The Identification of damage in Large Structures

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Introduction

It is necessary, when considering the identification of damage in large structures, to be very precise about both what constitutes damage, and of the precise requirements for successful identification. These considerations are not trivial, our classical identification of damage is often unhelpful in an assessment of the state of health of a structure. Additionally, precisely what leads to successful identification of significant damage is a question that bears further investigation.

Our appreciation of forensic engineering, as it applies to civil structures, is in its infancy. The tools available to us tend to deal with localized damage, and as such can be of limited used in an overall (holistic) assessment of the structure.

Whilst the tools available for structural investigation are technologically good, information available for the assessment of complete structures has to be pieced together from the clues left by investigations using such devices as X-rays, ultrasound, holography, thermography, radar, and eddy currents. In each of these cases the techniques have the advantage of being non-destructive, but a disadvantage of only yielding local information.

Tools available for the assessment of complete structures tend to involve destructive techniques. When disassembling a structure is possible to perform a detailed analysis of the state of health of joints within that structure. Clearly the problems associated with destructive testing and do not allow an in-service assessment of the structure.

Recently developed techniques, most of which have come from developments from space programs, and system identification of mechanical systems, have recently been used within the civil engineering arena to successfully identify significant damage within large structures. This paper addresses these problems, and analyses the requirement for the successful identification of significant damage within large structures.

1. Classical indicators of damage

The first issue to consider is precisely what indicators of damage we would consider to be useful. Traditionally, structural investigators or surveyors have relied upon observation of the presence of cracking to give indications of structural distress. The careful noting of crack patterns has been followed by an analysis, possibly backed by computer modeling, of the likely extent of damage. Knowledge of yield line theory can be helpful in this analysis.

In 1923 it was observed [Griffith, 1923] that materials do not achieve their theoretical maximum strength and imperfections within materials accounted for this loss of strength. The science of fracture mechanics quantified this effect as a result of Taylor's early work, and much progress has subsequently been made. In practice, all materials contain a myriad of micro-imperfections, each one of which can be made to work (to dissipate energy) when stresses appear on the surface of the imperfections. The larger the imperfection the smaller is the stress necessary to make the imperfection work. This working of the imperfection may appear as damage (e.g. an increase in a length of the imperfection), as a chemical change, or as a weakening of a process zone, which appears in front of a nascent crack. In each of these cases the working of the imperfection involves a sink for energy.

In addition, investigators have relied on the retrieval of cored samples followed by assessment of the mechanical properties of the core, normally in some form of crushing machine. Such an approach leads to an assessment of the mechanical properties of small parts of the structure. The analyst is then faced with the task of piecing together this information, either intuitively or with the help of computer package, so as to form a picture of the health of the entire structure.

2. Mechanisms of collapse

Before starting a measurement scheme it is necessary to carefully preview the precise mechanisms that may cause a collapse. The stage before such collapse occurs involves the loss of stability of an entire structure. The behaviour leading up to such a stage involves the appearance of those markers that structural investigators are accustomed to search for. Such indicators would include cracking, material degradation, loss of continuity, foundation degradation, and chemical attack. Each one of these items may play a part in the reduction of usable life of the structure, they are however, the most visible signs of a degradation that occurs, at least initially, at a microscopic level. Such microscopic imperfections inevitably lead to an overall prejudice to the entire structure, and it is merely the job of the forensic investigator to determine the degree of progression of such imperfections to a final state of untenability. A germane example here involves the progression of micro imperfections within the matrix of the material, to the point at which they are considered to be cracks by the mainstream engineering fraternity. The entire science of fracture mechanics deals with this micro regime which is a precursor to the engineer's predilection for observing and quantifying cracks. Both types of study are concerned with different aspects of the same process. Fig 1 shows a photograph taken using a scanning electron microscope of a damaged concrete sample.

In this figure nascent cracks can clearly be seen, and is clear that when these imperfections (typically of only a few microns in length) start to join together then cracks begin to form and we move from the realm of fracture mechanics into mainstream structural engineering. Nevertheless, an understanding of the fracture mechanics process allows the inspection of data for the purpose of identifying such small events. It is axiomatic that all data collected from a structure contain elements which are generated by even the smallest imperfections in the structure. If the analysis of such data is sufficiently detailed (and if the signal to noise ratio is acceptable) then those data must contain information about the smallest micro behavior occurring within that structure. In practice, recent tests have shown this to

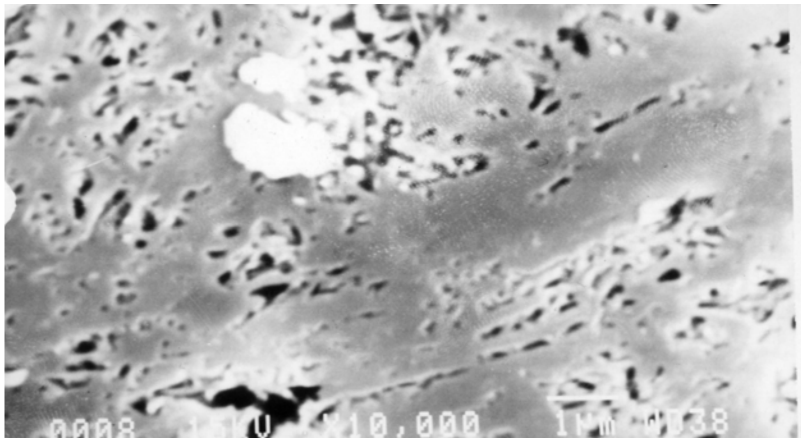

Fig 1. Nascent Crack in a concrete sample obtained with a scanning electron microscope

be the case, and data collected from entire structures have been shown to contain information about the progression of extremely small microimperfections within that structure.

The hierarchical model of progression from the smallest of imperfections to the instability of the entire structure is a philosophical approach to the identification of cumulative damage within a structure that is outlined in Fig 2 below. It is germane to observe that visual observation of damage is only possible at a stage at which the damage has progressed to such an extent that little time is available for remedial work. Additionally structures that are in the final stages of distress may not exhibit obvious signs for visual observation.

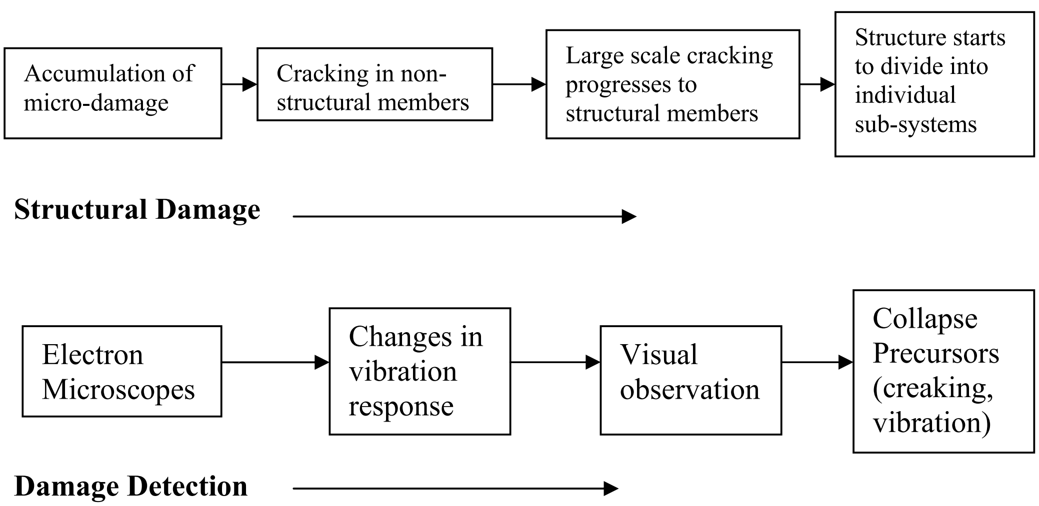

Fig.2 Progression from Nascent Damage to Collapse of a structure

3. Conventional methodology for damage identification

There are two basic methods for the identification of damage in structures. These consist of:

a) the use of large numbers of transducers; or
b) complex analysis techniques.

These are considered in turn.

In building and structural engineering investigations the transducers used are normally strain gauges, accelerometers or velocity sensitive devices, of one former another. When trying to use such devices to extract information about the behavior of localised parts of a structure such schemes are generally not particularly effective. In this respect early attempts at damage detection in North Sea oil rigs presented the dilemma that the amount of information emanating from a particular region of a structure may be severely restricted by the presence of large masses. In offshore oilrigs this was of particular concern when damage occurred near the base where large quantities of oil were stored (Jeary, 1974).

In other fields, such as the aerospace, automobile, marine and rail industries, a more diverse range of techniques has been tried. This has included the use of acoustic emission, x-ray radiography, thermography, shearography, A-and C-scanning ultrasonic inspection techniques, and the use of piezoelectric and fiber-optic sensors (Staszewski, 2002).

In the event that the time histories from many transducers is available, then analysis schemes that search for differences in the patterns of either mode shapes (Viero & Roitman, 1999), orthogonality conditions (Araujo dos Santos et al, 2000), the relationship between modes (Lee & Shin, 2002), or of the transit of signals from one transducer to another are available and documented (Castello et al, 2002). All such methods currently make an assumption that the damping takes on a value of zero in all modes of vibration.

Complex analysis techniques take on one of two forms. They involve either the analysis of a single transducer output (Jeary, 1978) or the analysis of the output of a transducer that is sequentially taken to locations within a structure (Severn et al, 1981; Brownjohn, 2002) coupled with some form of rather more complex analysis.

In some cases, changes in natural frequencies have been used for the identification of damage (Wang et al, 2001). Such schemes can be made to work quite well in laboratory applications, but have been shown to be rather insensitive in full-scale tests (Jeary,1986). In fact, the damping parameter has been shown to undergo up to 20 times the variation obtained by natural frequencies for real cases of damage in the full-scale (Jeary, 1986).

4. Full-scale investigations

Full-scale non-destructive testing is a rarity. The reason for this is that such tests when conducted with precision are often very expensive. Load testing provides the general limit of our approach to full-scale non-destructive testing. There are several reasons why this is so. In general, practicing engineers feel comfortable with an approach that is readily appreciated. The application of a large force allows the deflection of the structure to be measured, and such loads can be made to approach a reasonable magnitude. The behaviour of the structure is seen operating with all real-life conditions applying. Any load sharing effects are seen directly in the displacement of the structure. Whilst load testing is non-destructive, and leads to observations of the real behaviour in service of the structure, there are still problems. Firstly, the load is applied to the structure through the action of gravity on an applied mass. As a result loads are only applied in a vertical sense. Secondly, the application of a quasi-static load neglects any dynamic effects that may be present. Effects caused by wind, earthquake, traffic, and human movement are not seen.

Full-scale dynamic testing, is a very precise process that leads to accurate assessments of the parameters governing the behaviour of a structure. Quasi static behaviour is a special case of dynamics at extremely low frequency, and as a result the results of dynamic testing include the behaviour that is commonly termed "quasi static". However, there are three problems with full-scale machine induced dynamic testing. Firstly, such tests are expensive. Secondly, horizontal dynamic forces are much simpler to create than vertical ones, because of the interference of gravity with rotating or reciprocating masses. Thirdly, it is uncommon to generate very large forces in such testing. Whilst it is not impossible to create large dynamic forces, the provision of machinery capable of generating large dynamic forces generally adds significant extra costs.

Recently, new techniques have evolved that have allowed system identification from the monitoring of the behaviour of real structures in response to naturally occurring forces. These techniques are considered in more detail below.

5. Data analysis

Time histories obtained from civil engineering structures can be analysed in one of a number of ways. In the following, the discussion is limited to that of the analysis of vibration data, since the prospect for damage identification is enhanced in this way. This is a function of the fact that vibration data contain quasi-static data as a subset.

It should be pointed out at the outset that the search for damage involves a search for non-linear characteristics. As such, the use of conventional spectrum analysis techniques is invalidated since they use averaging techniques (Jeary,1992). Any use of such techniques will therefore average out the very effects being investigated. As a result any data analysis techniques that will give a direct indication of damage, must, philosophically, be a direct measure taken from a time history or must aim at identifying discontinuities within the fabric of the structure.

There are four basic techniques of data analysis available for the identification of damage within a structure. These are as follows:

a) amplitude indexed random decrement analysis
b) wavelet transform
c) amplitude indexed cross decrement analysis
d) real-time modal distortion measurement

These are considered in turn:

The amplitude indexed random decrement analysis has been detailed extensively and has been shown to be capable of indicating the onset of damage and the self repairing process occurring in a structure. Essentially, the random decrement is built up by repeatedly extracting real-time data from a similar situation (in this case, when the vibration excursion passes through a particular amplitude). this type of analysis is successful in the analysis of damage in structures because the amplitude related random decrement signature gives direct information about the non linear damping characteristic (Jeary, 1992), and this parameter is highly sensitive to damage within a structure (Jeary, Chiu &Wong, 2001).

The wavelet transform, when operated on real-time data, is more recent in its development, and has been successfully used for the diagnosis of defects in rotating machinery (Wang & McFadden, 1996). The wavelet transform, in its basic form, is analogous to a "waterfall" spectral analysis. The difficulties associated with resolution of very low frequencies in spectrum analysis are addressed by using the wavelet transform. This removes the problem of averaging of non-stationary data, but still leaves the analysis in a frequency domain. The wavelet analysis produces information that does not discriminate to any great precision in the frequency domain. As a result, it presents problems for the analysis of structures with closely spaced frequencies. Examples would include bridges, viaducts and some tall buildings.

The amplitude indexed cross decrement function is actually a reversion to an earlier form of the cross correlation function. Modern digital analysis machines habitually perform the cross correlation function by firstly performing a cross fast Fourier transform. This immediately creates the same problem as for spectral analysis, in that the non-linearities are again averaged. The earlier form of the correlation function, and by analogy, the cross correlation function, was performed using the time history alone. This version was popular before the introduction of digital computers, and as a result the techniques have been forgotten. However, deriving across correlation function from the raw time histories allows the preservation of the information about the non-linearities. The Cross-correlation function is a product of the energy flow between the two measurement positions, and as a result is modified by changes to the structure between the two positions. The potential for the use of this measurement in damage detection is a logical extension of the success obtained using the amplitude indexed random decrement method.

The use of modal information to identify damage has become popular quite recently (Hu et al, 2001). However, there are few examples of the use of the technique on full scale structures, and only one example taken from a full-scale structure that had undergone severe damage (Jeary, 1984). Discontinuities in a modal displacement function can be used to indicate the location of damage. However, this is most easily performed when the structure is excited with a constant sinusoidal input generated by a vibrator system. The use of such a system makes testing quite expensive, and would normally involve the shutting down of the structure for normal use. An alternative has been developed, and involves the use of random excitation from natural sources and the comparison of the output from a reference transducer and a traveler. The traveler is taken to locations of interest throughout the structure is required by the analysis team. The interaction between the measurements and the analysis is of paramount importance (Jeary et al, 2000). The use of the system on the severely damaged Ronan point building identified many examples of poor connections between cladding panels and floors, and between individual floor elements themselves (Jeary et al, 1984).

6. How important is the damage

The purpose of damage identification in large structures is for one of two main reasons. The more immediate of these is that a structure is assumed to have undergone damage that has occurred recently, and an assessment of whether the structure is still fit for purpose must be made quickly. The second, and more insidious, reason for wishing to identify damage is that the structure has undergone sufficient ageing as to raise alarms about its current state of health. The approaches to identification of damage, in the two cases, are different.

In the case that damage has occurred as a result of some large random forcing (such as an earthquake or a windstorm) the need for investigation is obvious. Under such a circumstance, the basic requirement is to decide as to which of the following categories may be used to epitomize the state of health of the structure:

1. Severely damaged - demolish
2. Structural damage - repair
3. Minor damage - cosmetic repair
4. Undamaged - fit for continued use

Definitions relating to these categories are considered in more detail below.
It is at this stage, that the differences between types of structure begin to play a large part in the decision-making process. Serviceability criteria for tall buildings and for industrial structures, for instance, are very different. Any assessment of a structure must be made against acceptable serviceability criteria for the particular type of structure. This question is considered in more detail below.

The decisions to be made about repairing or demolishing, have long occupied the attention of engineers and surveyors. However, often the decision will be taken on mainly economic grounds. In such cases the costs of repair are and the implications for future revenue generation may well be an overwhelming consideration. The true costs of such decisions may be hidden in the case that a large structure forms part of the infrastructure of a large city. This is the case with large bridges for instance, in which transport and between parts of the city or with other cities, may be completely dependent on the presence of such a structure.

In the case of the tall Building, decisions will be based not only on engineering judgment, but also on the critical serviceability criterion of human comfort. Human occupants of tall buildings generally expect not perceive motion. On the other hand, those same people will happily sit in a car on a bridge, and be quite sanguine about a vibration level that is several times larger than the maximum they would accept in their workplace in tall Building.

The decision about repairing or demolishing the structure can therefore be reduced to two phases. The first phase involves an engineering judgment about the safety and stability of the structure. The second phase involves an economic assessment of the two alternatives.

7. Californian definitions of states of damage

Definitions relating to the distinction between various states of damage have been produced recently, and adopted by the Federal emergency management authority in the USA [FEMA, 2000]. The particular concern in these definitions is related to the performance of buildings in earthquakes, and the establishment of criteria for deciding whether such a structure reaches a state of collapse prevention (CP), or a state that allows Immediate Occupancy (IO). The rules given for the identification of these two states are listed below:

The Collapse Prevention (CP) level is not achieved if any of the following occurs:

1. The structure experiences excessive drift resulting in initiation of a P-Delta instability and global collapse.
2. Beam-column connections in the structure, including those in gravity frames, experience sufficient inelastic rotation demand to cause excessive damage to the shear-resisting elements, which may lead to local loss of gravity-carrying capacity and collapse.

3. A column in a frame experiences sufficient axial load demand to induce buckling. It is recommended that P/P_{cr} be less than 0.75.
4. A column splice in a frame experiences sufficient axial tension plus bending demand to induce splice fracture. Fracture of a bottom column connection to the base plate should be avoided.

The Immediate Occupancy (IO) performance level is not achieved if any of the following occurs:

1. Damage detected after the design earthquake is significant enough that repair would be required. This would allow some yielding in the members, minor local buckling in some beams but not in any columns.
2. More than 15% of the connections fracture on any floor.
3. Observable damage occurs at any base plate.
4. Yielding of any column splice plate occurs.
5. Permanent residual drift exceeds 0.5% in any story.

Maximum interstory drift angle, thetạx, at any story will be the primary design parameter used to determine if the damage states related to connection fractures, loss of the gravity-load-carrying ability of connections, buckling of beam and column flanges, permanent lateral drift, and global instability are exceeded. Column axial forces and moments will be the design parameters used to determine if the column buckling or column splice fracture damage states have been exceeded.
Interstory drift capacity may be limited by global response of the structure, or by local behavior of the beam-column connection.

The definitions adopted in the Californian guidelines relate to the interface between categories 1 and 2, and categories 2 and 3, in section 3 above. Nevertheless, the definitions adopted depend on informed expert decision-making, aided by a categorization of buildings based on their height and the codes to which they were designed (these were modified at various times during the last twenty years).

8. What identification schemes must identify

It is clear that any successful scheme must distinguish between structures that are capable of continuing to perform their intended function, and those that require remedial action.
A successful damage identification scheme is capable of categorizing a structure in terms of its ability to perform this function. For this purpose, the identification scheme must be performed according to the logic flow shown in Fig. 3.

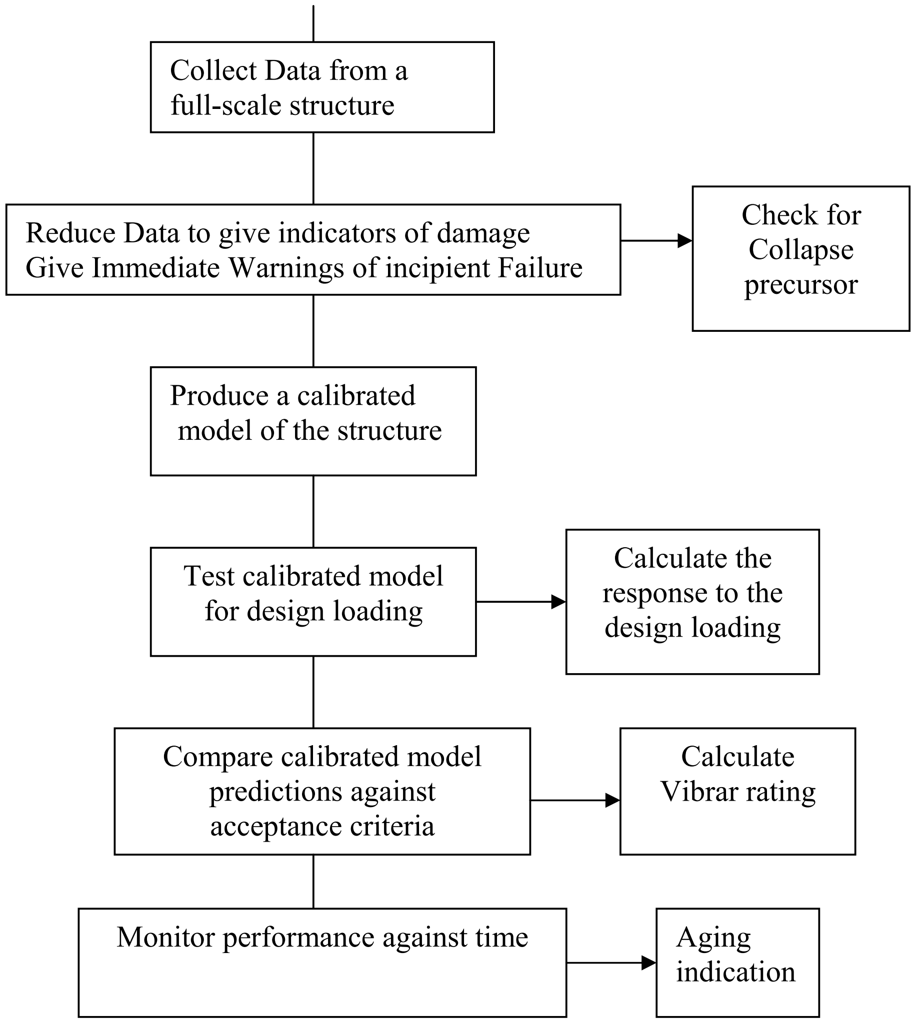

Fig 3: logic flow for and integrity monitoring scheme

It can be seen from diagram one above that there are various stages to the damage identification process. These are considered in turn:

1. The collection of data from the full-scale structure must be arranged so that the time histories from the various transducers when taken together, a good indication of the overall behaviour of the structure. There is a principle at work here; *the collected data must carry information about the process being investigated.* Essentially, this means that the positioning of transducers is important, and a knowledge of the most likely type of behaviour of the structure is a required prerequisite. This allows transducers to be placed in positions that will maximize the useful information obtained from the structure. Measurements obtained from previous studies of large structures are a good indication of optimal positions, but they are only indications with each structure having its own peculiar idiosyncrasies.
2. An immediate analysis of the data collected can be used as an ongoing indication of the general state of health of the structure. In particular, there now exist techniques to obtain from such data a pre-collapse indicator in the event that the structure shows signs of distress. This factor is considered in more detail below.

3. The techniques of system identification are used to obtain a calibrated model of the full-scale structure. Such models may take on one of several different forms, however computer-based models are becoming popular and the ability to change the model in subtle ways is optimized in such a model. By trial and error, or by the use of algorithms, such a model can be refined and used as the base for estimations of the behaviour of the structure when subjected to some required loading.
4. The calibrated model can be subjected to a series of different types of load. Such loads may be those considered in the design process (the design loading), or may be those loads that have occurred since construction under new social conditions (the increasing loads carried by vehicular traffic is an example).
5. The response can be checked against serviceability criteria or collapse criteria. It is possible in this process to produce an indicator of the overall state of health of the structure. In practice this indicator shows the margin between the expected response and the acceptable response (serviceability or collapse). In simpler times, this indicator would have been termed a safety factor.
6. Finally, criteria such as those produced in steps 2 and 5 above, are plotted as a function of time. Such plots give a good indication of the aging process occurring in a structure.

The approach above is holistic. It is concerned with observation of the entire structure and predictions about the behaviour of the entire structure. The structure itself performs this load sharing and redistribution of loads and the scheme looks at the overall results. As a consequence of this, it is not concerned with looking at the detail of individual cracks or of localized damage. However, when the indicator produced in step 5 above shows that the risks inherent in continuing to operate the structure are too large, then it is possible to utilize similar techniques to identify the areas of the structure under investigation, that may be susceptible to repair.

The calibrated structure produced in step 3 above can be used in this process to test the efficiency of such repairs. Figure 4 shows a model of a damaged building with areas of damage identified.

Such a model is particularly sensitive to changes in the areas of damage. The predictions of frequency response from such a model are correlated with the full-scale measurements until a satisfactory fit is obtained. In this particular case a fit was obtainable only for this particular configuration of damage. Even an extension of damage by one story in one location, had an effect on the frequency response function that made it a much poorer fit with observation.

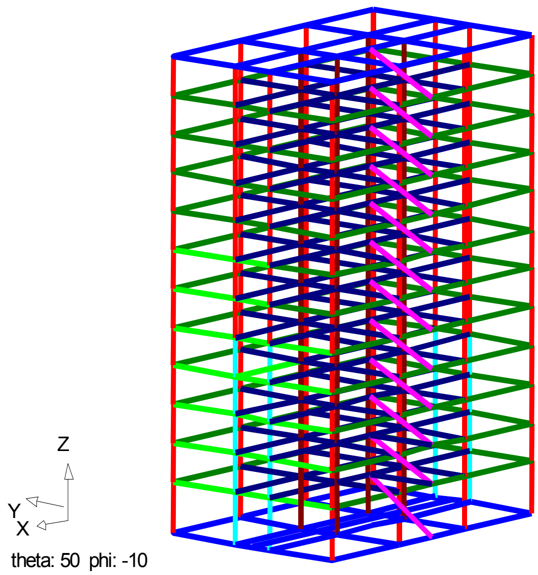

Fig. 4 Damaged Structure – Modeling showing areas of damage required for a complete match with measured parameters.

Key:

Blue	–	Strong base Conc 50 Pinned
Red	-	Columns Conc 50
Dark Blue	-	Floors Conc 50
Green	-	Cladding Conc 50
Light Blue	-	Damage F5
Brown	-	Elevator shaft Conc 50
Purple	-	Stairs Conc 50

9. Serviceability Criteria

It is been found particularly useful to establish a categorization of vibration intensity in which the strength of the vibration is correlated with damage to the structure. A rudimentary scale was produced (Koch, 1953) using Vibrar units. The calculation of the strength of vibration in Vibrar units is:

$$V = 10\log_{10}(160.\pi^4.A^2.f^3)$$

Where:

A is the maximum amplitude in centimetres
f is the fundamental natural frequency
V is the strength of the vibration

Strength of vibration (Vibrar)	Type	Damage
10-20	Light	None
20-30	Medium	None
30-40	Strong	Light (non structural cracking)
40-50	Heavy	Severe (damage to structural elements)
50-60	Very Heavy	Collapse

Table 1 Vibrar rating of vibration intensity [Koch, 1953]

The rating on the Vibrar scale clearly correlates well with the necessities of the decision-making process, both in the scheme outlined in section 3, and in the scheme used in California. A state of collapse prevention implies a Vibrar rating of just below 50, whilst a rating of immediate occupancy would be indicated if the Vibrar rating is below 40.

The scale has been tested on damaged buildings, and has been shown to give a reasonably good indication of the state of health of a structure when the measured parameters of that structure are used as a base for a model which is then subjected to the design force. The resulting Vibrar value gives an indication of the state of health of the structure. As an example, a building in Hong Kong were subjected to extensive tests involving the monitoring of its response to ambient wind excitation. The dynamic characteristics of the structure were assembled, and where used as the input for a wind design guide. Using this methodology the resultant amplitude was calculated. The result was as follows:

Design Force (F.)	=	0.963 MN
Design Amplitude (A)	=	5.01 mm
Fundamental Natural frequency (f)	=	0.831 Hz.

Thus, the value of V is 38.7.

This rating correlates with the building having been in a poor state of repair but not in immediate risk of collapse. In practice repairs were carried out to this building after which the value of V reduced to 34.5.

10. Using the dynamic response as an indicator

Conventional dynamic analysis is used to indicate natural frequencies, mode shapes, frequency response functions, and damping ratios. Such parameters may form the basis of a more detailed analysis, but in themselves are not good indicators of damage or aging of a structure. The damping parameter is a good indicator when analyzed in its non-linear form, and this is considered in more detail below.

Observation of the response of a severely damaged building in Hong Kong, resulted in the observation of response at extremely low frequency as depicted in Fig 5.

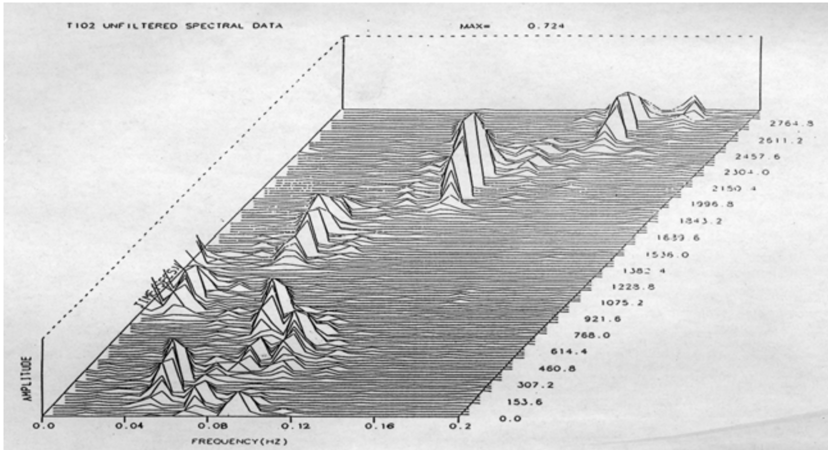

FIGURE 5 extremely low frequency response of a severely damaged building

It is clear from this figure that the very low frequency response changes periodically from one frequency to another. The explanation for such behaviour can only be that associated with this mode of vibration there is mass that sometimes participates and at other times does not. Additionally, the fact that this behavior occurs at very low frequency indicates that there is very low stiffness associated with the mode of vibration.

It is probable that a system that can produce such response would be severely damaged with such a large number of cracks present that the structure has effectively broken into a number of small parts and each of which is capable of participating in the mode of vibration, although it does not necessarily do so.

The presence of this type of frequency response at extremely low frequency is termed a collapse precursor.

11. The use of the damping parameter

The damping parameter is a measure of energy dissipation and is associated with each mode of response of a structure. It is a measure of the energy dissipation undergone in that mode of vibration. This parameter is highly non-linear for all structures. Fig 6 below gives a representation of the form of the damping parameter for all structures.

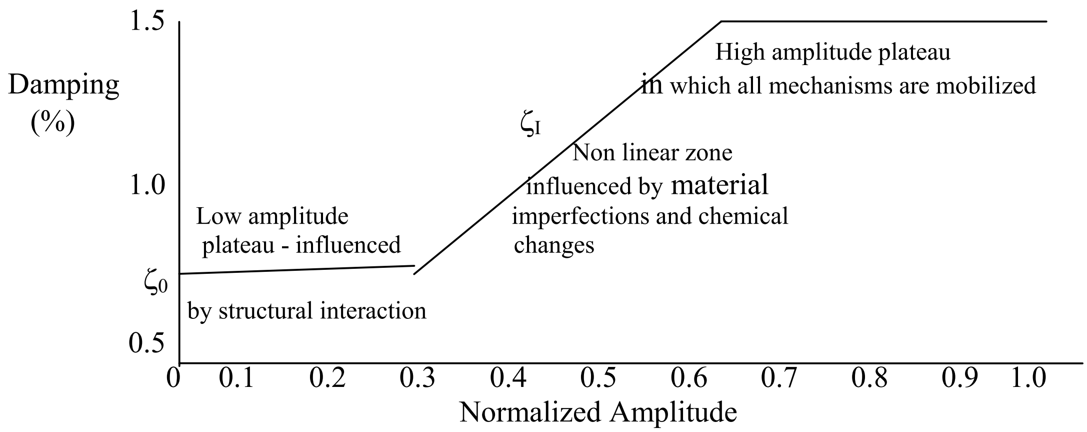

FIG 6 The Non-linear damping characteristic

Because the damping parameter is an indication of energy dissipation it is correlated with damage which occurs to different parts of a structure. The low amplitude plateau is influenced by large structural members and by the interaction. The rising characteristic is created by an increasing number of cracks and then micro-imperfections being worked by of vibration as the amplitude increases. As noted previously it requires larger stresses (that occur at larger amplitudes) to activate small imperfections. The final part of a damping characteristic is reached when all possible mechanisms within a structure are activated. This high amplitude plateau is an indication of the overall energy dissipation potential of a structure.

Changes to the non-linear damping characteristic are indicative of changes to the population of micro-imperfections and energy dissipation mechanisms within a structure. Such changes may occur when cracks elongated, when chemical changes take place, or when damage to structural elements effectively changes their operating length. In such cases, if the damping characteristic is being monitored long-term, then movements to the non-linear damping characteristic can be observed. In particular, aging reduces the high amplitude plateau (because the structure has used up potential energy dissipation sources), and the rising characteristic rotates as cracks elongate.

The non-linear damping characteristic is a very sensitive indicator of both aging and of damage within the structure. Its use in practical applications has been detailed previously [Jeary, Chiu and Wong, 2001].

13. Practical degradation identification - closure

The scheme outlined above, particularly that shown in the logic diagram, represents a feasible next step in the process of damage identification in large structures. It is clear that the technology already exists for the identification of damage and aging, but that such systems are infrequently used the present. The reason that such systems are not currently used rests largely with the fact that owners of newly built structures see little immediate benefits in monitoring the slow and gradual degradation of a structure of many decades. On the other hand, owners of old, or traumatized, structures who may need to decide whether that structure is still safe have immediate and identifiable requirement for such information. Recent events may give an impetus to the use of such techniques for the assessment of prestigious buildings or bridges, however, their use to predict the remaining usable life of a structure that is integral to the infrastructure of a city is a facility that is available now. A combination of the techniques referred to above already gives a good and practical identification of the presence of such accumulating damage.

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