The Response of Rough Partially Closed Cracks to Ultrasound at Oblique Incidence

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Abstract The detection and sizing of cracks in engineering structures is commonly accomplished using ultrasound inspection techniques. Most theoretical models assume that the cracks are open and smooth compared with the wavelength of the ultrasonic wave. However, fatigue cracks have rough surfaces and are often in compressive loading when inspected making detection more difficult. Previous work has investigated the response of a random rough surface interface to ultrasonic excitation at normal incidence and increasing compressive load, demonstrating good agreement between experimental results and the finite element model. However, inspection is often performed with an ultrasonic signal at an oblique incidence angle to the crack. This work describes models that have been used to investigate the effect of closure and surface roughness on the ultrasonic detectability of cracks at oblique incidence.

The interface of a crack is defined as an array of scatterers (voids). A contact model is used to estimate the size, shape and distribution of these scatterers under increasing values of compressive load for random rough surface interfaces and fatigue cracks grown in the laboratory. Finite element analysis has been used to investigate the reflection of an ultrasonic pulse at oblique incidence for scatterers of different shapes and sizes over a wide range of frequencies. The model results are compared with experimental measurements of ultrasonic reflection at oblique incidence on random rough surfaces.

1. Introduction

Inspection techniques used for the location and sizing of cracks include the measured reflection of an ultrasonic pulse. These inspections often occur when structures are not in service and any cracks that are present may be under compressive loading, closing the cracks and making detection more difficult. Most current models assume that the cracks are smooth compared with the wavelength of the ultrasound [**1**]. However, real cracks are often not smooth. Previous work on the detection of partially closed rough cracks [**2**] has demonstrated that an interface of random rough surfaces can be effectively modelled by an array of scatterers. Comparisons of the finite element modelling results with experimental measurements showed that this technique can be used to predict the response of a rough interface to an ultrasonic pulse at normal incidence. However, in many cases inspections utilise the response of a crack to ultrasonic excitation at oblique incidence. It is therefore the aim of this paper to investigate the interaction of ultrasound with partially closed cracks.

2. Contact model

The modelling techniques considered in this work all use the assumption that an interface can be described by an array of scatterers. A contact model is required to determine the geometry of the interface, the contact area and hence the size and distribution of the scatterers. Most contact models are based on the statistical properties of the surfaces, thus generating statistical interface contact parameters. Previous work described a contact model based on the work of Nayak [**3**] that utilises the digitised surface profiles of the interface. In this model, the digitised surfaces are combined and the composite surface profile is loaded against a flat surface to determine the geometric parameters of the interface (Figure 1). The estimated pressure at the interface can be calculated by using the assumption that the pressure at each point in contact is at the flow pressure of the material.

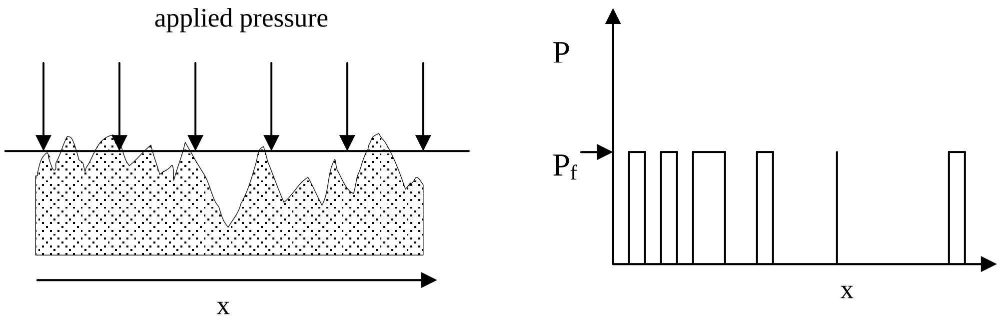


Figure 1 Plastic random surface contact model to predict the interfacial geometry

The estimated geometry for a crack interface with a surface roughness (R_a) of approximately 3.3µm is shown in Table 1 for EN24 steel. This material has a measured Vicker's Hardness of 288, giving a flow pressure of 2.8GPa. The geometric parameters for the interface have been calculated for two interfacial pressures, 27MPa and 77MPa. These pressures were chosen to coincide with the interfacial pressures applied in the experimental work. At 27MPa, the average width of the scatterers is 856.8µm, which reduces to 419.0µm at 77 MPa. The average ratio of the depth to the width of the scatterers (aspect ratio) at these pressures is 0.033 and 0.055, indicating that the scatterers are generally slit-shaped. Comparing the average width of the scatterers with the wavelength of ultrasound in steel, at 27MPa the scatterer size is similar to the wavelength of 1150µm at 5MHz but between three and four times the wavelength at 25MHz (236µm). At 77MPa, the average scatterer width is still twice the wavelength of the ultrasound at 25MHz, indicating from these estimations that for all the conditions considered in this paper, the scatterer sizes are the same order of magnitude as the wavelength of the ultrasonic pulse. The model also predicts that the area of contact at the interface is 0.95% at 27 MPa and 2.74% at 77 MPa.

Pressure at interface MPa	Average width of scatterers µm	Maximum width of scatterers µm	Percentage area of contact	Average aspect ratio of scatterers
27	856.8	2730.6	0.95	0.033
77	419.0	1771.9	2.74	0.055

Table 1 Interface geometry for an interface with R_a approximately 3.3µm

3. Modelling the response to ultrasound

In the work reported previously, finite element analysis has been used to model the reflection at normal incidence from an interface, assuming that the crack can be represented as an array of equi-sized, equi-spaced scatterers with the geometry determined from the contact model. Due to symmetry at normal incidence, a model of only one scatterer is required and boundary conditions can be applied to simulate an array of equally sized and spaced scatterers [**2**]. However, cracks in real structures are often inspected with an ultrasonic pulse that is at an oblique incidence to the crack. The model for an oblique incidence excitation is not symmetric and, therefore, a different approach to the modelling is required.

3.1 Secondary scattering

One approach to the modelling of the reflection of ultrasound from an interface is to assume that the interface can be represented by an array of point sources. The reflection from each point source is represented by the reflection measured from a single scatterer. Using Huygen's principle, the reflection from the whole interface is the summation of the responses from each of the point sources [**4**]. This technique assumes that the effect of secondary scattering is negligible. The reflection from individual scatterers can be determined using a finite element model to establish the scattering pattern around scatterers with different sizes and shapes, using defined excitation frequencies. These results have been used to study and quantify the effects of secondary scattering.

3.1.1 Single scatterer model

A schematic diagram of the model used in the finite element analysis to determine the reflection pattern around a single scatterer is shown in Figure 2. The commercial finite element package ABAQUS EXPLICIT 6.5 (ABAQUS UK Ltd., Warrington, UK) was used to generate a two-dimensional model of a single scatterer, using 4-node bilinear plane strain elements (CPE4R) with an element size of 0.01mm. This allowed a minimum of approximately 60 elements per wavelength at 10MHz which has been shown by other researchers to be more than sufficient to describe the ultrasonic response[**5**]. The scatterer was located at the centre of a square mesh (900 by 900) elements with a non-reflecting boundary of infinite elements at the bottom edge of the model. A plane longitudinal pulse was applied to the top surface and the displacement was monitored at 24 points located at equal angles around the scatterer and at a radial distance of 2.4mm from the centre of the model.

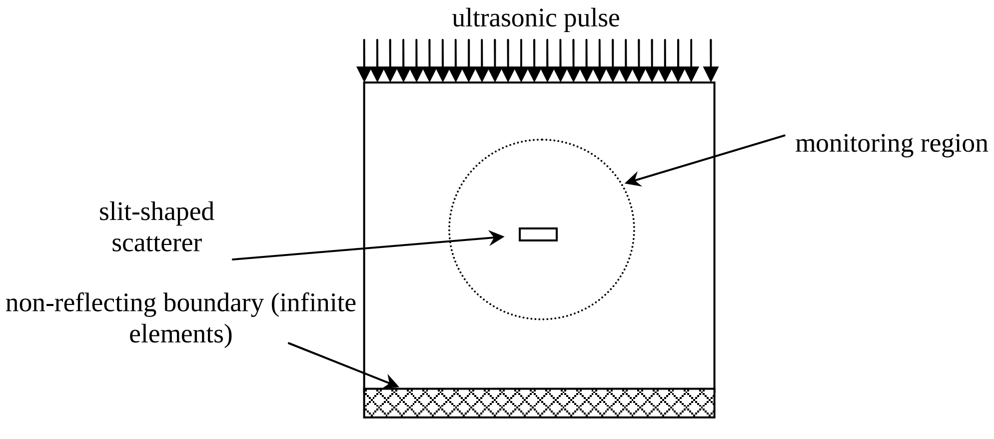


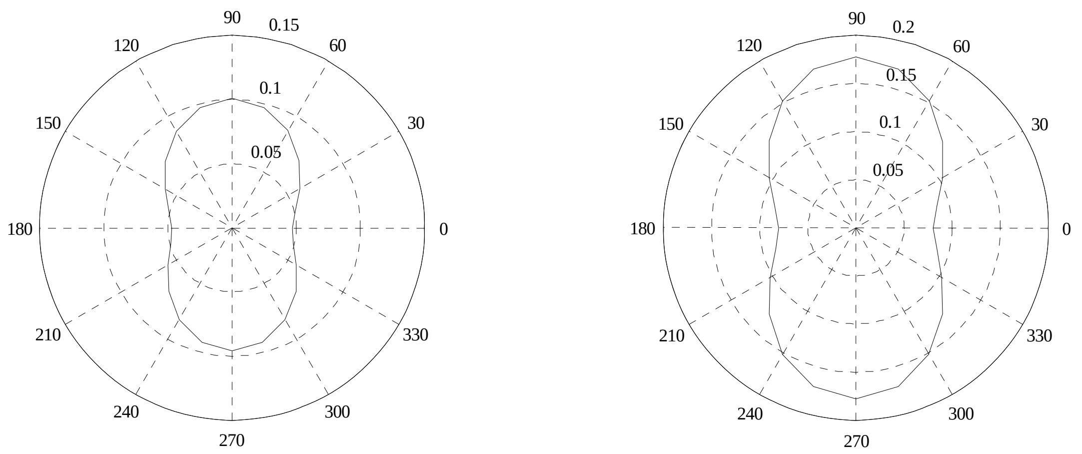
Figure 2 Schematic diagram of single scatterer model

The displacements in the vertical and horizontal directions at the monitoring points around the scatterer were resolved to give an angular displacement. The reflection from the scatterer is a circular wavefront and, therefore, a transfer function (T_{fr}) at a radial distance r from the centre of the scatterer has been defined as

$$T_{fr} = \frac{D_r}{D_i}$$

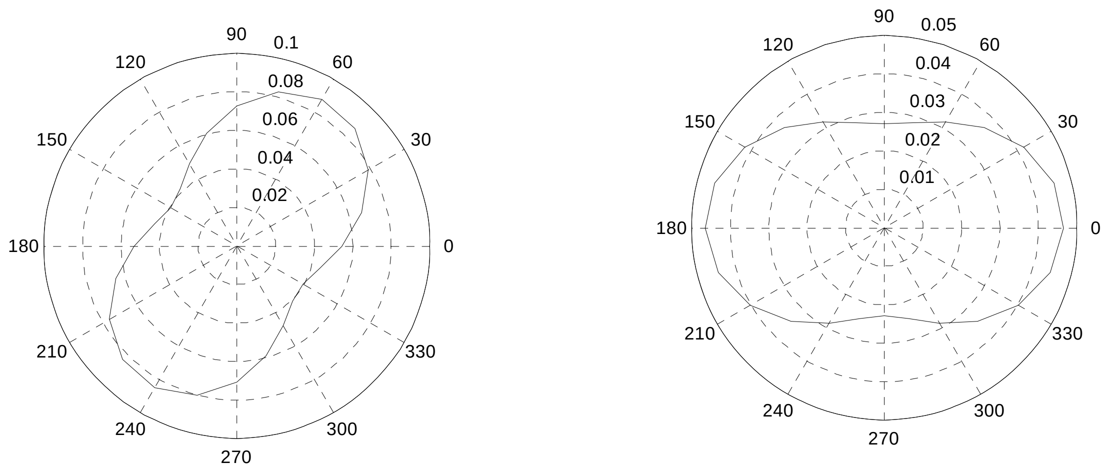
where D_r is the radial amplitude of the reflected wave
and D_i is the amplitude of the incident wave

Scattering patterns at 5 and 10MHz for a slit-shaped scatterers are shown in Figure 2 . It is interesting to note that the transfer function is greater for 10MHz that 5MHz.



(a) 5MHz (b) 10MHz

Figure 2 Angular displacement for a slit-shaped scatterer (width 0.18mm) at 5 and 10MHz



(a) 45^o (b) 90^o

Figure 3 Angular displacement and phase for a slit orientated at (a) 45^o to the incident wave and (b) 90^o to the incident wave

The reflection pattern for slit positioned at 45^o and perpendicular to the incident wave, respectively are shown in Figure 3. This demonstrates that when the slit is not located normal to the incident wave, the amplitude of the reflection is greatest in the direction normal to the plane of the scatterer.

3.1.2 'Hybrid' model results

Using the angular displacements obtained with the finite element analysis, a model of a crack interface was developed using Matlab, assuming that the interface is an array of scatterers at equal distances from each other. The reflection from the interface was calculated using Huygen's principle which states that a scattering surface in a material can be represented by an infinite number of point sources and these can be added together mathematically to produce a plane wave [**4**]. The schematic diagram in Figure 4 illustrates this model. The reflections from all of the scatterers were combined at the monitoring point, taking into account the different angles of the scatterer response with regard to the horizontal plane and the distance that the wave travels to the monitoring point. The relative amplitude *A(x,y)* at point(x,y) and a distance d_r from the centre of the scatterer is defined as

$$A(x,y)=\sum_{n=0}^{n=N} A_o(\theta_n)\sqrt{\frac{r}{dn}}$$

where $A_o(\theta_n)$ is the amplitude at distance *r* from the centre of the nth scatterer

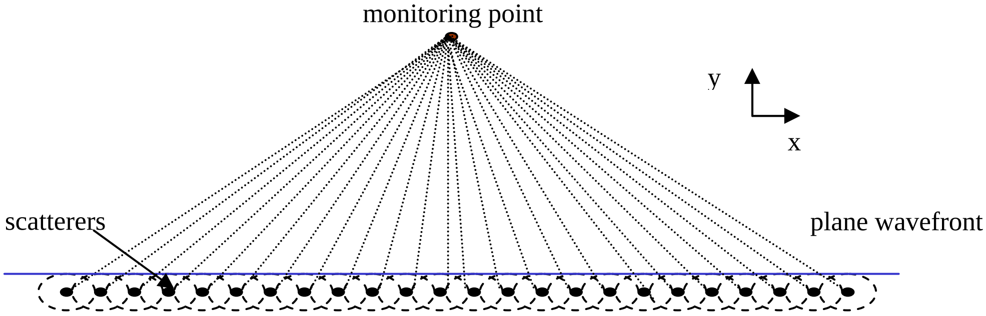


Figure 4 Schematic diagram of the 'hybrid' scattering model

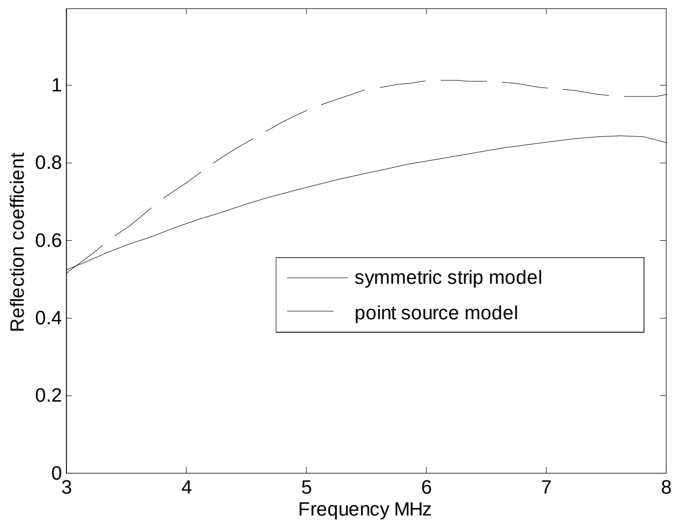


Figure 5 Comparison of results from the 'hybrid' model and symmetric strip model at normal incidence for an array of slit scatterers (30% contact)

Investigations of this 'hybrid' scattering model using a normal incidence ultrasonic pulse, showed that the reflection from the interface was a plane wave. Comparisons were made with the results from previous finite element analysis using a strip model with symmetric boundary conditions at normal incidence. In Figure 5, the results are compared for an interface of slit-shaped scatterers with a contact area of 30% at the interface. It was demonstrated that, for all values of contact area, the results show a higher reflection coefficient for the 'hybrid' scattering model. As the scatterers become closer together and the contact area reduces, the difference between the two sets of results becomes greater. It is obvious from the scattering patterns from the single scatterer models that the wave is reflected in all directions around the scatterer. The 'hybrid' scattering model does not take into account any secondary scattering at the interface, thus introducing an error in the reflection. As the scatterers become closer together and the contact area reduces, this secondary scattering will be greater and the difference in the results higher.

3.2 Finite element model of a complete crack

Modelling a complete crack interface using finite element analysis demands a large number of elements and, thus, considerable computing power, due to the requirements to model the ultrasonic pulse correctly and to adequately describe the scatterers. As for the previous modelling, ABAQUS EXPLICIT 6.5 was used to generate a two-dimensional model of the interface, using 4-node bilinear plane strain elements (CPE4R). An element size of 0.005mm was chosen as frequencies up to 25MHz were used for the excitation and also to ensure that the scatterers could be accurately described. A schematic of the finite element model is shown in Figure 6. The model is 15mm wide by 6mm deep (3000 by 1200 elements), with the interface located 5mm below the top surface. Elliptical scatterers have been located along the interface, with the incident wave applied at the surface over a 3mm distance to represent the ultrasonic transducer.

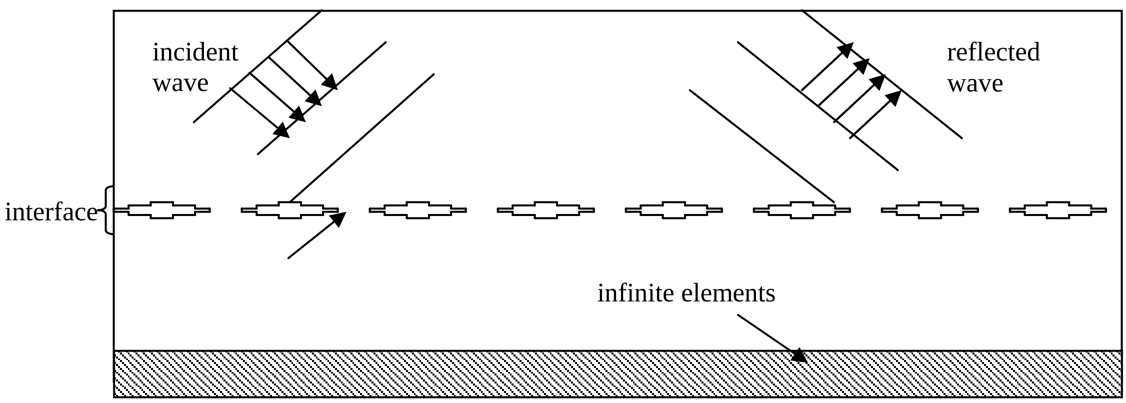


Figure 6 Schematic diagram of the whole crack model

Typical incident and reflected waves from a finite element model are shown in Figure 7. When the pulse is applied to the surface of the model, shear and longitudinal waves are generated (Figure7a). This mode conversion is apparent when the longitudinal wave is reflected from the interface (Figure 7b). The reflection coefficient was calculated from the incident and reflected waves signals.

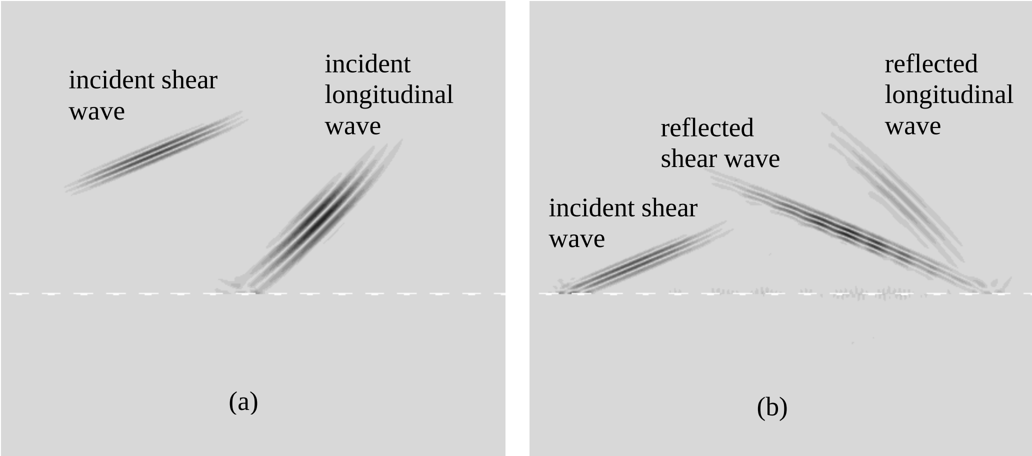


Figure 7 (a) Incident wave and (b) reflected waves from the finite element model

4. Experimental work

A rough interface was manufactured in the laboratory using grit-blasted steel specimens. The apparatus to measure the response of these surfaces to a longitudinal wave at oblique incidence is shown in Figure 8. The ultrasonic pulse was reflected from the interface at the calculated angle and captured by a second transducer (pitch-catch mode). The interface was loaded up to 77MPa and the reflected pulse was captured at defined pressures. The reflection coefficient was then calculated for the different pressures. Wideband transducers were used with centre frequencies ranging from 5 to 25MHz

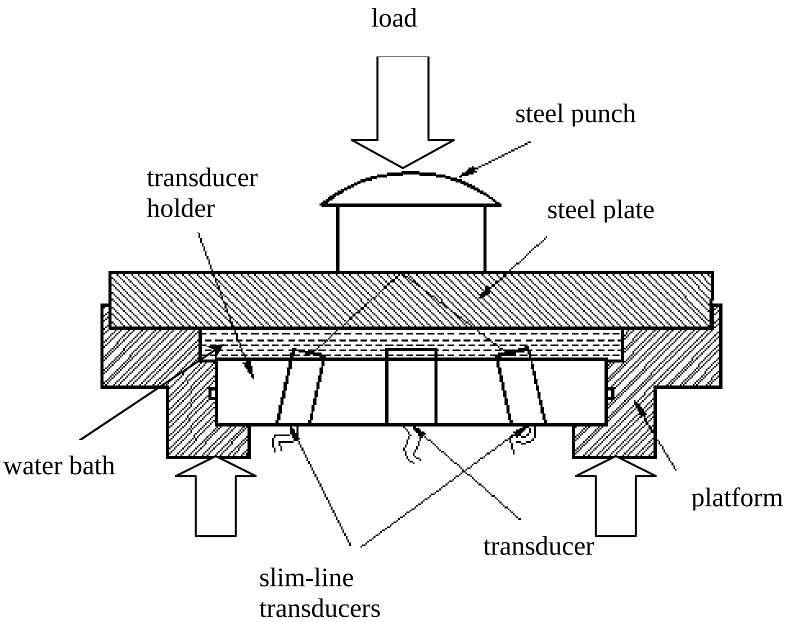


Figure 8 Schematic diagram of the experimental apparatus oblique incidence

5. Comparison of model predictions and experimental results

Predicted values of reflection coefficient for 60^o incidence are compared with the experimental results in Figure 9 for two different pressures and frequencies from 12 to 24MHz. The modelling predictions show little difference between the two pressures and across all the frequencies the reflection coefficient values are lower than the experimental measurements. The model is based on the average size of scatterers, estimated using the contact model. Previous work has indicated that large scatterers may dominate the behaviour of the interface. Furthermore, at the pressures used in the experimental work, there is very little difference in the contact area predicted with the contact model (0.95% at 27 MPa and 2.74% at 77 MPa).

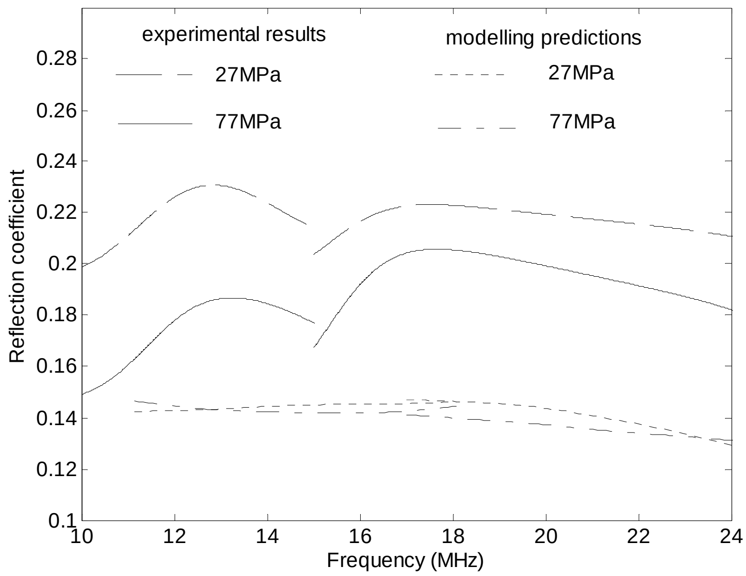


Figure 9 Comparison of experimental and model results

6. Conclusions

Different techniques for modelling the response of a rough partially closed crack to an ultrasonic wave have been discussed. A method utilising Huygen's principle has indicated that secondary scattering from the individual scatterers at the interface is an important consideration in the calculation of the reflection. A finite element model of the whole interface has been proposed. Initial results indicate that the model predictions are lower than the experimental results when applying the average scatterer size estimated with the contact model.

References

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