Dynamic response testing of columnar composite structures subjected to impulsive loading

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An experimental technique designed to study the dynamic response of columnar composite structures to impulsive loading has been developed. The technique uses a vibration shaker to subject a vertically mounted specimen to impulsive forces. Miniature accelerometers are used to monitor the dynamic response of the specimen. Results obtained from impulse tests with bone specimens have been presented to illustrate the testing technique.

1. Introduction

A number of situations are encountered in industrial processes involving the transmission of impulse waves through columnar structures of composite materials. Information obtained from laboratory-scale impulse tests can be used to calculate dynamic material characteristics required for design purposes. An instrumented testing procedure has been developed which can be used to study the response of composite columnar structures of arbitrary cross-section subjected to impulsive loading. The procedure utilizes a vibration shaker to subject the columnar structure to impulsive forces. Accelerometers mounted on the composite specimen are used to monitor the dynamic response. A detailed account of data acquisition and analysis is presented. Results obtained from impulse tests conducted on bone specimens are presented to illustrate the testing procedure.

2. Experimental procedure

Though our experiments were performed on the bones of the human lower extremity, the experimental technique described below is applicable for the impulse testing of any columnar composite structure. The composite specimen to be tested was mounted vertically over the vibratory shaker (to be described) during the tests using the suspension system shown in Fig. 1. The specimen was held vertically through four steel rings of 3 in. (76 mm) diameter. Each ring was provided with six set-screws to grip the specimen. Three symmetrically located steel wires, 8 ft (2.4 m) were used to support each of these rings. The wires were attached to the support rings through smaller strain-gauged load rings of diameter 3/4 in (19 mm). The tension in the suspending wires was determined by monitoring the output of the strain gauges. The other ends of the steel wires were attached to the three corners of triangular steel supporting frames. The corners of the frames were provided with screw mechanisms which could be used to centre the rings and adjust the tension in the suspending steel wires. The triangular frames were held parallel to the ground by three support columns. The height of these columns could be adjusted by using screw jacks (Fig. 1). This suspension system effectively eliminated extraneous vertical forces on the test specimen. In our tests, it was necessary to simulate the weight of the body acting on the lower skeletal extremity. This was achieved by placing a 70 kg load placed on a platform provided at the upper end of the specimen.

To simulate the impulsive loading of the column under realistic conditions, a vibrating shaker (Bruel and Kjaer, Model 4801) was used to provide the impulsive forces at the lower end of the specimen (Fig. 1). The shaker was driven at constant power by an impulsive waveform provided by a Hewlett-Packard signal generator (Model 3301A) (Fig. 2).

To ensure that only an axial force component was transmitted to the test specimen, a ball and plate coupling assembly (Fig. 3) was positioned between the shaker head and the specimen (Fig. 1). Miniature Bruel and Kjaer accelerometers were mounted on the shaker head and coupling assembly for reference (Fig. 3). A dynamic force transducer (Bruel and Kjaer, Type 2800) was positioned between the shaker and the platform to measure the force at impact.

As shown in Fig. 3, the lower end of the specimen was enclosed in a cylindrical cup and rigidly held in place by set-screws. To ensure good force transmission, the gaps between the cup and the specimen were filled in with epoxy glue. Miniature Bruel and Kjaer accelerometers were used at different points along the height of the specimen to monitor the transmission of the impulse wave. The accelerometers were attached to the heads of screws inserted into the specimen (Fig. 4). This method of monitoring the dynamic

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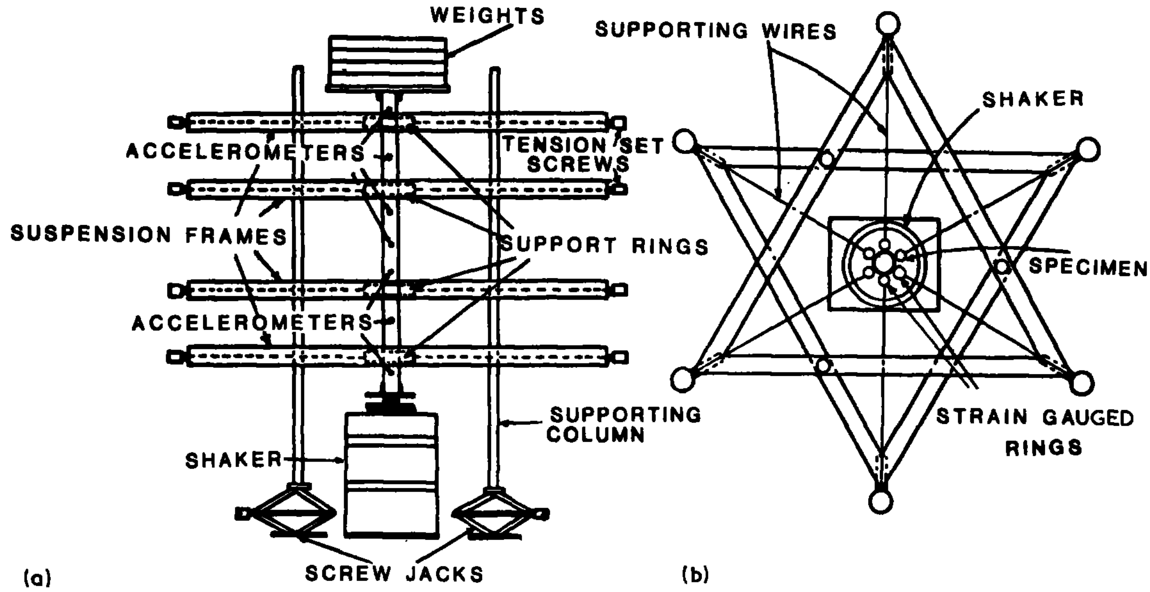

Figure 1 Schematic illustration of the specimen suspension and impacting set-up: (a) elevation, (b) plan.

response is superior to configurations where the accelerometers or strain gauges are mounted on the surface of anisotropic composite specimens.

Charge amplifiers (Bruel and Kjaer, Type 2635) were used to condition and amplify the signals generated by the accelerometers and force transducer. The signals were sent to an IBM-PC data acquisition system which was used to process, display and store the data.

The first step in the testing procedure was to adjust the tension in all the suspending wires to a uniform value. This ensured that the suspension system did not exert any forces on the test specimen. The tension in the suspending wires measured by the ring-mounted strain gauges and read by a strain indicator/switch and balance unit, was equalized by means of the screw mechanisms described earlier.

The nature of the impulsive force used to test the bone specimen was similar to that exerted on the human lower extremity during locomotion. The impact test was initiated by switching on the shaker with an impulsive step function input (Fig. 5) set at a frequency of 0.5 Hz. The amplitude of vibrations was maintained at 1/2 in (13 mm). The initial peak acceleration response from each accelerometer (output) was recorded and was normalized with respect to the acceleration of the shaker platform (input) to give a relative acceleration response ratio. This ratio was used as a measure of the transmission of the impulse input along the test specimen.

3. Results and discussion

Fig. 6 shows a typical time history of the response of each accelerometer along the human lower extremity specimen. The impulse wave can be seen to progress in time from the bottom of the specimen to the top.

In order to determine the speed of wave propagation in each complete bone section, the distance between two accelerometers on the same section was divided by the acceleration response time delay between these points. The average value of the speed of wave propagation (for four bone specimens tested) was

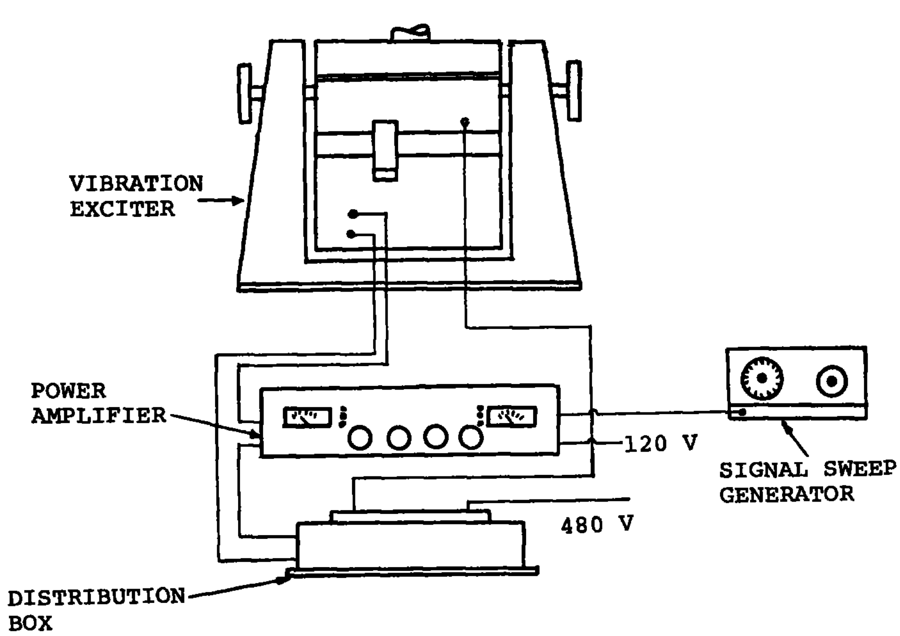

Figure 2 Schematic diagram of the electric circuitry for the vibration shaker.

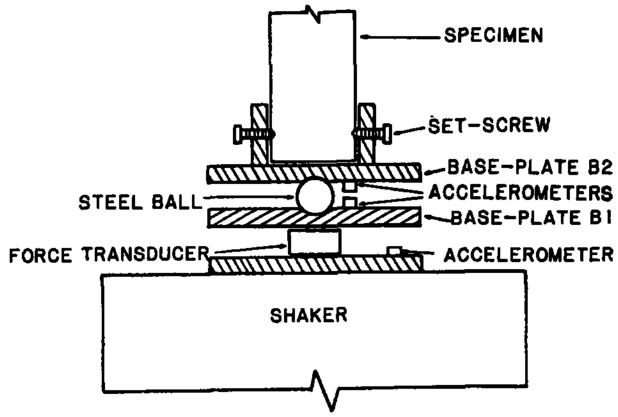

Figure 3 Cross-section of the impact centring mechanism showing the coupling assembly.

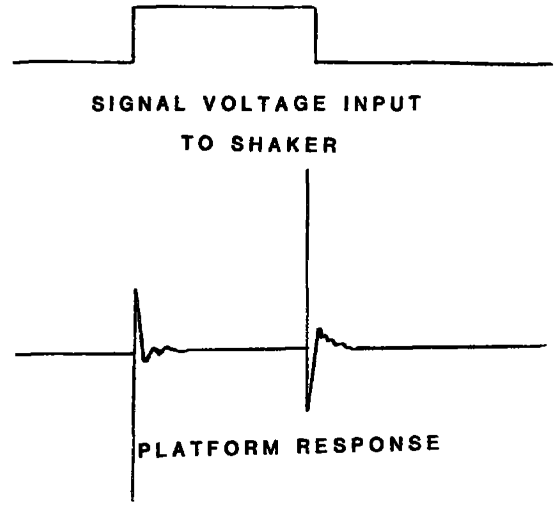

Figure 5 Typical signal voltage input to the shaker and the corresponding shaker platform response.

found to be $3100 \pm 50\,\text{m sec}^{-1}$. This value is close to the result of $3228 \pm 110\,\text{m sec}^{-1}$ found by Pelker and Saha [1].

Fig. 7 shows the relative acceleration ratio for the various accelerometers as a function of location along the specimen. The acceleration ratio curve gives a measure of energy dissipation along the length of the composite specimen.

In order to propagate a longitudinal plane progressive wave through the specimen, the input pulse wavelength must be greater than the specimen diameter, and the specimen should not be stressed beyond its proportional elastic limit. In this study, the average duration of impact was $120\,\mu\text{sec}$. This is equivalent to a wavelength (wavelength = speed of sound × duration of impact) of 13.8 in. (351 mm). The average diameter of the specimen used in our work was about one-tenth of this wavelength. The maximum stress generated by the impact was approximately $0.0013 \times 10^9\,\text{N m}^{-2}$ which is well within the elastic limit of long bones ($8.14 \times 10^9\,\text{N m}^{-2}$) [2].

The frequency of impact was kept constant at 0.5 Hz throughout the experiment. One reason for choosing such a value was to avoid resonance of the suspension system caused by an excitation frequency equal to its natural frequency (about 3 Hz for the first mode). This frequency was also low enough to provide enough time for the system to reach a steady state between impacts.

An advantage of the experimental set-up described in this paper is that the nature of the impulsive input provided by the shaker can be varied to give different types, frequencies and amplitudes of input waveforms. Thus the dynamic response of a columnar composite

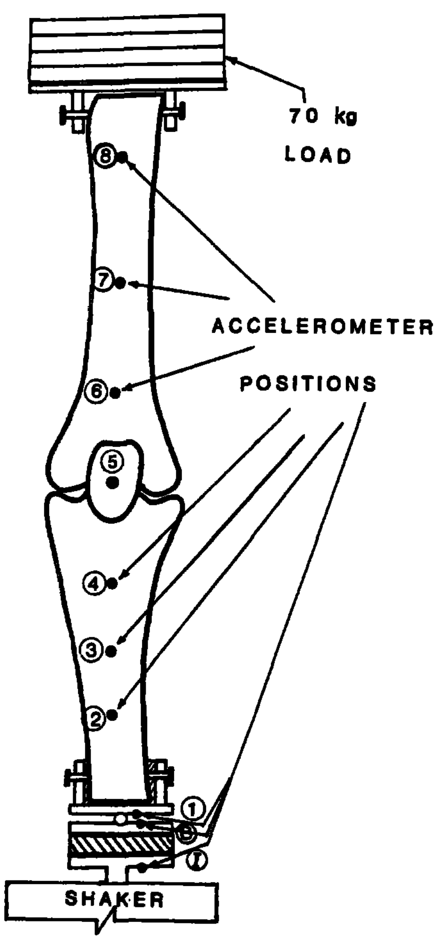

Figure 4 Schematic diagram of the experimental specimen (circled numbers indicate accelerometer locations).

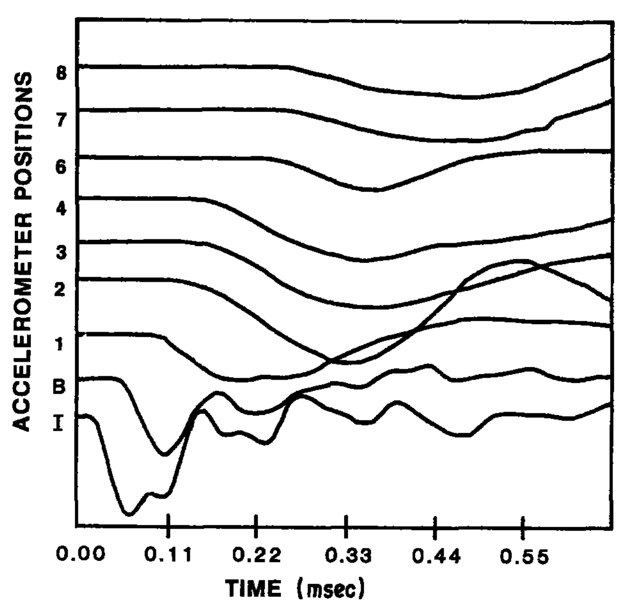

Figure 6 Typical accelerometer impulse response along the test specimen.

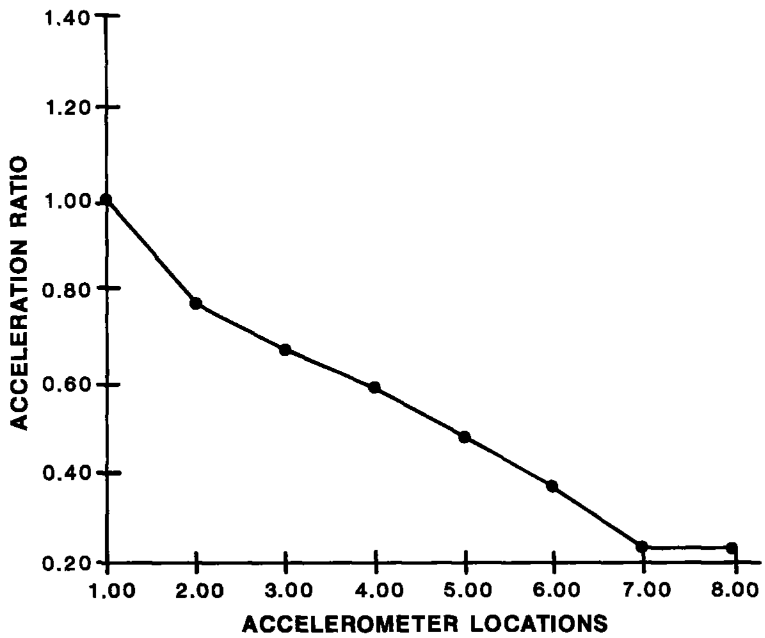

Figure 7 Transmission curve showing the longitudinal acceleration response ratio for the test specimen.

specimen can be tested under different types of impulsive loading.

4. Conclusions

A laboratory-scale technique designed to study the dynamic impulse response of a columnar composite specimen has been developed. The technique uses a vibration shaker to subject a vertically mounted columnar composite specimen to impulsive forces similar to that expected in actual application. The acceleration response along the specimen can be used to provide information regarding the transmission of impulse waves along the specimen. The method is applicable to the study of impulse-wave propagation in specimens when the input pulse wavelength is much larger than the characteristic diameter of the specimen, and the material is not stressed beyond its elastic limit.

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