ANALYSIS OF DYNAMIC TENSILE TESTING OF CEMENT-BASED COMPOSITES

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Summary This paper describes an experimental procedure to identify predominant frequencies of a servo-hydraulic high speed testing machine by conducting modal analysis. The effects due to both the predominant frequencies of the system and loading rate on the magnitude of system ringing and the flow stress were analyzed by using a single degree-of-freedom (SDOF) spring-mass-damper model. The SDOF model reveals that the predominant frequencies of the testing system are key parameters in dynamic tensile testing. The system was then used to study the dynamic tensile behavior of polyethylene fabric-cement composite at an intermediate strain rate of 22 s^{-1}. The results show that the stress oscillation obtained by this model agreed with the experimental results of the composite. It is feasible to use a power-law function or a properly designed low-pass filter to remove the stress oscillation caused by the system ringing when the cut-off frequency of the filter can be identified.
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INTRODUCTION

Numerous applications of structural materials involve dynamic or impact loading. In order to understand the behavior of these systems, it is necessary to know the mechanical properties of the materials involved at various strain rates. Different types of testing techniques have been used to simulate dynamic conditions with each serving a specific range of strain rates and providing a specific type of information. Among the many different techniques, the following are the more popular ones - Split Hopkinson Pressure Bar (SHPB), dropweight devices, flywheel facilities, hydraulic machine, etc. [1,2,3]. The SHPB also known as Kolsky bar [4], has been continuously subjected to vigorous modifications to improve the technique and generate reliable dynamic experimental data. However, at intermediate strain rates of less than 500 s^{-1}, the SHPB is less applicable necessitating the development of special testing equipment in order to obtain the stress-strain curve [5]. Experimental techniques to generate tensile stress-strain data at the intermediate strain rates (1 to 200 s^{-1}) represent a gap in the well established data. Servo-hydraulic high speed machines have been used to generate data for different materials [6,7,8] in this strain rate range. An understanding of the dynamic phenomena associated with this experimental technique, and the influence on the overall measurements are however far from complete. Furthermore, a discussion of the modal analysis of a servo-hydraulic high speed machine to characterize the system ringing phenomena is not available. This paper presents the modal analysis procedure to study the vibration characteristics of a servo-hydraulic high speed testing system and its application to polyethylene (PE) fabric-cement composite. The experimental results have been evaluated by quantifying the stress oscillation due to system ringing. The study is useful in further understanding of the issues related to dynamic tensile testing at intermediate strain rates.

MODAL ANALYSIS

Two accelerometers (Kistler, type 8702B500) with a capacity of ±500 g and a sensitivity of 10.32 mV/g, a four-channel power supply (Kistler, type 5134) for accelerometers, and an instrumented hammer (B&K, type 8202) with a steel tip were used for the modal test. Figure 1(a) shows the Frequency Response Functions (FRF's) of center rod at both sides of the upper grip and their corresponding coherence functions in the new configuration. There are five modes that are about 0.35, 0.9, 1.2, 1.4 and 1.6 kHz based on the FRF curves. In order to identify the rocking modes and axial modes, the average values of summation and difference between the two FRF's are shown in Fig. 1(b). The average summation values show that the mode at 0.35 kHz disappears, while the modes at 0.9, 1.2, 1.4 and 1.6 kHz remain indicating that the mode at 0.35 kHz is a rocking mode of the center rod while the others correspond to axial motions of this rod. This is further verified by the FFT curve of piezoelectric load washer output that has no mode at 0.35 kHz.

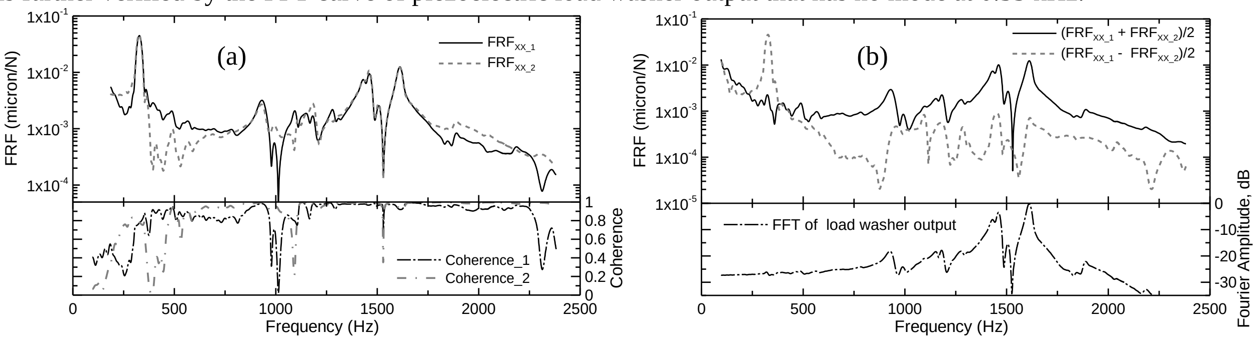

Fig. 1 Frequency Response Functions (FRF's) of center rod and coherence functions. FRF $_{XX}$ is the frequency response function of the grip. Both drive point and measurement point are at the grip.

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SYSTEM RINGING

System ringing is an important issue in dynamic material testing using a servo-hydraulic high speed testing machine. To understand the effect of the predominant frequencies of the testing system in dynamic tensile testing, the vibration response can be analyzed using a single degree-of-freedom (SDOF) spring-mass-damper model. The tensile testing system that introduces load through the use of a slack adaptor is comparable to a dynamic system excited by a suddenly applied impulse. Consider the SDOF spring-mass-damper system under free vibration, the response of such an under-damped system initially at rest and excited by impulse is given by [7]

$$x = \frac{V}{\omega_n \sqrt{1-\zeta^2}} e^{-\zeta \omega_n t} \sin \sqrt{1-\zeta^2}\,\omega_n t \tag{1}$$

The stress oscillation caused by system ringing can be expressed as [6]

$$\sigma = \frac{EV}{L\omega_n \sqrt{1-\zeta^2}} e^{-\zeta \omega_n t} \sin \sqrt{1-\zeta^2}\,\omega_n t \tag{2}$$

where V is the velocity of a mass at the end of impulse, ω_n is the natural circular frequency, ζ is the damping ratio.

APPLICATIONS OF THE HIGH SPEED TESTING MACHINE

In order to validate the workability of the high speed machine and understand the system ringing effect on the response of material, we studied polyethylene fabric-cement composite with silica fume (PESF) under dynamic tensile loading. Figure 2 shows the stress versus time curve of the PESF cement composite and the comparison of stress oscillation between the SDOF model and the experiment at a nominal strain rate of 22 s^{-1}. Note that the test duration is about 11 ms and the flow stress oscillates with time during strain-hardening region due to system ringing. As a remedy, the stress-time curve (grey line) in the strain-hardening region was fitted by a power-law function and also filtered by using a low-pass filter with a cut-off frequency of 0.5 kHz, indicated by solid line and dash line with circles, respectively. There is negligible difference among the curves processed by these two methods. So it is feasible to use a power-law function or a properly designed low-pass filter to remove the ringing effect when the cut-off frequency of the filter can be identified correctly. After obtaining the predominant frequencies by modal analysis and the damping ratio (estimated as 0.015), the theoretical response of the system with the predominant frequencies of 1.4 and 1.6 kHz and actual stress response are plotted in the lower part of Fig. 2. This analysis reveals that the predominant frequency of 1.4 kHz of the testing system is a key parameter in dynamic tensile testing. The modal analysis procedure and the SDOF model can provide quantitative information about the influence of the system ringing in dynamic tensile testing.

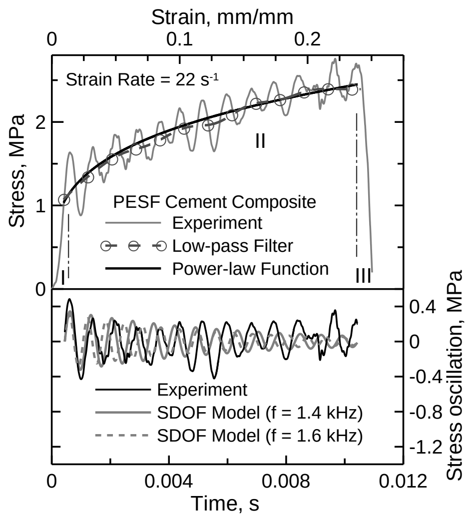

Fig. 2 Response of PESF cement composite and comparison of the stress oscillation between the SDOF model and the experiment

CONCLUSIONS

The vibration response of the servo-hydraulic high speed machine was characterized by modal analysis. The modal analysis results show that the 0.35 kHz mode is a rocking mode of center rod and the 0.9, 1.2, 1.4, and 1.6 kHz modes are axial modes, verified by the Fourier amplitude curves of the piezoelectric load washer output. Dynamic tensile tests were performed at an intermediate strain rate using the servo-hydraulic high speed machine on PESF cement composite. The SDOF model of an under-damped spring-mass-damper system was used to evaluate the effect of the predominant frequencies of the testing machine and loading rate on the flow stress of tested material. The stress oscillation obtained by this model agreed with the experimental results for PESF cement composite. It is feasible to use a power-law function or a properly designed low-pass filter to remove the system ringing effect.

References

[1] Chen W, Zhang B and Forestal MJ. Experimental Mechanics 1999; 39: 81-85.
[2] Kenneth GH. Experimental Mechanics 1966; 6(4): 204-211.
[3] Zhu D, Gencoglu M and Mobasher B. Cement and Concrete Composites 2009; 31: 379-387.
[4] Kolsky H. Proceedings of Physical Society B 1949; 62: 676-700.
[5] Lim JH. POSCO Technical Report 2007;10(1): 116-122.
[6] Zhu D, Mobasher B, Rajan SD and Peralta P. ASCE Journal of Engineering Mechanics 2011; 137(10): 669-679.
[7] Xiao XR. Polymer Testing 2008; 27(2): 164-178.
[8] Zhu D, Peled A and Mobasher B. Construction and Building Materials 2011; 25(1): 385-395.