ULTRASONIC INVESTIGATION OF THE STIFFNESS OF GRAPHITE-GRAPHITE INTERFACES

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INTRODUCTION

Many nuclear reactors incorporate large assemblies of enclosing graphite blocks. The load-deflection relationship and seismic response of these blocks are of great importance, and are believed to be partially determined by the surface roughness effects at the interface between blocks. Payne [1] has attempted to calculate the 'effective' modulus of a graphite core structure to include the effect of contact between the individual bricks. He noted that if the brick faces become curved through irradiation, the inter-brick load will be unevenly distributed across the interface.

This paper describes the use of longitudinal ultrasonic reflection coefficient measurements to investigate the stiffness of the interface under a variety of loading conditions and surface roughnesses. Cyclical loading of the interface has also been performed to determine its elastic/plastic nature, and the degree of asperity shakedown. A numerical model, which uses measured graphite profiles, is also reported, and gives further insight into the interfacial stiffness mechanism.

BACKGROUND

When an ultrasonic wave is incident on an interface between rough surfaces, the degree of transmission (and hence reflection) of the wave is dependent on the degree and nature of contact between the surfaces, and the acoustic properties of the two bodies. A high reflection coefficient indicates poor wave propagation across the interface and therefore a low degree of contact.

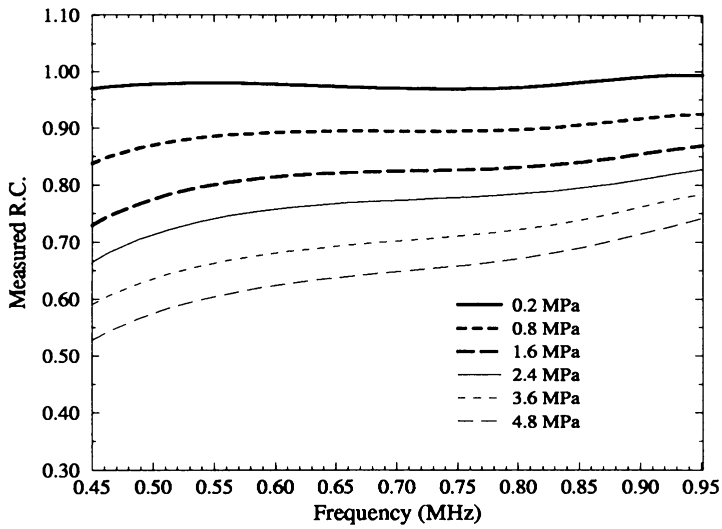

Figure 1. Measured variation in reflection coefficient from the interface as the applied pressure is increased.

Baik & Thompson [2] showed that an imperfect interface could be modelled as a spring-mass system, provided that the wavelength of the ultrasound was much greater than the size of the interfacial gaps. Measurements of the ultrasonic reflection from an imperfect interface can hence, at appropriate wavelengths, give an indication of the nature of contact, and can reliably give the stiffness of the interface. Using this spring model, it has been shown [3] that the amplitude of the reflection coefficient, $|R|$, and the interface stiffness, K, can be related by

$$|R| = \frac{1}{\sqrt{1 + \left(\frac{2K}{\omega z}\right)^2}} \quad , \tag{1}$$

for sound of angular frequency ω propagating between identical materials of acoustic impedance z. It should be noted that "interfacial stifness" is used here to mean the rate of change of nominal contact pressure with approach of the two surfaces' mean lines.

EXPERIMENTAL DETAILS

Specimens were cut from reactor-standard graphite blocks (of AGR type), prepared to various roughnesses, and loaded against one another in a specially designed loading rig. In this rig, a wide-band 1MHz transducer was used to interrogate (at normal incidence) the interface between two graphite specimens from below, with coupling achieved via a small enclosed water-bath. This low sound frequency had to be used due to the high ultrasonic attenuation in the graphite, caused by scattering from the millimeter-scale grain structure within the graphite-graphite composite material.

Figure 1 shows some typical reflection coefficient measurements from which it can be seen that as the load on the specimens is increased, the reflection coefficient at

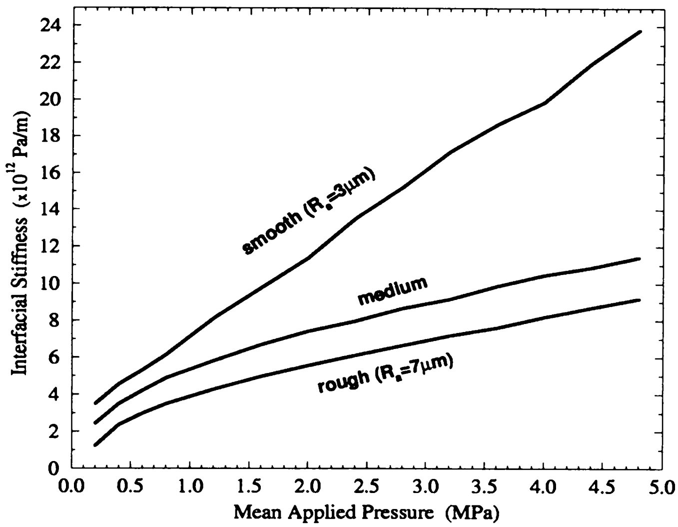

Figure 2. Measured variation in interfacial stiffness between specimen pairs of different surface roughness.

a given frequency reduces; this being due to the surfaces coming into better contact, making the interface stiffer. For a particular load, the reflection coefficient is greater at high frequencies, in accordance with theory [2]. The measured reflection coefficients can be converted to interfacial stiffness values using equation (1). Figure 2 shows the obtained stiffness for three cases of different measured surface roughnesses. As would be expected, the smooth surface pair has the highest stiffness at a given pressure, as there will be the greatest degree of surface contact in this case.

CYCLICAL LOADING

Cyclical loading and unloading of the specimens has also been carried out, with the results shown in Figure 3. Here it can be seen that there is a small amount of plasticity apparent in the first-loading cycle only, after which the loading follows a mostly elastic cycle. We believe that the hysteresis loop evident is due to inter-surface adhesion on unloading, i.e. extra work is needed to pull the surfaces apart. It should be noted that the applied load was not reduced completely to zero between loading cycles; a small residual load was maintained to ensure the same asperities remain in contact.

If the samples are roughened further (so that fewer points carry the load) then further plastic deformation occurs. This is illustrated in Figure 4a for surfaces of $R_a = 7\mu$m (corresponding to the "rough" line in Figure 2). Here there is a significant difference between the first and second unloading lines, indicating that irreversible deformation has taken place. Figure 4b shows the effect of increasing the peak load of the cycles; these results use the "medium" roughness surfaces of Figures 2 and 3. It can be seen that at this increased peak load, considerable plastic deformation occurs on each of the cycles shown, and hence even after three cycles, the surfaces are far from having completed their 'shakedown'.

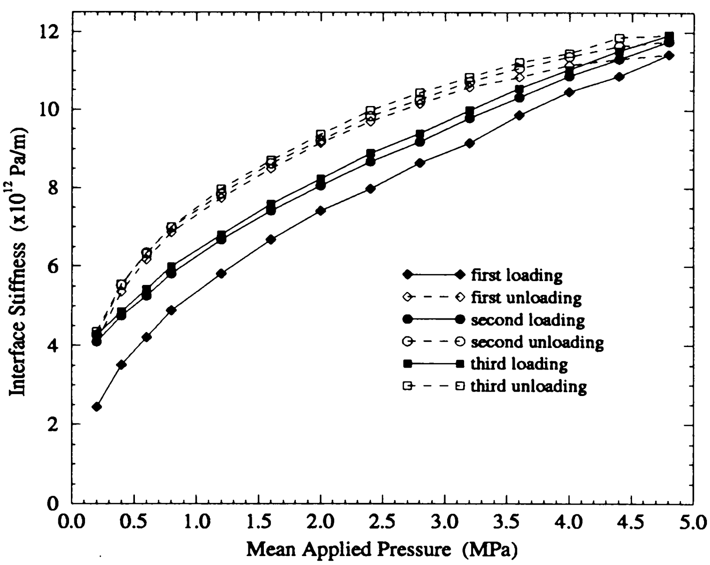

Figure 3. Effects of cyclical loading of specimen pairs (with medium roughness); a small amount of plasticity, and also adhesion are evident.

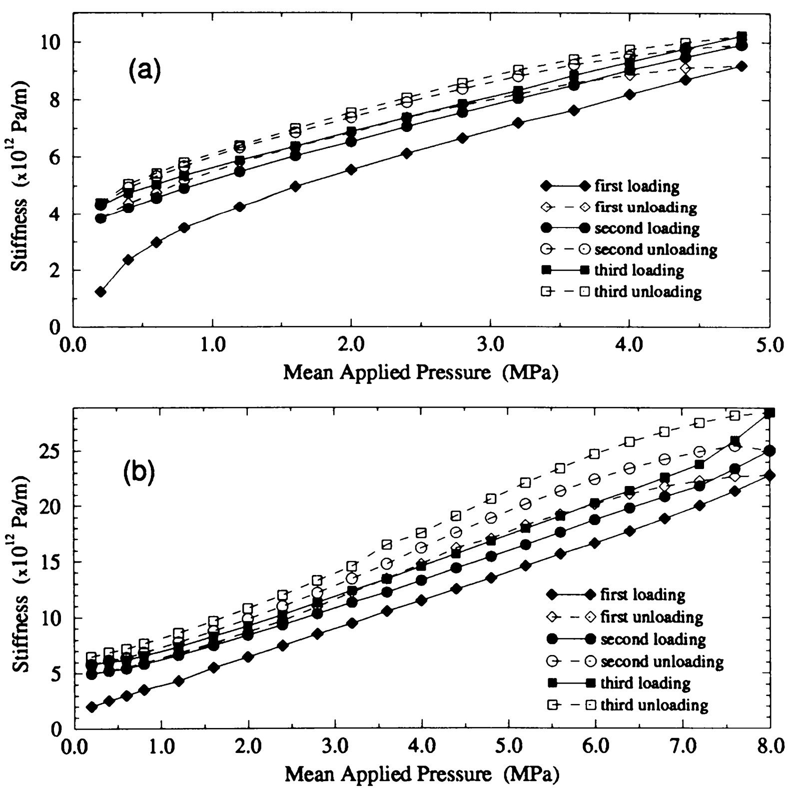

Figure 4. Cyclical loading of very rough surfaces (a), and heavily loaded medium surfaces (b); showing increased plasticity in both cases.

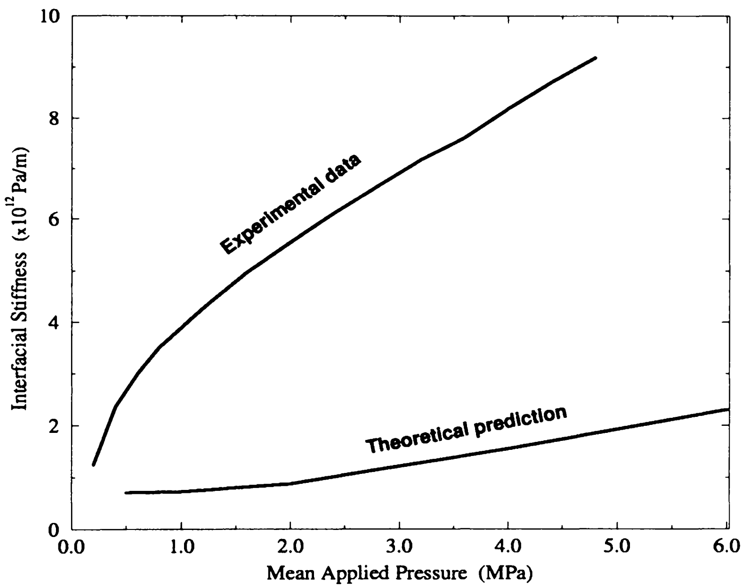

Figure 5. Comparison of experimental stiffness results and model predictions on assuming the bulk Young's modulus of 10 GPa — for rough surfaces of $R_a = 7\mu$m.

THEORETICAL WORK

A numerical contact model was developed to predict the interfacial stiffness. This is based on the two-dimensional, elastic contact model of Webster & Sayles [4]. As the graphite was known to be linear elastic over a large strain range, it was felt unnecessary to include any plasticity effects in its modelling. This model has also been utilized for the study of conact between other rough materials, notably for aluminum/aluminum interfaces in which it was found to give more realistic results than other widely used models [5].

Real digitized graphite profiles, containing approximately 6000 data points, are used in this model in an attempt to predict the stiffness in a number of cases. Figure 5 shows some typical results from this work. Here, the bulk value of the graphite Young's modulus (10 GPa) was used, and it can be seen to significantly under-estimate the required stiffness. The differing curvatures of the graphs at very low pressure is not considered to be significant as here there are very few asperities in contact in the theoretical case.

It is believed that this theoretical under-estimation is due to the structure of the graphite under investigation. The material consists of small, near-crystalline, grains embedded in a soft matrix. The stiffness (and hence the modulus) of the bulk material would be expected to be dominated by the stiffness of this softer matrix, whereas in the case of two interfaces being loaded together, the hard grain fragments would come into direct contact. Therefore the modulus of these grains will give a better guide to the true interfacial stiffness. However, crystalline graphite is highly anisotropic, and in certain directions its modulus can be in excess of 100 GPa [6]. It is believed that it will be necessary to choose an "effective modulus" in some manner to account for these much harder contact points if numerical modelling of these surfaces is to be successful. Further discussion of this and other features of our modelling can be found in another paper by the authors elsewhere in this volume, [7].

CONCLUSIONS

The behavior of the loaded interface between machined graphite blocks, as employed in Magnox-type atomic power reactors has been investigated. Low frequency ultrasonic reflection coefficients allow the true degree of contact between the blocks to be assessed, and the stiffness of the interface to be isolated from bulk effects.

It has been shown that this stiffness is a function of the surface roughness, but that there is very little dependence on loading history, i.e. the small degree of plasticity produces only a slight 'shakedown' of the surface asperities. Numerical modelling of the interface behavior has also been carried and only a fairly poor agreement with experiemntal data has been found. It is suggested that this is due to the granular nature of the graphite, and can possibly be allowed for in future modelling.

ACKNOWLEDGEMENT

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