Wholistic Structural Appraisal

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ABSTRACT: The use of the non-linear damping characteristics of structures for the assessment of the state of health of that structure is discussed and demonstrated. The methodology is based on results gleaned from more than thirty full-scale shaking tests of large structures, followed by the evolving of a methodology for the extraction of non-linear damping data from relatively short time histories of the response of the structure to randomly induced response. Examples from the use of the methodology are given.

1 INTRODUCTION

1.1 *Damage and Structural Behavior*

An indication of the state of health of structures from a measurement of the interaction of that structure with its environment has been sought for some considerable time, and yet it has been particularly difficult to achieve. The term "wholistic" is, in the authors' opinion, crucial in the attainment of this goal. Wholism refers to the entire behavior of the entire structure, and stands in contrast with the current approach to structural appraisal which tends to a methodology that attempts to arrive at an assessment through a summation of the effects due to small parts of the structure.

The problem with the summation approach is that the effects of load sharing are completely ignored and the effects of one element on another are also reduced in importance.

A series of forced vibration tests, conducted by the principal author, over a period of over thirty years demonstrated that every structure has its own idiosyncratic style of behavior, and that any understanding of this behavior can be achieved only by working from the wholistic behavior and working from there into the detail.

Modern approaches to the assessment of structural performance attempt an anti-wholistic approach, in that they start with detail and assemble this to form an overall model of the structure. Indeed all computer-based approaches essentially follow such a route, by the assemblage of small elements (either finite elements or individual structural elemental parameters) and by summation of the assumed effects of such elements. The lessons from full-scale testing of real structures suggest that, whilst such an approach gives a good approximation to the overall response of a structure, assessment of the overall response effectively performs the summation of the effects of all small elements and their interactions. The key to understanding structural failure is through the interaction of individual elements.

Many of today's approaches to structural appraisal actually use techniques that perform an averaging of the overall response, and accordingly all of the detail about the interaction of elements of a structure are averaged and lost.

The approach presented here is that of an essentially different philosophy. A basic assumption is that the detail of structural performance is contained in each small movement of the structure, and analysis of real time movements can lead to an assessment of the detailed behavior of small elements within the structure. It is a "top-down" technique. The most commonly used technique of spectral assessment is discarded because it spills and averages energy in adjacent discrete frequency bands. The use of the dynamic response of a structure is convenient because it is relatively easy to measure, and non-linearities are present in each and every cycle of oscillation. The analysis of such time histories of response is not simple, and considerable effort has been devoted to both interpretation and to cross referencing with the smallest detail of structural behavior. In this paper this methodology is outlined, and some of the results obtained are presented. The implications for the easy interpretation of a structure's state of health, is presented.

1.2 *Full-scale tests*

A series of full-scale tests on structures was conducted using three different vibrator systems, each capable of delivering a force of approximately one tonne at a frequency of 1 Hz.. Over a period of nearly thirty years, shaking tests were conducted on 11 large dams, 17 tall buildings, 2 offshore structures, 2 bridges and one special structure. These shaking tests were interspersed and then followed by the monitoring of the response of over sixty structures to random excitation such as that caused by the wind, earthquakes, traffic and human activity. Such tests have been extensively reported Jeary &Sparks (1977), Jeary &Ellis (1981,1984), Jeary (1994) and Li et al (1998).

As these tests progressed, it became increasingly apparent, that there was a significant difference between the observed behavior of large structures and that being measured using spectrally based techniques. In particular, Jeary (1986) reported that the damping characteristic was observed to be nonlinear in an unexpected manner, and that this nonlinearity was predictable. At that time such nonlinearities were observable only through the use of large scale induced vibration testing, through the use of large and precisely controlled vibrator systems.

The search for a methodology that would allow the measurement of structural parametric nonlinearities without the necessity of using large scale site testing was progressed (Ellis et al,1985) to the point at which nonlinear damping and frequency information could be obtained from the randomly induced response of very large structures. Wind and traffic form the most usable excitation sources for such measurements and have been detailed (Jeary & Wong,1999).

1.3 *Measurement Precision*

The use of servo accelerometers was supplemented by the use of an electronic platform that utilized military specification integrated circuits. The use of such a platform not only increases the signal to noise ratio but also reduces electronic drift to such a small effect, that the lean of a structure can also be measured quite clearly (Jeary &Wong, 1999). Fig. 1 gives an example of such a measured time history over a period of one month. The lean of the tall building in this case is caused by differential solar heating. The building can be seen to lean away from the source on sunny days.

Once the effect of static lean of a structure is removed it is possible to measure frequency changes of the order of one thousandth of a Hertz, and damping changes of the order of 0.01%. When such

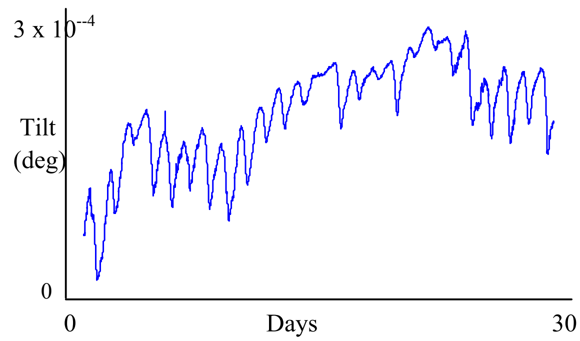

Figure 1. Tilt of a building over a one-month period

a precision of measurement is achieved then it is possible to observe the relative importance of these two parameters in the determination of the response of a structure.

An example is shown in Table 1 below. In this case the response of a 12 storey building to excitation caused by the use of a vibrator system is presented. The forcing is for one mode only of the building.

Table 1. Results from a forced vibration test at Sutherland House, UK.

Force	Freq.	Amp.	ζ	Mass
N (p-p)	Hz.	mm(p-p)	%	x10^6 Kg
5,600	1.46	0.41	2.77	2.93
3,890	1.47	0.29	2.44	3.22
2,220	1.51	0.16	2.11	3.65
1,110	1.51	0.10	1.72	3.58

The results of such tests very quickly demonstrated two important points:

1) Changes in damping are much greater than those for frequency over a similar amplitude range
2) The measurement of modal mass is a good indicator of the precision of the measurement.

1.4 *The implications of observations of modal mass participation*

In the case of the particular test results demonstrated in table 1, above, the precision of the measurement was to about +/- 10%, which, for damping measurements at that time was quite remarkable. Subsequently, the precision of measurement has been increased to approximately +/- 2%. It has also been observed that the modal mass of a building or other structure indicates the amount of mass participating in a mode of vibration, and that this quantity can change. The particular, extreme example which alerted the authors to this effect was when a ten storey building with a one storey attachment was shaken and the participating mass altered by a factor of three over a small range of amplitudes (Jeary, 1997). Clearly in this case (the Exeter building), the adjoining structure was being shaken by the principal building only when a certain amplitude had been attained. After this point the extra mass was available to participate and the modal mass changed to reflect this fact.

On a smaller scale the same effect is seen in all structures. Parts of the structure participate in a mode of vibration only when adjoining parts of the structure excite them. For a structure that behaves essentially monolithically this effect is small, but still observable for all structures, whilst for a structure in distress the effect is remarkable.

1.5 *The measurement of Damping*

The measurement of damping (as depicted in table 1) was initially obtained from the decay of oscillation of a structure that had been shaken to a forced amplitude required. The damping measurement was obtained at that amplitude. However, a development was to allow the decay of oscillation to die away to a very small level, whilst at the same time monitoring this extended decay. The resulting decays of oscillation correlated well with the values obtained in shaking tests at the high amplitudes excited. The extended decays, however, demonstrated a new effect. Fig. 2 shows a measurement of an extended decay of oscillation, with the amplitudes of each cycle replotted on a logarithmic scale.

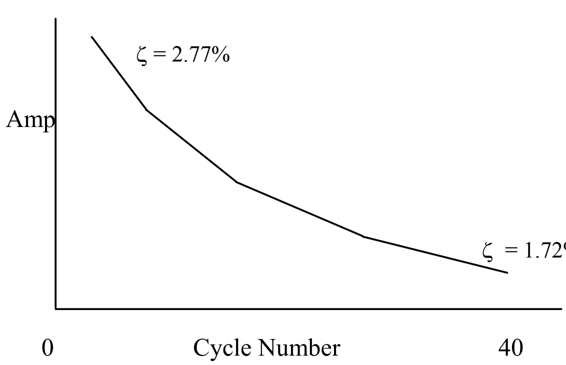

Figure 2. Extended decay of oscillation during an artificially induced shaking test

On such a plot a straight line represents a constant value of damping. What is seen in Fig. 2, and in many other such plots (Jeary, 1996b and Jeary, 1998) is that the instantaneous amplitude of damping reduces with decreasing amplitude to a base value. At smaller amplitudes the value of damping remains essentially constant. Even more remarkable is the fact that such “low-amplitude” damping values are correlated with the natural frequency of the mode of vibration in which the vibration was occurring, and this applies to all types of structures monitored (Jeary, 1998).

Damping measurements made using spectral techniques did not demonstrate the non-linearity, and it was a simple matter to see that the averaging of spectra was the reason for the obscuring of this important behavior pattern. However, a useful technique, previously used for detecting a problem on the Shuttle wing, (Cole, 1973) was adopted and modified for use on civil engineering structures, and resulted in good correlations with the damping data produced in forced vibration tests (Jeary, 1981). The original author of this technique named the methodology the Random Decrement. The most interesting part of the use of this technique is that it is capable of producing non-linear damping measurements for low frequency structures in a short timespan (Jeary, 1992).

1.6 *The Random Decrement*

The random decrement technique originally was used within a specific circumstance to produce a signature that indicated whether a fatigue problem was present. The technique was used on high frequency data under turbulent excitation at high frequencies (Cole, 1973). The transition to usage for the very low frequencies encountered in large civil engineering structures signified that further techniques needed to be added to make the methodology workable. In particular the values of damping were referenced to amplitude (Jeary, 1986a). This in turn allowed the measurement of damping at many different amplitudes from relatively short lengths of data. Several conditions in the time histories have to be met to allow this methodology to stabilize (Tamura 1996). It is worthy of note that the measurement of damping from short data lengths is possible because in each cycle of oscillation information about the damping characteristic in the amplitude range undertaken in that cycle is present. The repeated use of each cycle of oscillation, but with a view to retrieving information from different amplitudes at each pass, makes this possible.

The Random Decrement was initially introduced as a signature that could indicate the presence of fatigue damage. The fact that the signature was also an indicator of the damping parameter established a positive link between damping and damage (Jeary, 1981).

2 DAMPING AS AN INDICATOR OF DAMAGE

2.1 *Fracture mechanics and damping*

In order to understand the mechanisms causing different damping behavior, it was necessary to introduce the subject of fracture mechanics to structural engineering. Fracture mechanics essentially deals with mechanics at the micro-scale, whereas structural mechanics is involved with the meso-scale. That structural mechanics used none of the techniques used by fracture mechanics was a bar to the introduction of efficient integrity monitoring schemes.

The science of fracture mechanics grew up as a direct result of the observation that materials do not achieve their theoretical maximum strength based on a calculation of inter-atomic forces (Taylor, 1923). Imperfections in the matrix of materials means that they do not achieve their potential strength. In order to account for this it was necessary to postulate that micro-cracking occurs when forces appearing on the surfaces of imperfections (such as that caused by shear) reach a critical level that just overcomes the resistance caused by the geometric properties of the imperfection. In turn this predicts that at the smallest forces the largest imperfections will be mobilized, whilst the smallest of imperfections require much larger forces to make them "work". The work done in enlarging an imperfection can be considered not only to be an energy sink, but is also a mechanism for damping. Work on bridges was the first to establish the link between such imperfections and the value of damping inherent in a structure (Wyatt, 1977), although the formal link with fracture mechanics was introduced later (Jeary, 1986a).

As a result of these pieces of work, the mechanistic link between damping and damage in structures was established.

2.2 *Non-linear damping and types of damage*

The general form of the damping characteristic has been established from measurements to be of the form shown in Figure 3.

The general form of damping such as that in figure 3 can be obtained for many different structures when the random decrement technique is suitably modified to cater for the amplitude dependency of damping and to exclude the data conditions that lead to instabilities in the function. Under such a circumstance the characteristic can be interpreted as an indication of the state of health of a structure.

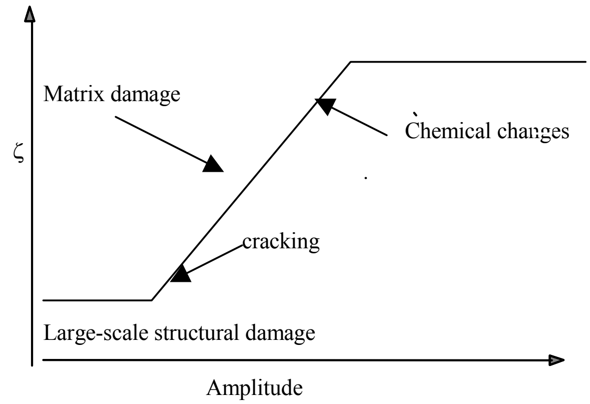

Figure 3. Non-Linear Damping Characteristic and the correlation with damage

2.3 *Indicators for the state of health*

Using the characteristic shown in figure 3 the structure under investigation is monitored continuously for any deviation. A "template" is established over the first three months of monitoring, and this gives the base characteristic for the particular structure under investigation. Three months has been found to be sufficient to establish the basic template for any structure, although it is possible for the non linear damping characteristic to stabilize in a shorter time given benign conditions. It has been estimated that 500 to 1000 averages of each damping measurement are necessary for good stability (Tamura, 1996). Once the template has been established it provides a base line against which to compare subsequent changes.

The signature obtained on any one occasion then gives instantaneous readings in a given situation and this can be compared with the base-line template. If the template is obtained when the structure is young then it is possible to use the techniques as an indicator of aging. If the template is established later in a structure's life then the indicators are of change form the first monitored conditions. Notwithstanding this there are certain conditions that are normal for particular structures (Jeary, 1997).

There are three basic changes to the form of the nonlinear damping characteristic that have been found to occur. These are:

a) A raising of the low amplitude plateau
b) A rotation of the rising section of the curve
c) A lowering of the high amplitude plateau

These are considered in turn below.

3 INDICATORS OF DAMAGE

3.1 *Monitored examples of damage*

Structures have been monitored under many different conditions and the three characteristics, noted above, have all been observed under different operating conditions, using a purpose built integrity monitoring system that is installed into a structure. Conditions causing changes to the damping characteristic have been:

i) nearby tunneling
ii) ongoing subsidence
iii) aging

Structures have been monitored under conditions that included small earthquakes and strong winds (with gusts up to 30 meters per second) without any observable changes to the characteristic.

3.2 *Observed Changes*

Changes that have been observed thus far have been of the following type:

1) A raising of the low amplitude plateau and a rotation of the rising characteristic caused by the construction of a nearby tunnel to the subject building. In this particular case the immediate change to the characteristic was large and immediate. Over a period of one week there was a recovery of all but a small permanent set to the characteristic. This permanent set amounted to a 10% rise in the low amplitude plateau and of a 10% rise in the higher amplitude parts of the rising characteristic. This was interpreted as being indicative of actual structural damage resulting in a loss of stiffness in the main structural frame combined with a general increase in the working of the material fabric of the structure. In other words, very small imperfections had increased in length, but had not lost all of their ability to dissipate energy. The length of the largest crack in the structure was still ostensibly the same dimension. The high amplitude plateau remained at the same overall value, thereby indicating that the capacity of the structure to continue to take load, in the way that the original design considered, was unimpaired.

2) A rotation of the rising characteristic over an extended period. In the case of this particular building it was exposed to nearby subsidence, and the monitoring exercise was short term. Without the benefit of establishing a long-term template it was only possible to see the immediate changes to the rising characteristic. It is however, supposed that the low amplitude plateau must have risen from its original level. In the case of this particular building the high amplitude plateau was still at a level that has come to be considered normal, and is presumed to point to the extraordinary capacity of structures to withstand even quite extreme levels of unusual loading before collapse ensues.

In both of the cases mentioned above, the indicators showed that the structure monitored, despite having undergone a traumatic incident, was still able to fulfill its intended purpose. In both cases the – measurements were followed by an assessment of the probable response of the structure to the design conditions. This involved an assessment of the response to wind action in both cases.

In such a case the prescribed loading conditions are assessed either by reference to those chosen for the original design, or by reference to local code requirements. The dynamic and quasi-static response of the structure can then by assessed by direct reference to measured properties, such as the overall stiffness. The normal approach is to match the response obtained from a computer model to the observed response, and then to alter the action to represent the design case. Under such a condition, the confidence in the result is high, and assurances (or otherwise) can be given in terms of the probable response under the design loading.

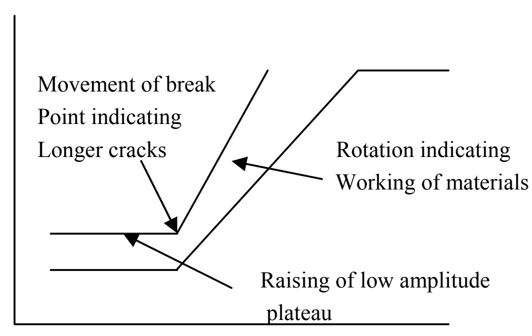

Figure 4. General form of observed damage characteristics

In several structures the nonlinear damping characteristic has been noted to undergo small changes over a small time interval. These changes, however, are followed by a recovery to the historic template over a period of as little as one week. This factor seems to point to the fact that structures have a capacity (at least during the main part of their working life) to self-repair. This process in the material concrete is well established, but also appears to be occurring within the fabric of entire structures. It is supposed that the mechanism for this self-repair must involve the grinding of small particles within the interstices of structures, followed by some chemical recombination.

4 USEFUL LIFE ASSESSMENT

4.1 *Practical assessment of a structure*

Using the technique outlined in the previous section it is theoretically possible to assess the useful life of a structure. Under such an assessment the response to the design load is continually updated using the measured characteristics of the structure. The calculated response to the design load is then referenced to an acceptable response under any criterion that is considered justified for continued satisfactory performance. Whilst this may appear to be a loose performance criterion, it is actually a reflection of the design process, as commonly used. Performance can be seen to be considered in terms of deflections as a fraction of span or dynamic response as a function of human perception without any reference to the real state of distress of the matrix of the structure. These heuristics are useful criteria during this epoch in which there is almost no information about structural distress, and provide a convenient and constant marker with which to compare the changing response of the structure with the passing of time.

4.2 *An on-going indication of the state-of-health*

The performance of the structure can then be represented graphically as a representation of the calculated response to a theoretical design event against an acceptable performance criterion. Figure 5 shows a conceptualization of such a procedure.

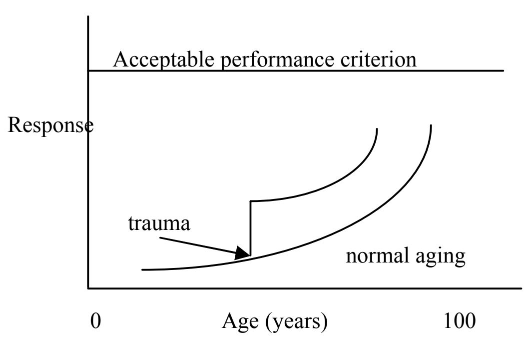

Figure 5. Conceptual Useful Life assessment

5 CONCLUSIONS

The non-linear damping characteristic for full-scale structures has been established, through the medium of a series of tests, to be an indicator of damage or aging.

Under normal operating conditions, damage has been noted in structures, and this damage has been of a level that justified the continued usage of the structure for its intended purpose. Such measurements can be used to give reassurances to structure owners after the occurrence of a traumatic incident.

The life expectancy of a structure is theoretically assessable using the techniques outlined in this paper, and an example of the concept has been given.

6 ACKNOWLEDGEMENTS

Many people have contributed to the full scale program of testing referred to in the text. Particularly significant contributions by Brian Ellis, Malcolm Beak and John Littler are gratefully acknowledged. Grants have been obtained from various sources for the continuation of the work over an extended period. Grateful thanks are extended to The University and Polytechnics Grants Committee of Hong Kong, The National Science Foundation of USA, City University of Hong Kong, The Arthur Chiu Foundation of Hawaii, LERA of New York, USA, The Building research Establishment, the Central Electricity Research Laboratories, and to all those team members who willingly supplied financing for the small pieces of equipment that needed immediate purchases to achieve a result.

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