A New Paradigm for NDE (**N**on **D**estructive **E**valuation)

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The Electromagnetic Armor Team has developed methods for **N**on **D**estructive **E**valuation (NDE) for several very different types of armor. At first glance these methods seem quite distinct, however when they are considered from the appropriate vantage point they can be viewed as two particular instantiations of the same basic concept. The two applications will be described in some detail, and then it will be shown that they are quite similar.

NDE for Ceramic Armor

A Basic Description of the Testing Method

The first application is NDE for ceramic armor. The initial step is determining specific physical properties of the armor which are correlated with armor structural health. A pair of Lead Zirconate Titanate (PZT) sensors is bonded or embedded to the armor plate. One of the transducers acts as the actuator and is the "transmitter" while the other is the "receiver"; this is commonly called the "pitch and catch" method. The armor plate vibrates when it is excited by a mechanical vibration from the PZT actuator transducer, and this vibration is transmitted through the plate and induces an electrical signal in the PZT receiver transducer by virtue of the piezoelectric effect. All transducers have a spectrum which can be measured with an impedance analyzer. There is often a group of resonance peaks, and always a maximum. The idea is to select PZT transducers which have one relatively strong resonance frequency that is close to that of the ceramic armor plate's resonance frequency whose structural health we wish to monitor (i.e. check to see if the armor response to the actuator induced ultrasonic waves has changed

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14. ABSTRACT
The Electromagnetic Armor Team has developed methods for Non Destructive Evaluation (NDE) for several very different types of armor. At first glance these methods seem quite distinct, however when they are considered from the appropriate vantage point they can be viewed as two particular instantiations of the same basic concept. The two applications will be described in some detail, and then it will be shown that they are quite similar.

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since the time when it has been known to be healthy). The armor plate is tested as follows:

Excite vibrations in the healthy armor plate with frequencies from 1 to 200 kHz in one kHz increments. Then the magnitude of the responses is stored.

Creating a "Normal" Distribution from the Data

Unfortunately the data from a single test have random noise which always occurs whenever testing is done in the real world. This noise can originate from changes in the ambient conditions (such as temperature and humidity), computer timing and various other factors. Our task is to find a method to capture the data which represents the healthy plate after removing the random noise. Fortunately, mathematical theory (the central limit theorem) states that random noise with an expectation of 0 can be removed by merely averaging the data from several tests. It also says that averaging independent random variables produces a distribution which can be closely approximated by a normal distribution. The behavior of normal distributions is well understood by statisticians and is often used by engineers. So for the ceramic armor plate there are 200 variables (the magnitude of the root mean square of the signal, one for each kHz value). By measuring the plate 25 to 30 times over a few hours and averaging the responses, we get 200 pseudo normal distributions, one for each kHz value. The properties of a certain normal distribution are preferred by statisticians, namely the one with a mean or average value of 0, and a standard deviation of 1. So let us imagine that we have done 30 replications of the same test. For each index i ranging from 1 to 200 let

X_i represent the i_{th} variable and μ_i represent the average of the root mean square of the i_{th} frequency values and σ_i represent the standard deviation of the test data. Then the new variables

$$Z_i = (X_i - \mu_i) / \sigma_i \qquad (1)$$

will closely approximate a normal distribution with a mean of 0 and a standard deviation of 1. The Z_i variables can be ranked based on how much energy they contain. Experiments have shown that usually 25% or less of the variables will contain 90% of the energy of the test. The remainder of the variables can be considered as noise. One can consider the 200 variables as a vector with 200 components. If each component of the vector is divided by the square root of the sum of the squares of all the components the resulting vector will be a unit vector. By using unit vectors variability in the data which is caused by differences in input signal strength is eliminated since a stronger input signal usually generates a larger greater output response, and unit vectors are commonly used to concentrate on shape. Figure 1 shows a ceramic armor plate with embedded PZT sensors and wires. Figure 2 below shows the response of all of the 200 variables, while Figure 3 shows that by taking a small subset of all the frequencies we can capture the essence of the plate's vibrations. We call this reduced set, the "fingerprint". The amplitudes in the fingerprint are different from those in the raw data due to the fact that the fingerprint vector has been normalized to be a unit vector. At some time in the future we wish to determine if the armor plate has changed. Experience has shown that cracks in the armor plate change the way it responds to the ultrasonic vibrations. To check armor health we only need to test the armor again and compare the new results to the armor database. For example, consider Figures 4 and 5. Figure 4 shows the variability of the results when the armor is healthy, while Figure 5 shows the results when the armor is damaged. (In this case we know that the armor is damaged because it has been shot and has visible damage). While this method seemed to work reasonably well it sometimes produced results which are less than what is desired. Figure 5 shows a periodicity in the results which is not random.

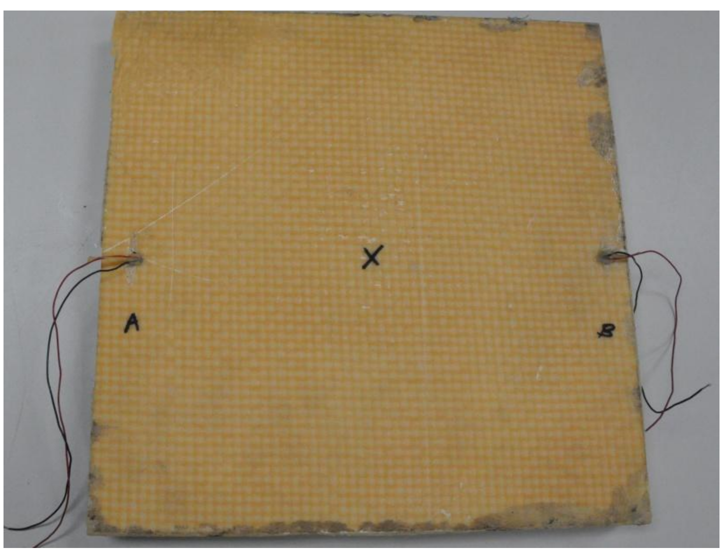

Figure 1: A Ceramic Armor Plate with Embedded PZT Sensors

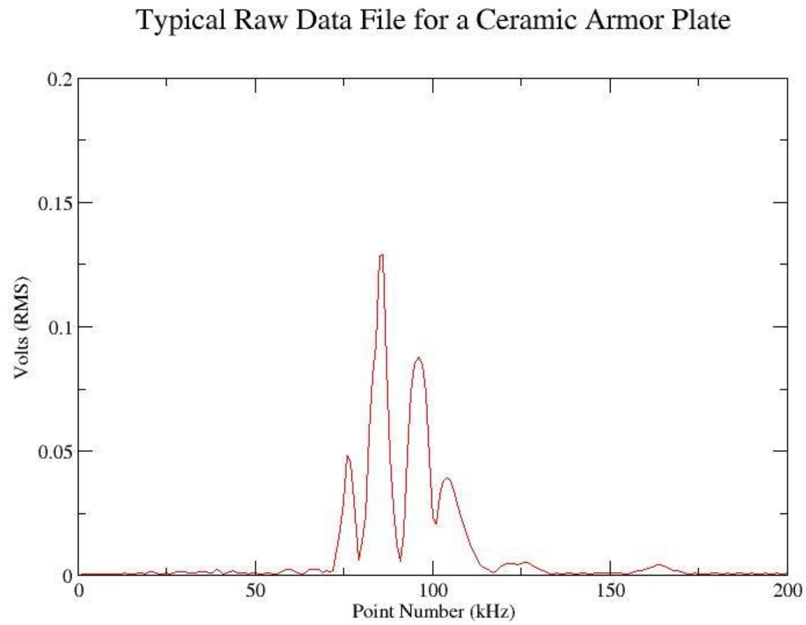

Figure 2: Graph of the Raw Data from a Test of an undamaged Armor Plate

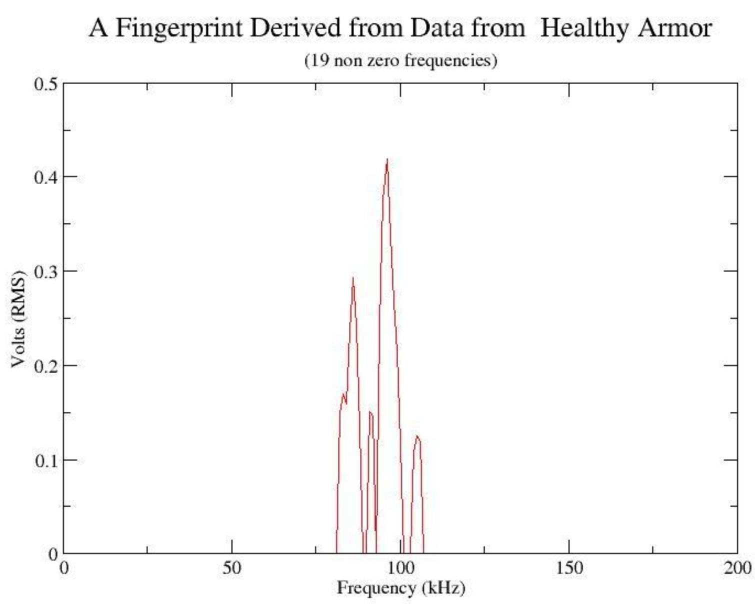

Figure 3: The Fingerprint Derived from Several Tests of the undamaged Armor Plate

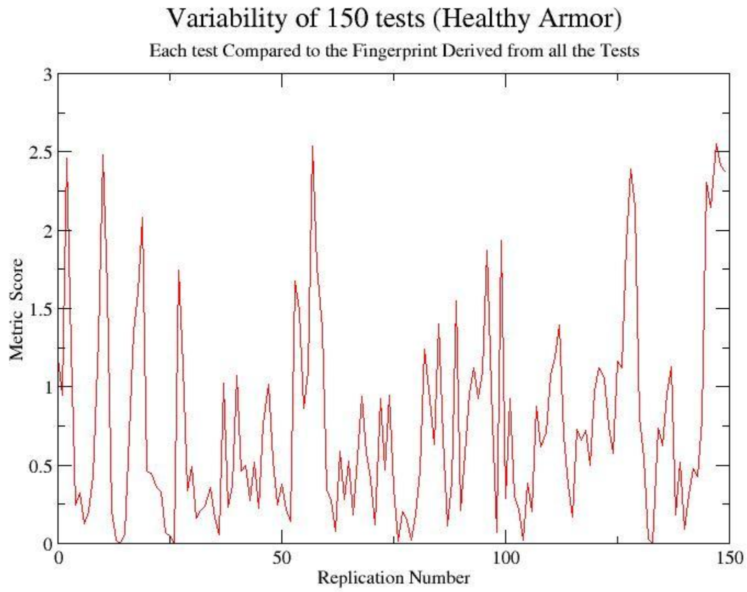

Figure 4: Variability of the Individual Tests as Compared to the Fingerprint

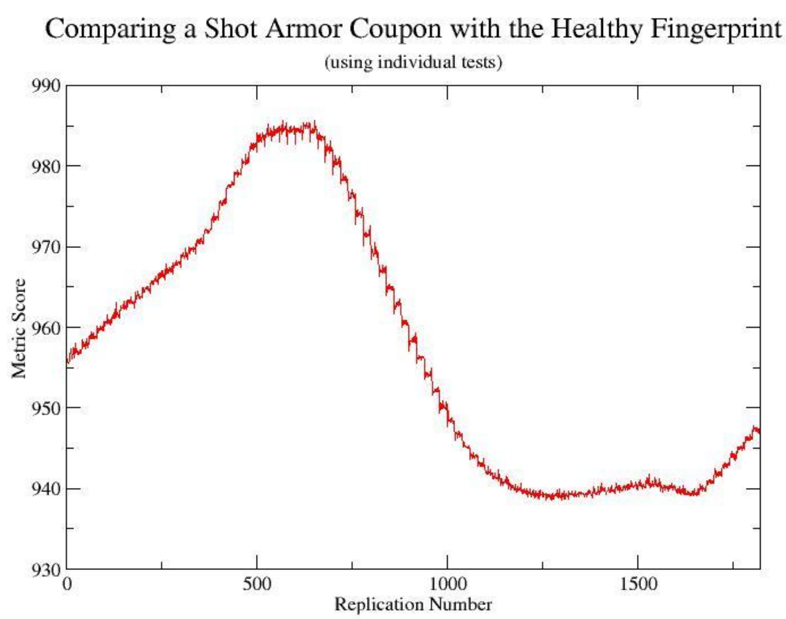

Figure 5: Variability of the Individual Tests of the Shot Armor as Compared to the Healthy Fingerprint

Since the healthy armor plate scores are all less than 3 and the damaged scores are greater than 935, the method clearly discriminates between healthy and damaged armor. The scores are computed by comparing the individual data sets to the fingerprint file. More information about computation of the scores may be found in reference [1]. By inspecting Figures 4 and 5 it is possible to see that the method still has sources of variability, and it is desirable to eliminate them if possible.

Removing an Additional Source of Random Noise

After some consideration it was decided that a lack of symmetry existed in the system used to evaluate subsequent data to determine if the armor had been damaged. Although an effort had been made to remove the random noise from the healthy data (by averaging several data sets and creating the fingerprint) no similar effort was made with regard to the new data used to determine armor health. (Armor health was evaluated by comparing the fingerprint database with a **single set** of new data.) The decision was made to create an additional fingerprint database from new data. Then this new database could be compared with the healthy one using calculations which are analogous to comparing the healthy database to a single file.

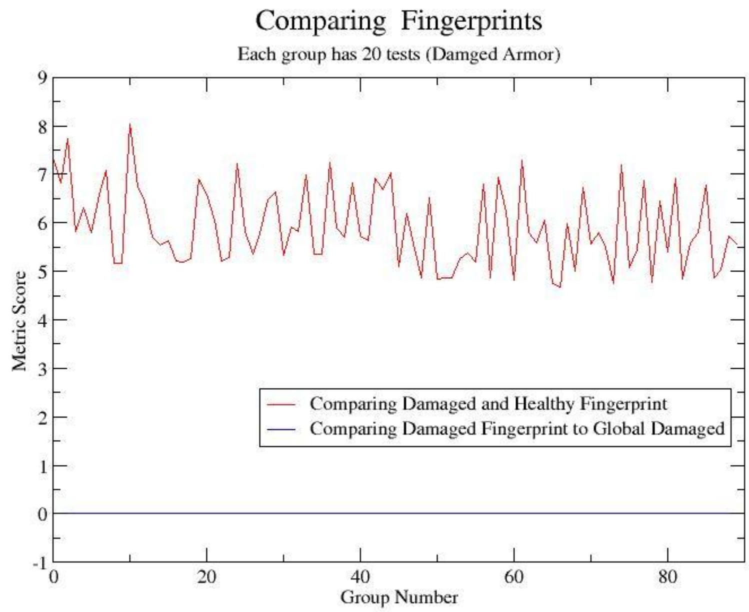

Figure 6: Variability of the New Fingerprint Databases of the Shot Armor as compared to the Healthy Fingerprint

The data in Figure 6 was created as follows: Data was collected every 15 minutes over several days. Each group of data consists of 20 tests that were collected over a period of several minutes. The red curve shows the comparison between the healthy fingerprint database and each damaged fingerprint database created from 20 tests (one group of tests). An interesting fact is that the red curve doesn't exhibit periodicity in Figure 6 as compared to the analogous curve in Figure 5. Instead the curve appears to have random noise about some average value. The blue curve compares the same damaged fingerprint databases and the global damaged fingerprint database created from 1800 tests (all 90 groups). The blue curve shows that the difference between the local databases and the global one is almost 0. It is difficult to see the variability in the blue curve because of the scale in the Y axis in the graph. In Figure 7 the new scale in the Y axis shows how close the data is to 0.0.

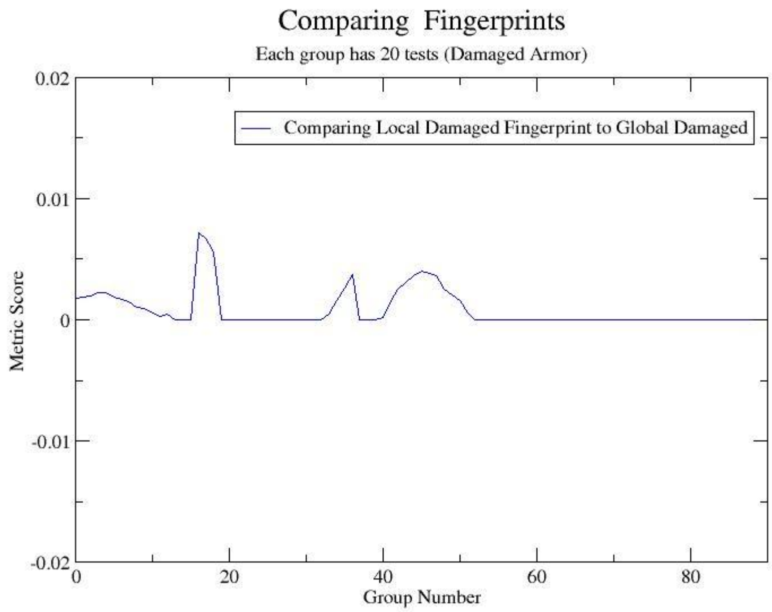

Figure 7: A Close-up View of the Variability of the Local Damaged Fingerprints when Compared to the Global Damaged Fingerprint

In Figure 6 and 7 the global fingerprint was developed by using 150 replications of data collection from the undamaged armor specimen. Figures 8 and 9 show the results of using much less data, i.e. 50 tests instead of 150 to produce the global fingerprint. As can be seen in Figure 8 the curves which compare the local fingerprints with the global fingerprints have very similar shapes, the only difference is a slight one in magnitude of the response. Figure 9 shows that there is no noticeable difference in creating a database from 50 files or 150 files. This is in agreement with general theory that says that if you have 30 or more replications of independent random variables you will get a good distribution which closely approximates a normal distribution. The only caveat is that the data must be collected in such a way that all environmental factors that affect the results are considered. They may include temperature, humidity and other factors.

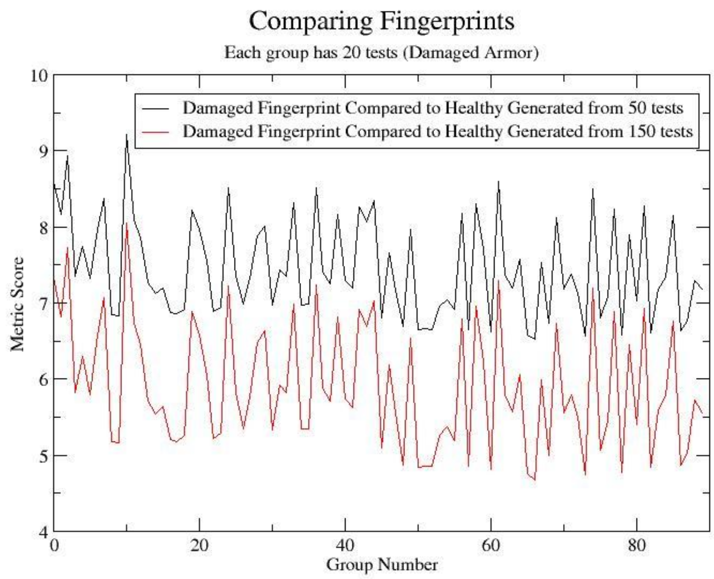

Figure 8: Comparing the Local Damaged Fingerprints to two Versions of the Global Healthy Fingerprint

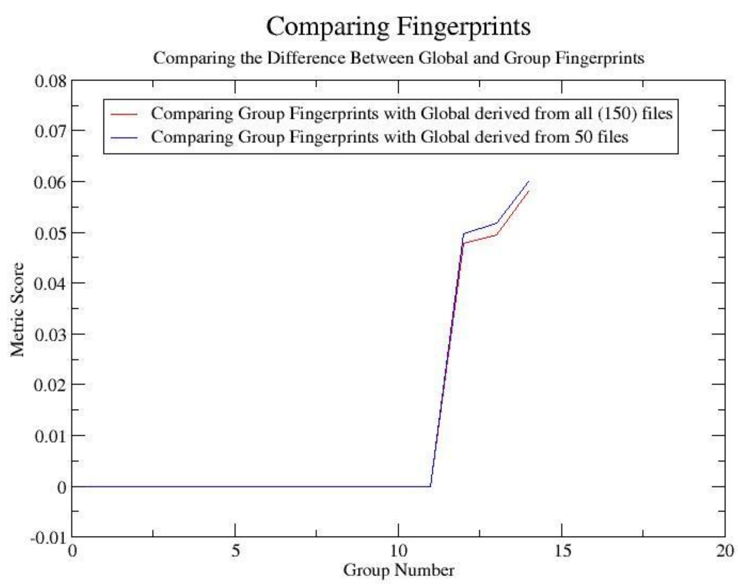

Figure 9: Comparing Global and Group Fingerprints using all the Data or a Reduced Set

NDE for Glass Armor

A Description of the Armor

The second application is NDE for armor which consists of glass plates. To protect the glass plates from chipping due to road hazards when mounted on a vehicle, the plates are inserted in a plastic box to prevent movement. The plastic box is then enclosed inside a metal box. Figure 10 shows some of the glass plates and Figure 11 shows the plates inside a plastic box. Figure 12 has an image of the metal box. The standard way to inspect the armor inside the metal box is to remove the metal box from the vehicle and X-ray it. This is very time consuming and expensive. An alternative method which is quick and inexpensive has been developed. It is based on the fact that if light is shined through glass the pattern of dispersion of the light changes if the glass becomes cracked.

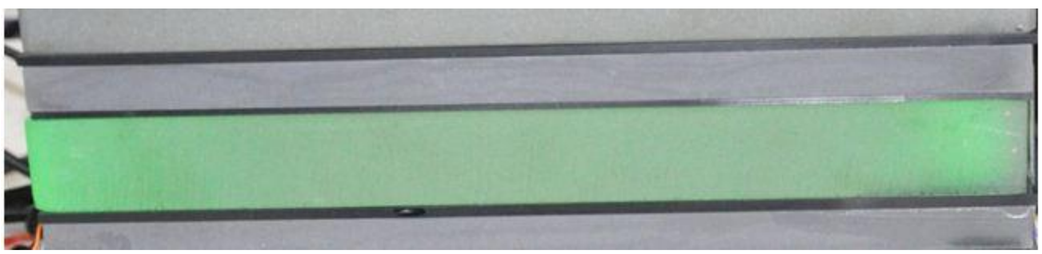

Figure 10: Glass Plates with one Layer Illuminated

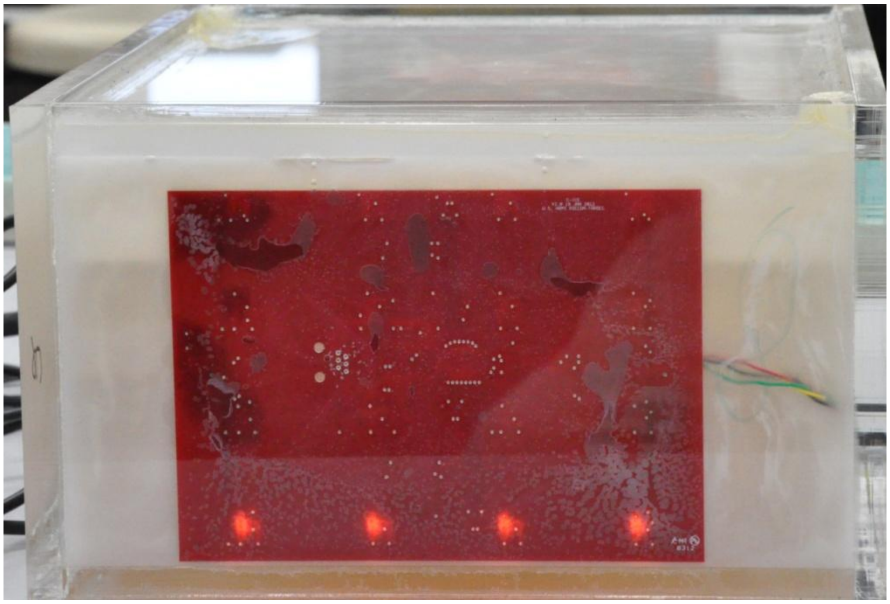

Figure 11: Glass Plates in a Plastic Box with an LED Circuit Board

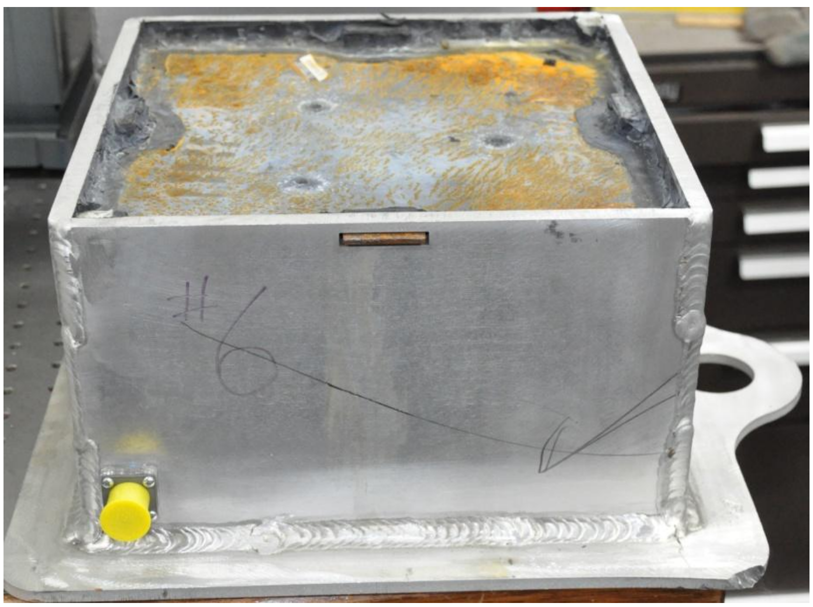

Figure 12: The Plastic Box is inside A Metal Case

The Testing Method

Because the armor is encased in a metal box no light can penetrate the box. However the new NDE method is based on internal light transmission from Light Emitting Diodes (LED’s). The solution to this problem is to integrate the testing apparatus inside the armor. This can be accomplished by inserting two circuit boards of LED’s on opposite sides of the plastic box which is inside the metal box. Each circuit board contains 4 rows: One for each layer of glass in the plastic box. Each row contains 4 LED’s for light transmission and 4 phototransistors to measure the light that is received on the opposite side of the box. This provides redundancy in the system since we get 2 sets of measurements for each layer, one from each side of the board. Each layer of armor can be considered by itself since there are opaque layers between the glass layers so that light can’t be transmitted between the layers. Each layer of LED’s and the corresponding phototransistors on the opposite board are activated one at a time.

Details of the Data Collection

The details of the data collection are identical for each layer, so it is sufficient to consider one layer, say the top layer. Each of the 4 LED’s in that layer is activated one at a time. When an LED is activated, the 4 phototransistors on the opposite side measure the intensity of the incident light, and the values are recorded. Therefore we get 4 readings from each phototransistor from each of the 4 LED’s for a total of 4x4=16 readings per layer per board. Since we have 2 boards we have 2x16= 32 readings per layer for a total of 4x32=128 readings per data replication. As in the previous example, 30 or more sets of data are collected and the averages and standard deviations are stored for each of the 128 variables. Since each layer is considered separately it is only necessary to deal with the 32 variables for that layer.

For each of these 32 variables we form a set of Z_i scores as in equation 1, for i varying between 1 and 32. By taking 25-30 sets of data when the armor cube is known to be healthy, a fingerprint database can be created which represents the status of the cube layer when it is known to be healthy. An armor cube was tested 20 times and a cube fingerprint database was created. Figure 13 shows the results of comparing each individual trial to the fingerprint database before the cube was subjected to a ballistic event. There are 4 lines in the graph since the results of each layer are reported separately. There is some variability in the scores but the maximum score is quite low.

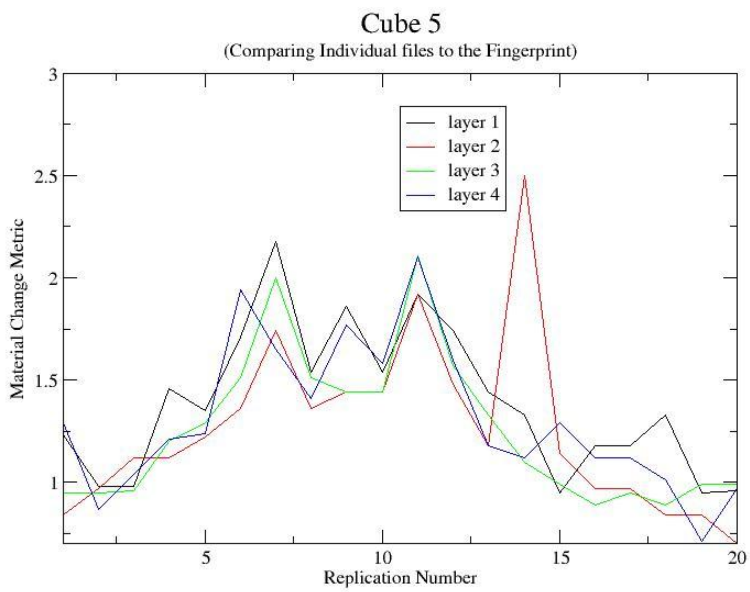

Figure 13: Comparing Individual Files to the Fingerprint

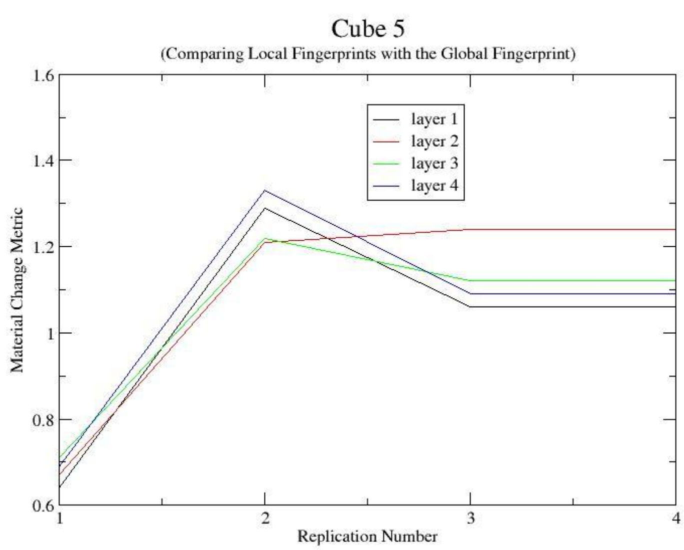

Figure 14: Comparing Local Fingerprint Files to the Global Fingerprint

The data in the plot in Figure 14 were produced as follows: The 20 sets of data that were collected when the cube was healthy were divided into 4 groups of 5 sets each. In these groups a local fingerprint database was created, and then these local databases were compared with the global one that was created from all the data. By comparing Figures 13 and 14 we can see that the variability and maximum scores have both been reduced.

After collecting the healthy data the cube was subjected to a ballistic event after which new data from the cube were collected. Figure 15 shows the results of comparing the individual files collected from the shot cube with the healthy cube fingerprint database. Figure 16 shows the results of creating local fingerprint databases from the shot cube data files and comparing them with the healthy cube database.

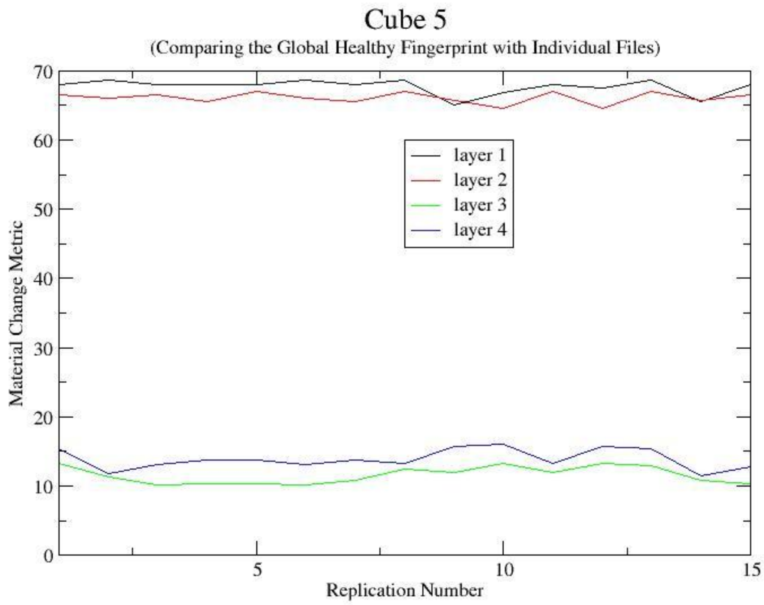

Figure 15: Comparing Individual Files (after ballistic event) to the Global Fingerprint (Healthy)

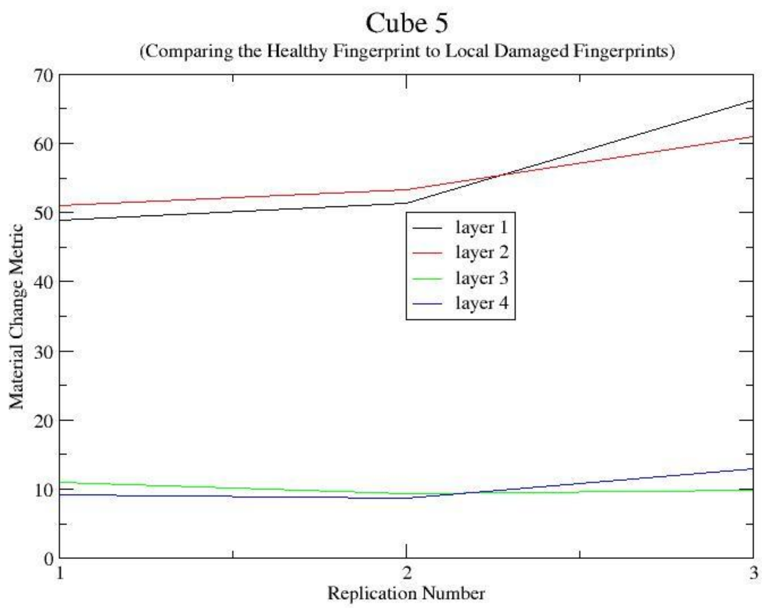

Figure 16: Comparing Local Fingerprint Files (after ballistic event) to the Global Fingerprint (Healthy)

An analysis of Figures 15 and 16 shows that similar results are obtained by comparing individual files or local fingerprints to the original global healthy fingerprint database. However, by using local fingerprints we get less variability. Both Figures indicate that layers 1 and 2 are cracked (metric change values greater than 30, the threshold) while layers 3 and 4 are hardly changed. This analysis was verified by X-raying the cube. Since the cube was shot from the top it is not surprising that the top layers sustained damage while the bottom layers did not. All 7 cubes were subject to various events including ballistic events and being dropped from a height of 10 feet. In all cases the results of the method using the embedded circuit boards agreed with the independent X-ray findings. In one particular case the circuit board method gave ambiguous results, but so did the X-ray.

The New Paradigm

After describing the two examples (ceramic and glass) armor health monitoring methods, which appear to be quite distinct, we shall show that they are really quite similar.

1. The critical idea in the new paradigm is to measure the health of an object in an indirect manner which is non-destructive.
2. The first step is to find some measurable aspect of the object which is highly correlated with its health or functionality and is repeatable
3. Collect repeated measurements of the object when it is known to be healthy and store the means and standard deviations of these measurements in a database.
4. At some time in the future the health of the object can be measured by creating a new database of current observations and comparing it with the original healthy database.
5. The validity of the method needs to be verified by a more traditional means of measurement

How Our Two Examples Fit the New Paradigm

1. What is Measured
    - Ceramic Armor

    We measure the energy transmitted through the armor by means of ultrasonic vibrations of different frequencies.

    - Glass Armor

    We measure the dispersion of light through the glass plates.

2. How are the measurements collected
    - Ceramic Armor

    PZT transducers are used to both generate and receive the ultrasonic vibrations. Ultrasonic vibrations of different wavelengths are used to collect sufficient data to distinguish between healthy and damaged armor panels. Usually only a pair of PZT transducers is used, but the data is collected from 1 to 200 kHz at 1 kHz intervals. Usually, if we take the top 20% of frequencies based on energy content (roughly 40 frequencies out of 200) we get 90% of the energy content in the system. (Energy content is measured by the root mean square of the signal). By doing this we get roughly 40 critical variables per armor plate.

    - Glass Armor

    We measure the attenuation of light through the glass plates. Only one wavelength of light is used. To get sufficient data each layer has 4 LED's on one side of the cube and 4 photo transistors on the opposite side. The LED's are energized one at a time, and the light received by the 4 opposite photo transistors is stored. This gives 16 readings from one side of the board and we also obtain 16 readings from the other side. From the other side of the board we also obtain 16 readings for a total of 32 readings per layer.

3. Collect repeated measurements of the object to create the original database.
    - This process is the same for both the ceramic and the glass armor. If possible the measurements should be conducted in such a way as much of the variability that will occur due to environmental conditions when the product is used will happen during the testing. This is especially important for getting accurate standard deviations for the variables.

4. At some time in the future the health of the object can be measured by creating a new database of current observations and comparing it with the original healthy database.
    - This is analogous to gathering the measurements for the initial healthy database. It is preferable to collect several measurements to create a new database of current observations to compare to the original healthy database. As has been shown in the previous examples, comparing databases usually gives less variability (i.e. more repeatable results) than comparing a database to a single file. This results in a more stable metric.

5. Since the methods we have described are purely statistical, (i.e. they only measure health indirectly), they must be verified or calibrated by some other method. In the case of the ceramic armor the method was verified by both visual inspection and X-rays. The glass armor was verified by using X-rays.

Similarities between the Two Examples

Number of Variables Used

The glass armor consists of 4 glass layers and each layer is evaluated separately. Although the system has 128 total variables there are only 32 variables per layer. This is analogous to the ceramic case where 200 frequency responses are recorded however; usually 40 or less are significant in the calculation.

Benefits of the Method

The method does not require X-ray testing and facilitates real-time non-destructive health monitoring of ceramic and glass armor.

Independent of Manufacturing Variability

- We evaluate health by comparing certain current characteristics of an armor object by comparing them to these characteristics when the object was known to be healthy. This greatly reduces the need to reduce manufacturing variability since each part is being compared to itself at some previous time. Any process which uses a CAD model or a "golden part" for health monitoring relies on making sure that manufacturing variability is minimized to produce accurate results.

Versatility (No Part Model Required)

- Since the method uses no specific properties of the part being tested it is quite versatile. For example, if a large ceramic armor panel needs to be tested it is possible to use more than one pair of PZT transducers. If a glass armor set has more than 4 layers this is easily accommodated. If the individual layers grow in size it is possible to use more LED's and photo transistors per layer

Ease of Computation

- The computations required for the method are mostly the means and standard deviations of the data. This requires very little CPU computations and minimal memory requirements. Both applications have been ported to small micro computers. The data computations require only a few seconds.

Ease of Interpretation of the Results

- It is relatively simple to quantify the results of the metric using the following procedure:
    - Collect 10 to 20 specimens of healthy armor and test each one 20-25 replications. Let M represent the maximum metric value obtained from these measurements.
    - Now subject these specimens to a minimal amount of damage, and let N represent the minimum metric value obtained from these measurements.
    - Set T= (M+N)/2 to be the threshold value. Then Metric values greater than T represent damage, while those less than T indicate a healthy part.

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