SHAKING TABLE TESTS OF REINFORCED CONCRETE BEAMS FOR DAMAGE PROGRESSION EVALUATION

Rogerio Bairrao1), Joaquim Duque1), Marcin Chrzanowski2), Pawel Latus2)

1) National Laboratory for Civil Engineering, Lisbon, PORTUGAL

2) Krakow University of Technology, Krakow, POLAND

ABSTRACT

In several situations the failure of a reinforced concrete structure is preceded by a gradual deterioration of the materials whose condition can be recognised by measuring the change of their physical properties [1]. The main purpose of the destructive tests described in the present paper was to obtain an evaluation of the damage evolution in a reinforced concrete beam, submitted to controlled harmonic displacements imposed by a shaking table.

A reinforced concrete beam, with two different spans, was designed to sustain a static load of a central mass at the longer span. Ten identical specimens were built and tested at the LNEC (Portuguese National Laboratory for Civil Engineering) shaking tables facility [2]. This paper presents those tests, which have been performed in the aim of the European Commission programme ECOEST/PECO (European Consortium of Earthquake Shaking Tables / Central and Eastern European Countries extension). The beams were fixed to the shaking table and submitted to a sinusoidal displacement in the vertical direction, having a pre-established duration and constant amplitude. The tests were carried out by successive stages, of increasing amplitudes, until the collapse of each beam was reached. The collapse mechanism consisted in the formation of two plastic hinges located around the mid support and close to the added mass. The tests aimed to give an evaluation of the loading history influence on the occurrence of the critical state. During the tests, displacements and accelerations were continuously recorded at several points of the structures, alongside with ultrasonic measurements taken along different directions, before and between the successive stages.

In the present paper the design of the specimens is showed. The instrumentation plan, the test set-up and the test procedure are also described. Finally, the most relevant results are shown together with the formulation of a global damage law governing the prediction of the limit state of the beams.

INTRODUCTION

The project was mainly focused on the failure of a reinforced concrete structure caused by damage accumulation, under variable dynamic loading. A 4.2-meter long two-span beam (Fig. 1) was designed to sustain a static load of a central mass at the longer span. The beams were fixed to the shaking table and submitted to a sinusoidal displacement in the vertical direction, having a pre-established duration and constant amplitude. The tests were carried out increasing the amplitude on each successive stage until the beam was totally collapsed. The collapses usually occurred by the formation of two hinges on the longer span of the beam at the middle support zone, close to the mass, and were manifested by the crushing of the concrete under compression. The tests aimed to give an evaluation of the loading history influence on the occurrence of the critical state.

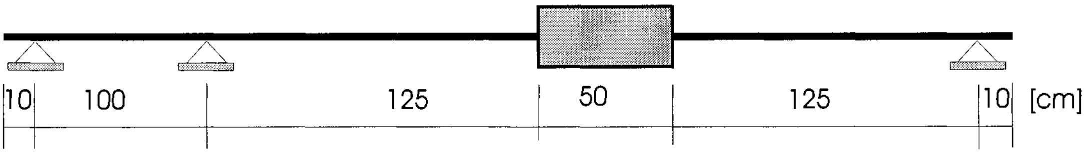

Fig. 1 - Scheme of the tested beams

SPECIMEN GEOMETRY

Reinforced Concrete Beam

The specimen geometry is given in Fig.2 showing details of the beam dimensions and reinforcement. The beam mass was of about 125 kg.

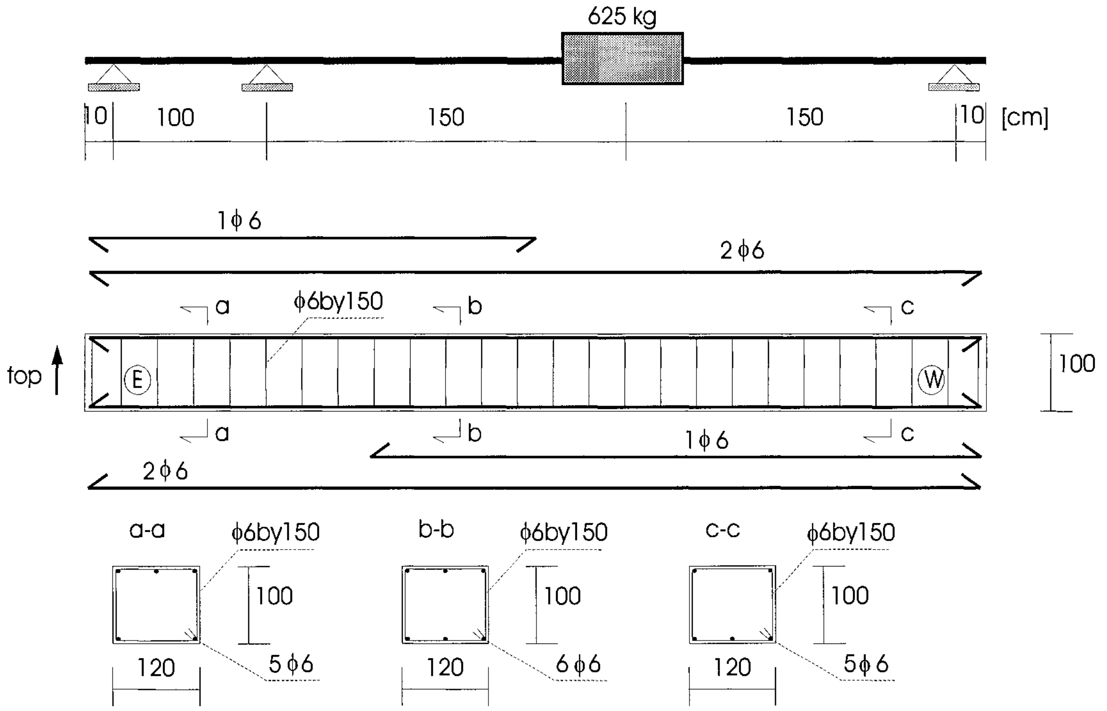

Fig. 2 - Beams geometry with detailed dimensions and reinforcement

Payload and Supports Configuration

Each beam was fixed to the supports, with rubber cushions to allow free rotations, and duly loaded with the mass. Details and positions of the elements are shown in Fig.3.

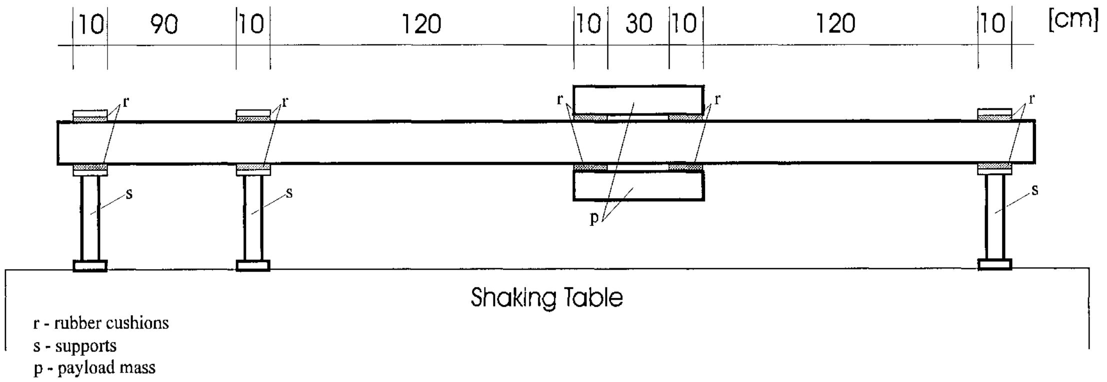

Fig. 3 - Payload and supports configuration

LOADING HISTORIES

It was decided that kinematics excitation would be in the form of successive stages of constant amplitude (A) and duration (t). For each one of the stages the amplitude was increased by a constant value of Δa=1 mm, except for the test K0 which amplitude was increased by Δa=2 mm, under a frequency of 2 Hz, and by Δa=1 mm, under 4 Hz. Between two consecutive stages there was an undefined period of rest time, that can be considered as negligible for the test results, during which ultrasonic measurements were performed.

All ten beams were divided into four groups: the first one (K0) consisted of only one beam for which a calibration test was performed, in order to define the parameters to be applied to all the other tests. The three other groups (of 3 beams each) were all tested at a frequency of 4 Hz but did have different values of Δt. The consecutive tests were identified by the symbols K1 through K9. Each test was stopped when the beam presented the occurrence of hinges.

K0 Calibration Test

The initial program instructions for K0 test, besides the 2 and 4 Hz stages, already mentioned, also included a third frequency of 6 Hz. This third frequency test was however never performed, due to the early beam collapse (during the stage corresponding to the parameters f=4 Hz and a=8 mm).

Following K0 test, it has been decided that frequency would be 4 Hz, for all the other tests, with stage durations of 30 seconds for K1 to K3, 90 seconds for K4 to K6 and 180 seconds for K7 to K9. The amplitude increment was always of 1mm. The tapering (time to reach a stationary amplitude for each phase and to come back to zero) was set to 3 seconds.

K1 to K3 test series

Tests K1 and K2 were interrupted at stage 8, K3 at stage 7.

K4 to K6 test series

Test K4 was interrupted at stage 5, K5 at stage 7, K6 at stage 6.

K7 to K9 test series

Test K7 was interrupted at stage 7, K8 and K9 at stage 6.

DATA ACQUISITION

Acquisition Set Up

Several parameters were measured during the tests; they are described in the following subsections. Measurements were taken at characteristic cross sections shown at Fig. 4.

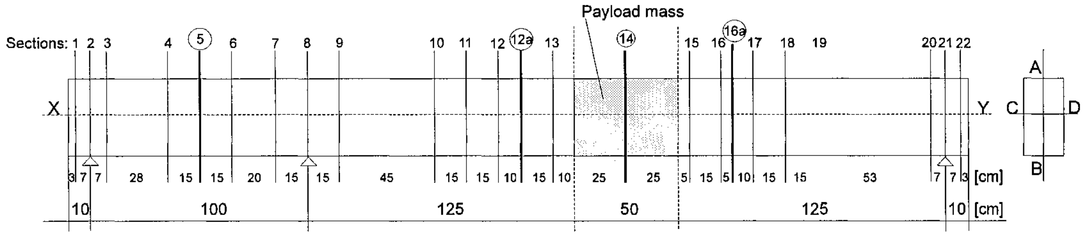

Fig. 4 - Characteristic cross sections of the beams

Accelerations

Accelerations were measured at several sections of the beams. On top surface, vertical accelerations were measured at cross sections: S5, S12a, S16a, and on the payload mass at cross section S14. Shaking table vertical acceleration was also measured.

Displacements

Displacements were measured along two directions: longitudinal and vertical. Sensors were placed on the side of the beam at the same cross sections as accelerometers (S5, S12a, S14, S16a).

Static deflections of the beams, 5 minutes after payload, were measured at the characteristic cross section S14. Results are given at table 1.

Table 1. Static deflections of the beams [mm]

Beam	K1	K2	K3	K4	K5	K6	K7	K8	K9
Deflection	24.7	27.0	26.7	25.6	24.3	28.4	29.4	26.2	26.7

Ultrasonic Measurements

Ultrasonic measurements were taken at different times of the test procedure: before beam loading (referred to as PRE), five minutes after static loading with the payload mass (referred to as STATIC), after each stage of kinematics loading (referred to by the values of frequency/stage), and after collapse (referred to as PO).

Measurements were made at several sections between opposite points along the longitudinal vertical middle plan (containing direction A/B, in Fig. 4) as well as along the longitudinal horizontal middle plan (containing direction C/D, in Fig. 4). Besides those, ultrasonic measurements along the longitudinal axis, from end to end, were also taken (referred as X/Y in Fig. 4).

During the test, in between the stages, ultrasonic measurements were only performed in the vicinity of the areas suffering most damage (close to the middle support and close to the payload mass), and also along the longitudinal direction (beam axis) [3].

Photography and Video Recording

After static loading and after each stage of tests K1 to K9, tagged labels were posted near the areas to be photographed, for identification purposes. Photos of the most damaged areas were taken. Video recording was also made but only for tests K7 to K9.

As an example, Fig. 5 presents the crushing of the beam close to the payload, on test K4, after being submitted to stage 5. On the right side are visible one accelerometer and the LEDs of one of the optical displacement transducers, on top and front of the beam, respectively.

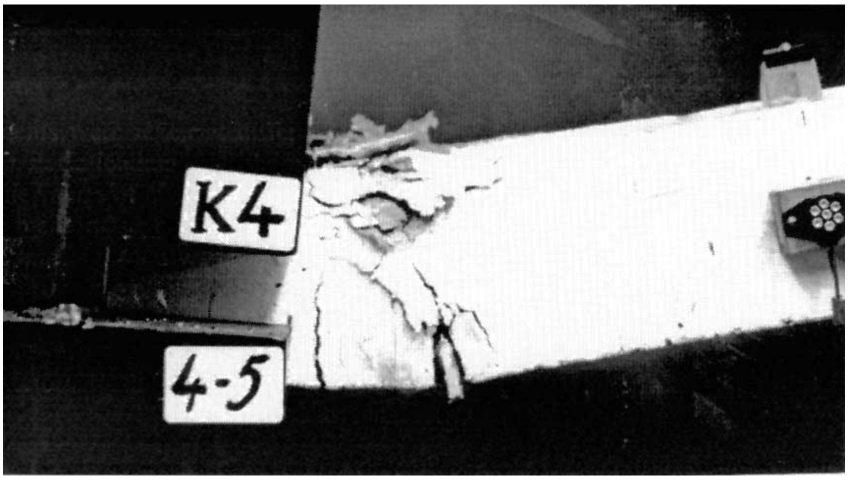

Fig. 5 - Test K4 after stage 5

Steel Position Measurements

After all the tests, the exact positions of four of the longitudinal reinforcement steels were identified, in the damaged section near S15, giving the values shown in table 2. The position of the middle bar at the tensile zone was not checked.

Table 2. Positions of the steel bars [mm]

Beam	K0	K1	K2	K3	K4	K5	K6	K7	K8	K9
Top	34	31	34	34	29	30	28	24	36	30
	24	29	34	28	27	30	29	29	29	31
Bottom	19	21	18	14	19	21	23	19	15	17
	29	24	18	19	19	21	22	20	23	16

COLLAPSE OCCURRENCE

Table 3 gives the amplitude values of the imposed displacements, the phase durations and the number of cycles for which the collapse of the beams occurred.

Table 3. Stage duration [s], collapse amplitude [mm] and cycle of the collapse

Beam	K1	K2	K3	K4	K5	K6	K7	K8	K9
Stage Duration	30	30	30	90	90	90	180	180	180
Collapse Amplitude	6	8	6	4	7	6	6	6	6
Cycle of the Collapse	615	870	715	1320	2260	1980	4200	3760	3620

There were several parameters measured during the test as previously referred. As an example of the ultrasonic measurements Figs 6 to 8 show the sound speed reduction, along the beam axis, with the number of stages applied. This allows for correlation between the damage evolution and the ultrasonic sound speed.

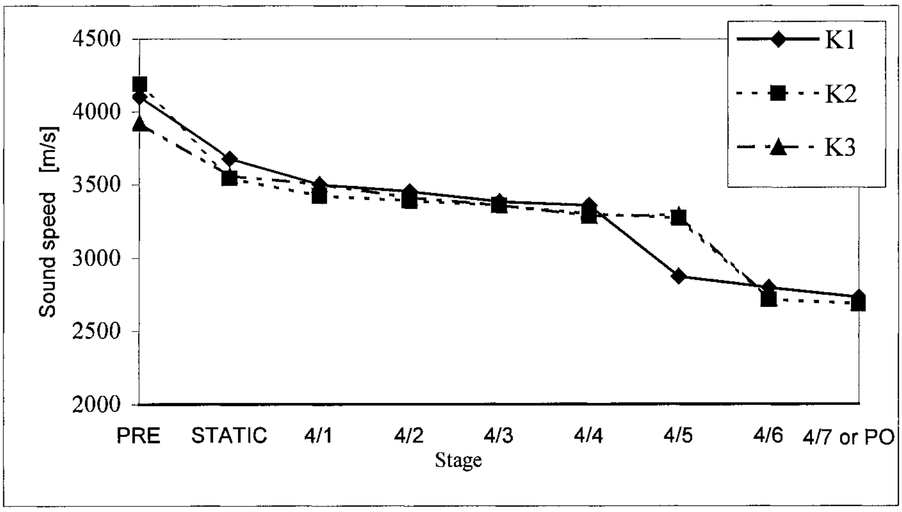

Fig. 6 – Results of ultrasonic measurements along the beam axis (K1 to K3 tests)

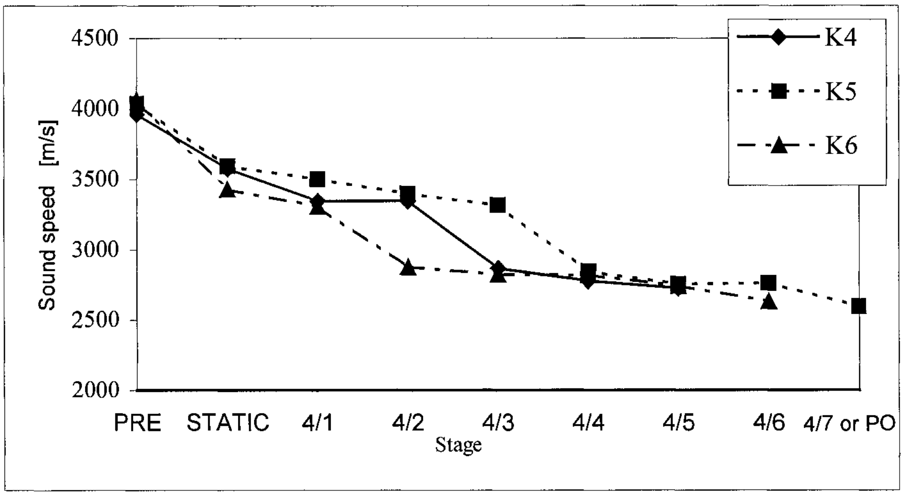

Fig. 7 – Results of ultrasonic measurements along the beam axis (K4 to K6 tests)

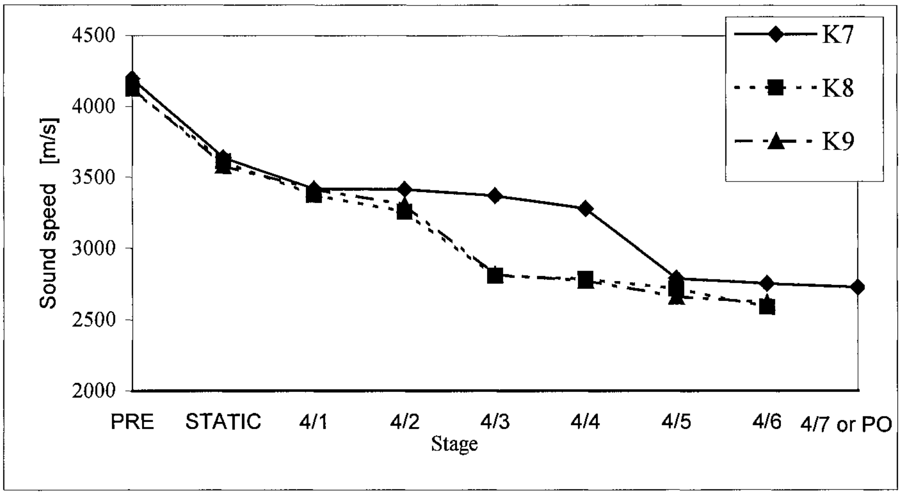

Fig. 8 – Results of ultrasonic measurements along the beam axis (K7 to K9 tests)

DAMAGE LAW

This paper goal was to get a description of the evolution of the mechanical characteristics of a reinforced concrete beam submitted to different kinds of material damage caused by variable actions. Essentially, two different main approaches can be considered: either local or global descriptions.

Local description

Local description is based on the assumption that it is possible to establish an evolution law of a local damage parameter at each point of a given structure. In general, this law, given by Eq. (1), defines a damage variation as a function of a set of state variables and time (or the number of cycles, if the process is of periodic nature [4]), where σ, ε, ω, t are stress, strain, damage and time, respectively:

$$\dot{\omega} = \frac{\partial \omega}{\partial t} = f(\sigma, \varepsilon, \omega, t) \qquad (1)$$

Such a formulation is possible when studying the behaviour of homogeneous materials (e.g. steel). In this cases damage evolution laws have to be used along with the constitutive equations from structural analysis, in which the damage parameters should be conveniently considered.

Eq. (1) concerns only the macro-crack nucleation period, which appears in some areas of the structure. To evaluate the capacity of the structure it is also necessary to take into account all the period of macro-crack propagation and, finally, the ultimate state for which a network of macro-cracks develops causing a mechanism of total collapse of the structure.

The situation is even more complex when materials are macroscopically non-homogeneous (e.g. composites). For such cases a damage evolution law must be defined for each independent phase of the material deterioration thus becoming necessary the use of homogenisation techniques to assure a well-defined representative volume element.

Giving the need for specifying the analysis of each one of the three independent phases above considered (nucleation, propagation and collapse), the study may get much more complex. In fact, errors committed during the evaluation of the constitutive equations, for each phase, and incertitude on the values of the material constants, may get this type of structure analysis hardly reliable.

Global description

It is possible to avoid the above-referred difficulties by using a damage law formulated non-locally, taking a global formulation for the whole structure.

In this case the constants in the evolution law depend not only on the material properties (as for the local formulation), but also on the structure geometry. The universality of the evolution law is lost, but the difficulties of the dependence of the constitutive equations and damage laws for all material phases are avoided.

Such a law has the general form of Eq. (2), where P denotes loading, u stands for the kinetic excitation and Ω defines the state of the structure deterioration (from Ω=0 at virgin state to Ω=1 at the structure collapse).

$$\dot{\Omega} = F(P, u, \Omega) \qquad (2)$$

For the analysis of a given structure it is necessary to define a function F and a set of constants, to be evaluated for a specific kind of structure, and considering its geometry and the type of loading. Such a description, based on adequate experiments for several intensity levels of the considered type of loading, should allow the structure safety evaluation under any value of the considered type of loading.

DAMAGE ACCUMULATION UNDER KINETIC EXCITATION

Kinetic excitation is a case of loading which often leads to an important deterioration of the structure. It can be a periodical waveform or an irregular input signal, as in the case of an earthquake. Specifying the time dependence of the loading:

$$\dot{\Omega} = F(P, u(t), \Omega) \tag{3}$$

if the excitation is harmonic then

$$u(t) = a(t)\sin(2\pi t / T) \tag{4}$$

where $a(t)$ is the time dependent amplitude and T is the period .
For $t >> T$ the following is a good approximation:

$$t = TN \tag{5}$$

with N representing the number of cycles.
Hence:

$$u(t) = a(TN)\sin(2\pi t / T) \tag{6}$$

Thus, the kinetic excitation can be defined by an amplitude $a(TN)$ and an excitation frequency $f = 1/T$. If the damage growth is independent of the waveform it can be assumed that the evolution law will depend only on a and T. Then, for constant T, Eq. (3) can be written as [1]:

$$\dot{\Omega} = C\frac{a^m}{(1-\Omega)^m} \tag{7}$$

The term $(1-\Omega)^m$ is introduced here to reproduce a non-linear damage growth under constant amplitude. Differentiating Eq. (5) gives $dt = TdN$, which after substitution in Eq. (7) leads to:

$$\frac{\partial \Omega}{\partial N} = c_2\frac{a^m}{(1-\Omega)^m} \tag{8}$$

where $c_2 = CT$

Constants Evaluation

After the loading of several consecutive stages, having constant amplitude and constant frequency, the summation of damage, occurring in accordance to Eq. (8), after integration gives:

$$\Omega = 1 - \left[1 - c_2(m+1)\sum_{i=1}^{k} a_i{}^m N_i\right]^{\frac{1}{m+1}} \tag{9}$$

where k is the number of the stage at which failure occurred, N_i is the number of cycles at stage i and a_i is the amplitude of the cycles at the same stage.

When failure occurs, the damage parameter Ω is equal to one and Eq. (9) becomes:

$$c_2(m+1)\sum_{i=1}^{k} a_i^m N_i = 1 \tag{10}$$

where the constants c_2 and m have to be found from experimental data.

It can be proved [5] that using an intermediary constant c_1 defined by:

$$c_1 = \log\left(\sum_{i=1}^{k} a_i^m N_i\right) \tag{11}$$

Eq. (10) can be written as:

$$c_1 = -\log\left((m+1)c_2\right) \tag{12}$$

After replacing a_i and N_i, in Eq. (11), by the nine sets of experimental values given on Table 3, and by minimizing a quadratic function of the averages corresponding to each of the three groups with the same number of cycles, the following values for the constants are obtained [5]:

- $m=8.08$
- $c_2=2.7 \times 10^{-10}$ $[\mathrm{mm}^{-8.08}]$

Replacing these values in Eq. (9) and defining the characteristic parameters for a given history of imposed displacements, the value of Ω characterising the correspondent damage state of the structure can be obtained.

In the specific case of the series of tests referred on this paper, the number of cycles, corresponding to the theoretical beam collapse ($\Omega = 1$), is $N_i = 736$ for the experimental data K1 to K3, $N_i = 1912$ for K4 to K6 and $N_i = 3615$ for K7 to K9. These computed values are, as expected, a very good estimative of the ones effectively measured and presented on Table 3.

CONCLUSION

The main goal of the present series of tests was to evaluate, using a global behaviour law, the deterioration of the mechanical characteristics of a reinforced concrete beam submitted to a series of harmonic displacements, imposed by an earthquake simulator.

For a specific case of geometry and for the type of materials considered, a law giving a good evaluation of the damage state of that structure was deduced, as a function of the imposed displacement history (number of cycles with increasing amplitude phases). Such a knowledge is given by a damage parameter value going from $\Omega = 0$, for an undamaged structure, to $\Omega = 1$, when its collapse occurs.

REFERENCES

1. Lemaitre, J. and Chaboche, J., *Mechanics of Solid Materials (in French)*, Ed. Dunod, Paris, France, 1985.
2. Bairrao, R., Duque, J. and Martins, A., "Damage Evolution in RC Beams under Periodic Excitations. Test Design, Implementation and Data Acquisition. ECOEST/PECO Project", *LNEC/C3ES Report*, 99/97, May 1997.
3. Carvalho, F., Rodrigues, F. and Braga, M., "Ultrasonic Wave Propagation Experiments of RC Beams under Dynamic Tests" (in Portuguese), *LNEC/DB/NO Reports*, NT 9/97 and NT 10/97, July 1997.
4. Kachanov, L., "Time of the Rupture Process under Creep Conditions" (in Russian), *Izvestiya Akademii Nauk SSSR, Otdelenie Tekhnicheskikh Nauk*, Vol. 8, 1958, pp. 26-31.
5. Bairrao, R., Chrzanowski, M., Latus, P. and Oliveira, S., "Damage Development in RC Beams under Periodic Kinetic Excitation", *Proc. of the Third International Symposium on Risk, Economy and Safety, Failure Minimisation and Analysis*, pp. 351-357, Bakubung Lodge, Pilanesberg, South Africa, July 1998.