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MONITORING STRUCTURAL HEALTH THROUGH CHANGES IN FREQUENCY

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1. INTRODUCTION

As stated by Salawu is an excellent, recent survey article [1]: "The presence of damage or deterioration in a structure causes changes in the natural frequencies of the structure. . . . It would be necessary for a natural frequency to change by about 5% for damage to be detected with confidence. However, significant frequency changes alone do not automatically imply the existence of damage since frequency shifts (exceeding 5%) due to changes in ambient conditions have been measured for both concrete and steel bridges within a single day"†.

On the other hand ambient conditions do not play such an important role in mechanical components such as cracked rotors and successful studies have been performed on these machine elements, monitoring their structural health by analyzing their dynamic response [2, 3].

A recent study deals with the analysis of the dynamic behaviour of annular plates with periodic radial cracks [4] in an ingenious attempt to model cracked flywheels, clutch plates, etc.

It is the purpose of the present Letter to discuss two situations which are related to the general field under study, at least from a philosophical viewpoint: (1) the effect of cracks in reinforced concrete structural elements, (2) the variation of natural frequencies of a long, fractured bone as an indication of its healing stage.

2. EFFECT OF CRACKS IN REINFORCED CONCRETE STRUCTURAL ELEMENTS

From a historical viewpoint this is probably the first situation where the effect of cracks upon the dynamic properties of a structural element was analyzed [5]. According to this pioneering study the ratio (actual damping/critical damping value: c/c_c) is in the range 0·0032 to 0·0064 for concrete free from cracks, and for concrete with cracks the value of c/c_c is of the order of 0·0127–0·0207. The mean values of δ (logarithmic decrement) would be of the order of 0·03 (uncracked) and 0·1 (cracked) [6]. Accordingly: the appearance of cracks do possess, in the present situation, a beneficial effect in many practical applications since damping is increased.

3. FEASIBILITY OF EVALUATION OF THE HEALING STAGE OF A FRACTURED LONG BONE

Assessing the structural condition of a healing bone is an extremely difficult task for the physician. Since Lewis published his important effort [7] dealing with a simplified fractured bone model, which consisted of two aluminum bars connected by a compliant element glued between the bars with an epoxy adhesive, considerable progress has been made on

† An exhaustive listing of references is presented in [1].

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this important medical problem: the quantitative assessment of fracture healing. Two recent studies are particularly important in view of their practical significance.

Nakatsuchi *et al*. [8] investigated the use of the impulse response method, in the assessment of fracture healing. (Vibration responses can be classified into two types according to the techniques of dynamic excitation: bone resonance analysis with the impedance head mounted on a shaker and the impulse response method with a hammer impactor).

Two modes of vibration were investigated: one with dynamic displacements in the lateral direction and one with relatively small amplitudes in the anterior–posterior direction. The authors studied the effect of simulated callus consolidation. Since the vibration mode in the lateral direction can be identified clearly, the authors conclude that the impulse response method is quite adequate for use in clinical practice.

Nakatsuchi *et al*. [8] studied also the possible effect of several fracture systems placed on the *in vitro* model, such as a plate, Ender's pins, and Russell–Taylor intramedullary nail. They observed that the relationship between the consolidation of the callus and the variation in resonant frequency of the bone was not altered.

An important investigation has been reported recently by Lowet *et al*. [9] who developed two finite element models of a fractured tibia with healing callus. The callus was placed at the middle of the diaphysis in the first model and at two-thirds of the length, distal from the knee, in the second model. The static torsional stiffness, resonant frequencies, and mode shapes of the first four vibration modes were determined for a set of increasing values of Young's modulus of the callus, for both models.

Lowet *et al*. found that, as expected, the resonant frequencies were found to increase with increasing stiffness of the callus. The single bending modes were found to be more sensitive when the callus was at the middle of the diaphysis, while the double bending modes were more sensitive when the callus was located distally. In the case where the stiffness of the callus was five percent of the stiffness of the intact bone or higher, the mode shapes were similar to those corresponding to the original intact bone. It was found that the resonant frequencies and the torsional stiffness of the bone were related by a quasi-linear relationship. Lowet *et al*. conclude that their investigation supports the quantitative interpretation of vibration analysis measurements for the evaluation of tibial fracture healing. Earlier work on this area of research has been recently discussed [10].

CONCLUSIONS

The practical importance of the variation of dynamic properties in two completely different areas has been discussed. Future research to be performed by the authors will include the analysis of circular plates with radial cracks, modelled as structures with polar orthotropy.

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