Experimental Study of Ultrasonic Guided Wave Propagation in Steel-Rubber Structure

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Keywords: Steel-Rubber, Ultrasonic Guided Wave, Leaky wave, Shear wave

Abstract
This paper describes the investigation for feasibility of generation and propagation ultrasonic guided wave within steel-rubber double layer structure. It also describes the possibility of detection of debonds present at the interface of the structure. A straight beam probe was used to generate the guide wave within the structure. Another straight beam probe was used to receive the guided wave signal on and around the debonded region. The guided wave was generated by exciting the specimen from both sides and wave is also detected from both sides of the specimen. It was found that rubber layer does not support the guided wave mode and guide wave does not propagate through rubber layer. However, point-wise inspection of the specimen is possible and that can detect presence of debond in the specimen. The normal displacements of the guided wave generated in the steel layer leaks and propagates through the rubber layer and the same is the basis for the detection of debonds.

Introduction
In the case of rocket motors [1] manufactured with case bonded technology, rocasin rubber layer is bonded to the metal casing of the rocket motor. The rocket motor bonded with rubber is initially inspected for presence of debond at the interface. Ultrasonic testing method [2] with pulse echo or through transmission technique is conventionally used for inspection of such specimens. In this method, probes are physically positioned at the desired locations for inspection. In contrast to that, ultrasonic guided waves can propagate a long distance in such kind of specimens (plate-like or cylindrical structures) and provide information along the line of sight which makes the process of inspection to be faster and less tedious.

In the recent past, significant progress was made worldwide for utilisation of guided wave [3] for detection of debonds within the materials of inspection like composites [4,5,6]. In most of the cases, the most sensitive mode is chosen for excitation and accordingly the interaction of that mode with the delamination or debond type flaws is studied for detection of these kind of flaws. To work with this method, it is essential that the ultrasonic guided wave gets generated and propagates within the structure and the guided mode interacts with the flaws. Hence the investigation for the feasibility of generating guided wave in the double layer structure of steel-rubber is very important. In this regard, experimental investigation for feasibility of generating and propagating guide wave within the steel-rubber specimen was taken up. This paper describes about the experimental study for understanding of interaction of ultrasonic waves with the steel-rubber double layer specimen. The study highlights the feasibility of using guided wave for detection of debonded regions in the two layer structure. This paper describes in detail about the experimental setup, and the experimental outcome of the interaction of the excitation signal with debonds.
Experimental Specimen
A rocasin rubber of 2 mm thickness was bonded with a steel plate of thickness 3 mm. The above thicknesses are the usual thickness of material used in rocket motors. As per the standard procedure, initially the steel plate surface was roughened and the rubber layer was also abraded and bonded using the recommended adhesive. During application of adhesive within the layers, few regions were left without any adhesive and same size of Teflon release films were put on that region. The placement of release film ensures that the interface is remained unbounded. The process was repeated with an open ended unbounded region in another steel-rubber specimen to confirm the process for successful generation of debonded region. The photograph of the specimen prepared is shown in figure 1. Although the boundaries of the debonded regions are not sharp, but can comfortably be assumed for the purpose of testing. The presence of created debonds were confirmed by testing with conventional contact ultrasonic methods.

![Figure 1: Photograph of specimen with known debonded region](image)

Experimental setup
Excitation from steel side
Initially a straight beam probe of 200 KHz was kept in contact with the steel side of the specimen.

Case: I
Detection from rubber side
The detector was then placed at various positions along the line passing through the debonded region. The corresponding signals were observed. The schematic of the arrangement is shown in figure 2.

Case: II
Detection from steel side
In the next set of experiments, the detector probe was placed along the same line but on the steel side. The schematic for the same is shown in figure 3.
Excitation from rubber side
In this case, the straight beam probe of frequency 200 KHz was kept in contact with the rubber side of the specimen.

Case: III
Detection from steel side
The detector was placed at various positions on the opposite side of the specimen along a line passing through a debonded region. The schematic for the experimental setup is shown in figure 4.

Case: IV
Detection from rubber side
The detector was placed on the same side of the specimen i.e., on the rubber again on the line passing through the debonded region as shown in figure 5.

For each case, the qualitative nature of ultrasonic signal which was received by the detector is mentioned at the right hand side.

Case: I
Excitation from steel side and detection from rubber side

High amplitude signal
Signal was observed
No Signal was observed
Signal was observed

Figure 2: Schematic for excitation from metal side and detection from rubber side

Case: II
Excitation from steel side and detection from steel side

Signal was observed
Signal was observed
Signal was observed

Figure 3: Schematic for excitation from steel side and detection from steel side
Case: III  
Excitation from rubber side and detection from steel/rubber side

Figure 4: Schematic for excitation from rubber side and detection from steel side

Case: IV  
Excitation from rubber side and detection from rubber side

Figure 5: Schematic for excitation from rubber side and detection from rubber side

Case: V  
Excitation only with rubber specimen of 2 mm thickness

Figure 6: Excitation and detection on rubber layer only

Results and Discussion

Guided wave was generated in the double layered structure by using a 200 KHz straight beam piezoelectric ultrasonic transducer.

At the first instance (Case-I), transmitter was pressed against the steel side and the detector was placed at various positions on the rubber as shown in figure 2. It was observed that when the detector probe was kept opposite to the transmitter probe, very high intensity signal was observed. When the detector probe was placed away from transmitter but on a bonded region, the obtained signal was of good quality but intensity was reduced. The reduction of signal amplitude was observed with the distance between the transmitter and
receiver. When the receiver probe was placed just below the debonded region, sudden absence of signal was observed.

In Case-II, as shown in figure 3 the receiver is placed on the same side that of the transmitter i.e., on the steel side. In this case also the signal amplitude reduces with the distance between the transmitter and receiver. However, interestingly there was no sudden change in received signal when the receiver was placed above the debonded region.

In Case-III, the transmitter was placed directly on the rubber side and the receiver was placed on the steel side as shown in figure 4. When the transmitter and the receiver were placed exactly opposite to each other, the received signal was observed to be of very high amplitude. When the receiver is moved along the steel side, the signal amplitude was observed to be reducing with respect to the distance between transmitter and receiver. The same trend was used to maintain even when the receiver was placed directly on the debonded region.

For Case-IV which is shown in figure 5, the transmitter was placed on the rubber side and the receiver was also placed on the same side i.e., on rubber. When the receiver was positioned at different places along the rubber, it was again observed that the signal amplitude as observed by the receiver reduces with respect to the distance of separation between transmitter and receiver which holds true for all the cases. However in this case again, when the receiver is placed on the debonded region, there was sudden absence of signal as observed in the case of Case-I.

The results represented in Case-I indicates that there is some interaction of debond with the guided wave propagated within the double layered structure whereas Case-II indicates that the debond does not play any role in the received signal from steel end. Like Case-II, Case-III also indicates that when the signal is received from steel side the received signal does not interact with the debond or the debond does not affect the signal received from steel surface. Again in case-IV, it is shown that whenever the signal is received by the detector placed on the debonded region and observed from rubber side, then only the indication of debonded region is observed. Complete signal loss in the case of Case-I and Case-IV for placement of probe on the debonded region and observation from rubber side indicates that there is no ultrasonic energy available on the rubber present above the debond portion. Whereas other regions i.e., bonded region has the ultrasonic energy which is possible because of presence of ultrasonic guided wave only on the steel plate. The normal vibration caused by the guided wave present in the steel plate passes through the rubber specimen and gets detected from the rubber side in case of bonded region. In the case of unbounded region, the normal vibration available in the steel plate does not pass through the unbounded region and hence does not get detected by the receiver placed on the rubber side. When the detector is placed in the steel side, the signal received is the normal vibration available to the steel plate because of the guided wave in the steel plate alone. As originally there is no ultrasonic energy (guided wave) available in the rubber side so the received signal does not get affected when detected from steel side.

The observation also indicates that the rubber is only able to pass the normal vibration to the steel plate. To corroborate the fact, experiment was carried out as shown in figure 6 (Case-V). In the first instance of Case-V, the received signal is of very high amplitude which directly indicates that the attenuation of longitudinal wave through rubber is not very high as usually thought off. In the second instance of Case-V, there was no signal received by the receiver when placed adjacent to the transmitter probe as shown in figure 6. This clearly indicates that shear wave mode of ultrasonic is not able to sustain in the rubber specimen whereas rubber offers very less attenuation to the longitudinal wave mode.

From the inferences drawn from the experimental outcome, Figure 7, 8 & 9 shows the ultrasonic wave propagation or availability of ultrasonic energy for case of transmission from
steel side and rubber side and also shows the case of ultrasonic wave interaction only with rubber specimen respectively.

![Figure 7: Availability of ultrasonic energy for source excitation from steel side](image1)

![Figure 8: Availability of ultrasonic energy for source excitation from rubber side](image2)

![Figure 9: Availability of ultrasonic energy for source excitation only for rubber specimen](image3)

Conclusions
The feasibility of using ultrasonic guided wave generated by normal beam transducer for detection of debonds at the interface of steel-rubber interface was studied. The experimental study was carried out to understand the ultrasonic wave propagation within the specimen of steel-rubber layers with known debonded regions. It was observed that the debond detection is possible but with point-wise scanning method. The guided wave is not able to generate in the rubber layer as the shear wave mode is not able to propagate through the rubber layer. In that case, the advantage of using guided wave for line scanning of the region is found to be not feasible. The point scanning method can very well be used for detection of debonds at the interface for the condition of generation of guided wave in steel layer and detection from rubber layer.

References