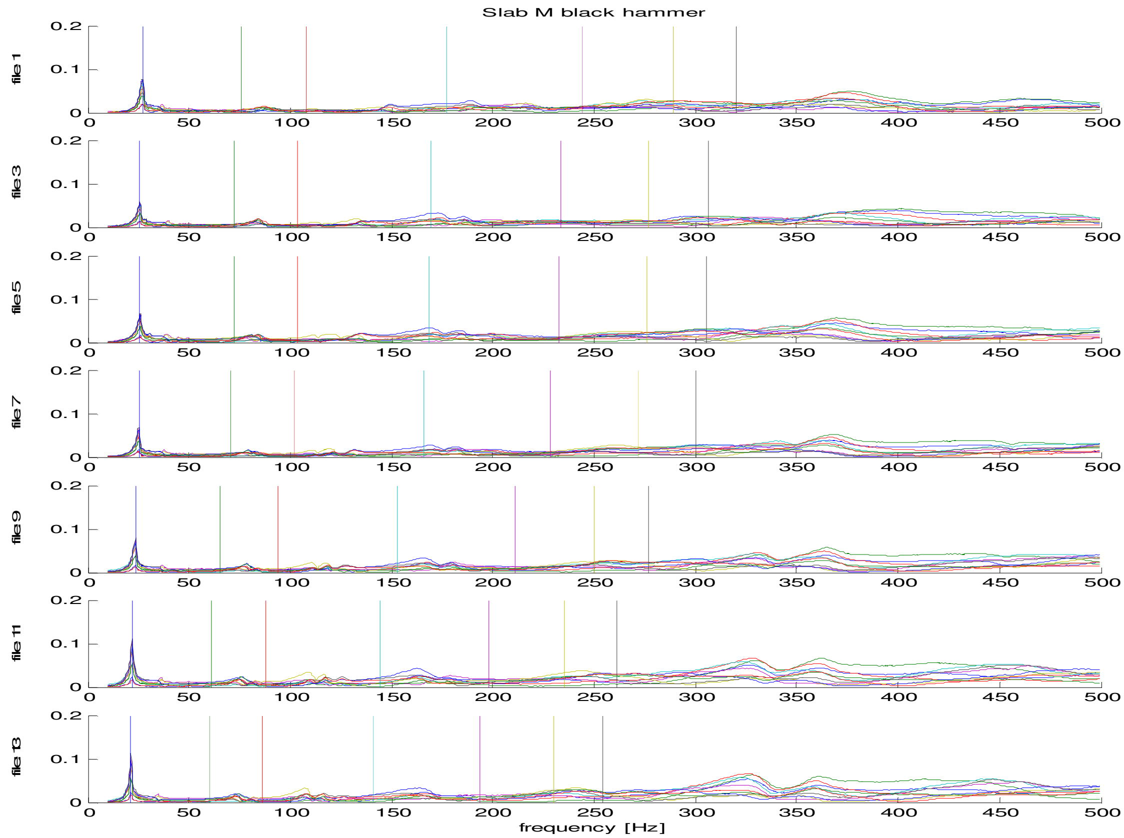


Figure 4: Measured frequency response functions for slab M, for different preload levels. The vertical lines indicate the theoretical frequencies of vibration from Table 5.

Slab H: comparison of the measured eigenfrequencies with the theoretical eigenfrequencies.

The calculated eigenfrequencies for slab H are given in Table 6. In Figure 5 the experimental frequency response functions spectra of slab H are shown.

Table 6: Theoretical eigenfrequencies for slab H.

Frequency [Hz]		File 1	File 3	File 5	File 7	File 9	File 11	File 13
	EI [kNm^2]	1625	1208	1042	625	617	533	367
Mode no.								
1	Ω_{11}	39	33	31	24	24	22	18
2	Ω_{12}	108	93	87	67	67	62	51
3	Ω_{21}	155	134	124	96	96	89	74
4	Ω_{22}	254	219	203	157	156	145	120
5	Ω_{31}	349	301	280	217	215	200	166
6	Ω_{13}	415	357	332	257	255	237	197

If the measured first eigenfrequencies of slab S (no hole) and slab H (with a drilled hole) are compared, the differences as is shown in Table 7 are small. However, the spectra of slab H differ considerably from the spectra of slab S. In the case of Slab H, the first measured eigenfrequency is dominant independently of the damage level. In the case of slab S, in the more or less undamaged levels some of the higher order modes were of the same order of magnitude as the first eigenfrequency.

For slab S in the initial stage, the higher order eigenfrequencies correspond with the calculated ones, whereas for slab H this would not seem to be the case. This effect could probably be explained by the presence of the hole, which may lead to a shift in the frequencies of higher modes. However, there are two arguments against this. First of all, there are two peaks in the region of the first eigenfrequency of slab H. If the lowest of these two is selected (corresponding to 36 Hz instead of 39 Hz), all theoretical eigenfrequencies shift to towards the origin, matching more closely with peaks in the frequency response functions. A better match is obtained if a fitting procedure is used to obtain the experimental modal frequencies. The second argument is that from a simulation of the two slabs are (for example using finite elements), it emerges that the shift in eigenfrequencies is minimal. The hole apparently leads to a reduction in stiffness and a reduction in mass which would seem to cancel each other out. With this knowledge, it is concluded that damage from flexural cracking has a much greater influence on the dynamic response of the slabs than damage in the form of a hole in the slab.

Interestingly, the results of the dynamic tests on slab S alone give no indication as to its lower ultimate strength as observed from the static loading testing (refer to Table 2 for the obtained load levels).

Table 7: 1^{st} eigenfrequency of slabs S and H compared (frequency in Hz).

Slab	File 1	File 3	File 5	File 7	File 9	File 11	File 13
Slab S	38	35	32	28	25	23	13
Slab H	39	33	31	24	24	22	18

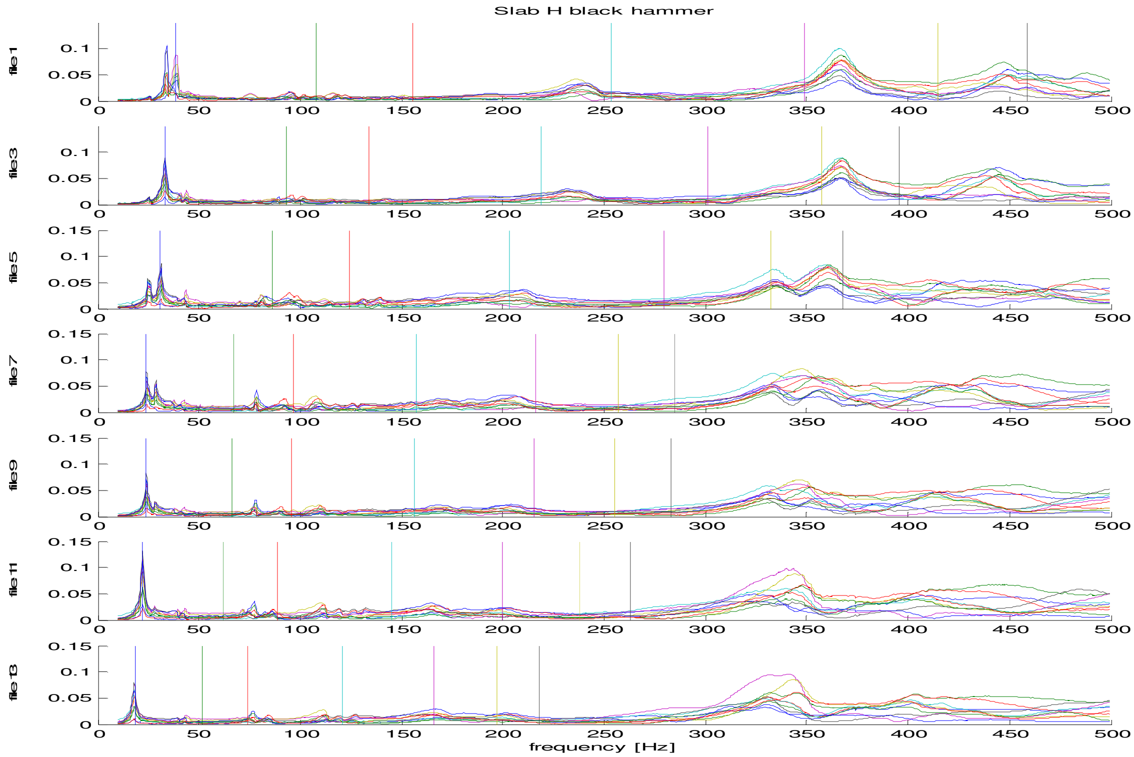


Figure 5: Measured frequency response functions for slab H, for different preload levels. The vertical lines indicate the theoretical frequencies of vibration from Table 5.

Conclusions

The eigenfrequencies of the slabs are much more sensitive to the extent of flexural cracking due to preloading than the presence of a severely damage zone such as a hole. The results suggest, however, that the latter type of damage may lead to higher damping of higher modes with respect to a slab without such damage. Nothing in the results of dynamic tests of slabs H suggested that this slab was in fact weaker than the slab S. Dynamic modal parameters alone are therefore not sufficient to determine the location of severe damage in a structure nor its residual bearing capacity.

The present study represents only one of the various analyses which have been carried out. More information has been obtained for example from a study of the mode shapes, from which it was possible to determine the distribution of stiffness along the slabs. The sensitivity of mode frequencies to the extent of flexural cracking suggests that it may be possible to estimate the amount of reinforcement in a structure. Studies will be carried out in the future to determine whether this is possible. The possibilities of using dynamic testing in combination with other types of tests in order to estimate the residual bearing capacity of a structure will also be considered.