RECENT WORK ON THE DYNAMIC BEHAVIOUR OF TALL BUILDINGS AT VARIOUS AMPLITUDES

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SUMMARY

Recent work has shown that both the natural frequencies and damping ratios of buildings vary with the amplitude of motion. These variations can be significant, and examples are presented to illustrate the behaviour of buildings during an earthquake and during forced vibration tests. The characteristics and significance of the non-linear behaviour of several important modal parameters are discussed.

INTRODUCTION

The matrix equation $M\ddot{x} + C\dot{x} + Kx = f(t)$ has often been used to describe the dynamic behaviour of buildings, and if it is assumed that a building behaves in a linear visco-elastic manner, then the matrices M, C, and K will have constant elements. However, this is a much simplified model of the behaviour of real buildings, and recent tests have shown that both the natural frequencies and damping ratios vary with the amplitude of vibration. Nevertheless, the previous equation can be useful in certain applications where the variations in frequency and damping are not significant.

During the last three decades the construction of several large vibration generators has allowed the observation of the response of whole buildings to controlled motion, and in 1956 Hisada(1) showed a change in natural (or resonance) frequency with amplitude. Since then many authors (2-12) have demonstrated variations in natural frequency and damping both from forced vibration experiments and from observations during earthquakes. To show that these non-linearities are significant, consider one example which was described in a report of the San Fernando earthquake of 9 February 1971(6). The earthquake was of magnitude 6.4 on the Richter scale; it occurred in a heavily populated area, and it produced accelerations of 0.4 g in some buildings. Non-linear behaviour (or a change in structural characteristics) was noted in many buildings, and a typical example was the Sheraton Universal Hotel. The fundamental translation frequency changed from a pre-earthquake value of 0.79 Hz to 0.45 Hz during the earthquake, and the damping ratio during the earthquake appeared to be about 10% of critical, whereas most buildings have a damping ratio between 0.5% and 2.5% for small amplitude motion. (The pre-earthquake damping ratio is not given in the reference). After the earthquake the fundamental frequency was measured for small amplitude motion and was found to be 0.67 Hz. This indicates a loss of stiffness in the structure and can be attributed to damage or plastic deformation caused by the earthquake; the report states that observations indicated no structural damage.

BUILDING RESEARCH ESTABLISHMENT TESTS ON STRUCTURES

During the last six years the Building Research Establishment (BRE) has been conducting investigations into the dynamic behaviour of tall buildings(13,14). The later tests have involved the use of eccentric-mass vibration generators, whose phase and frequency can be controlled to accuracies of 0.01 Rad and 0.001 Hz. The four generators are capable of delivering a maximum peak-peak force of one tonne at one Hertz, and can be used over the range 0.1 Hz to 10 Hz. In all, fifteen buildings have been tested and these have ranged from six to forty-six storeys. A typical example of the results from one test which shows the variation of both natural frequency and damping with amplitude of motion is presented in Figs 1 and 2 (these results are from tests on a 49 m tall mill at Dunstan, Newcastle). The natural frequencies were defined by a maximum response criterion and the damping ratios (equivalent viscous damping) were calculated from the first five cycles of decay curves obtained by suddenly stopping the excitation. It can be seen that although only a small change in frequency (3%) is recorded, a much larger change in damping occurs (30%).

Tests on a model of an offshore platform, under well controlled conditions, enabled a greater range of controlled forcing to be applied and, hence, a more complete picture of the variation of natural frequency and damping with amplitude was obtained. The results of tests on the lowest frequency mode are shown in Figs 3-6. Figure 3 shows that the frequency reduces with increasing amplitude of motion. The fact that the normalised mode shape, and hence modal mass, remained constant, indicates that the modal stiffness is the varying parameter. In Fig 4, damping is plotted against amplitude, and shows a general increase in damping with increase in amplitude. Figure 5 shows the same two quantities but with amplitude plotted on a logarithmic scale, and this shows an approximately linear relationship between damping and the logarithm of amplitude. Figure 6 shows damping plotted against the square of the natural frequency (which is proportional to stiffness or elastic modulus) and an approximately linear relationship is obtained, which corresponds to the linear relationships between damping and modulus for various types of soil(15).

Although two approximately linear relationships are presented, it must be remembered that these are the results of one experiment at model scale, and therefore it is unwise to draw general conclusions until more data has been obtained. The non-linear behaviour of real buildings reported in references 1-12 and observed in recent BRE work does not always show similar trends (especially with the variation in damping) although in most cases the number of amplitude levels tested was small. For most of the buildings tested the behaviour was in the non-linear elastic region. However, if the amplitude of vibration is sufficiently large, it is probable that the stiffness/deflection characteristics will change from non-linear elastic to elasto-plastic (ie similar to many materials when a yield point or maximum damping capacity is reached) and hence produce irreversible changes.

THE EFFECTS OF AMPLITUDE (OR STRAIN) ON MODAL PARAMETERS

(a) Mode shape and modal mass

In the few tests where mode shapes have been measured at different amplitudes, the normalised versions have been shown to be similar, hence indicating a constant modal mass (this applies even to the tests soil-structure interaction was active). This implies that the ch of natural frequencies are due to variations of modal stiffness.

(b) Natural frequency

Recent tests have shown that natural frequencies decrease wi creasing amplitude of vibration, and that the change is greater t that predicted by the visco-elastic equation $f_d = f\sqrt{1-\zeta^2}$. Thi ation of stiffness (modulus) with amplitude (strain) is similar t observed in most materials. In materials where the hysteretic da is small (eg metals) the variation in modulus is small, whereas i materials where the hysteretic damping is large (eg soils) the va in modulus is large.

To assess these changes in a realistic context, it is necess realise that predictions of fundamental natural frequencies can b than 50% in error(16). Within this context it can be appreciated although the large change in frequency noted in the earthquake is ficant, the typical 3% change observed for amplitudes of motion n excited by wind is ~~not~~ significant.

(c) Damping

There is a paucity of data obtained from real structures und controlled conditions, and at present it can be said that the mec of damping are not well understood. There is a general trend for damping to increase with amplitude of vibration, but the range of tudes so far examined is small. Perhaps further investigations e this range might be instructive.

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