A Method and Device for Health Monitoring of Glass Armor

By Thomas J. Meitzler*, Thomas Reynolds+ and Samuel Ebenstein+

ABSTRACT

A method and device for health monitoring of glass armor plates is described. Because the armor plates are enclosed in a steel box for protection, visual inspection can't be used. Traditional inspection requires dismounting the armor from the vehicle, and then using a high energy X-ray machine. Removing the armor from the vehicle is very time consuming and labor intensive, and the X-ray machine is expensive and often not available in the war theater. Our solution to the health monitoring problem is to embed the inspection device inside the steel enclosure. The inspection device uses LED's to transmit light through the glass and photo transistors to measure the amount of light received. A relatively simple algorithm is used to compare the current amount of light received with that when the cube was healthy. The system is very easy to use, is not labor intensive, and gives a status report in a matter of seconds.

Keywords: glass armor plates, nondestructive testing, damage detection, embedded inspection device.

Introduction

The U.S. Army has developed a new kind of armor protection for vehicles which consists of several glass plates. The plates are inserted in a plastic box and epoxy material is used to prevent the plates from being damaged by moving inside the box. To prevent the plates from chipping, the plastic box is encased in a steel box. The typical NDE procedure for this type of armor is to check for cracked plates using a high intensity X-ray machine. However the X-ray equipment is relatively expensive and usually not available in theater. Dismounting the cubes from the vehicle for the purpose of inspection is also inconvenient and quite labor intensive. We have developed a new method of NDE which is inexpensive, available everywhere (the testing apparatus is inside the cube) and the output is readily understandable.

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General Description of the Technique

The glass plates are transparent, and light is readily transmitted through them. We noticed that light waves that are transmitted from one side of a glass layer to the other are diffused and scattered if the layer has a crack and that the light fall-off changes drastically at the crack interfaces. In Figure 1, LED's were used to illuminate the top two layers of the three glass layers of the opposite side. (The bottom layer is dark because it wasn't illuminated)

Figure 1 LED's illuminate top two layers of a piece of glass armor.

In Figure 1 the light intensity is relatively uniform in the top layer; however in the second layer there is a sharp discontinuity in the light intensity in roughly the middle of the layer. (The second layer has a crack in it.) We measured the light output with photo transistors at five equidistant locations along the top two layers. Then we calculated delta, the maximum change in slope in each layer.

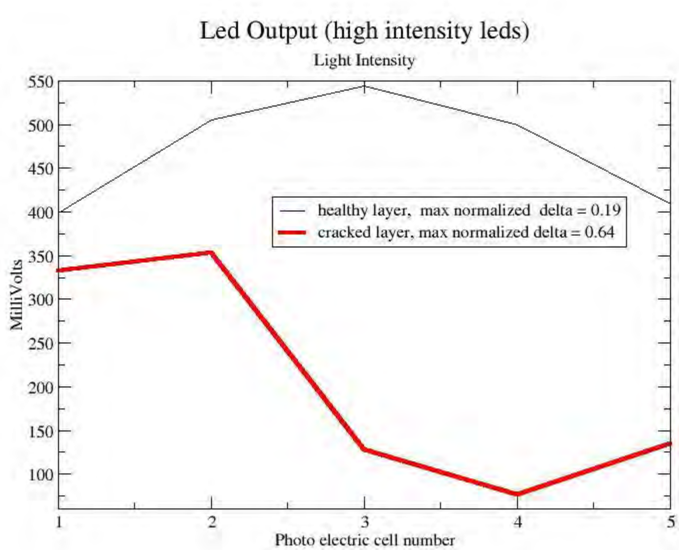

Figure 2 LED output per layer of the glass cube

Figure 2 shows the change in light intensity in moving from each photo transistor to the next one. Based on the sharp change in photo intensity in layer 2 as compared with layer 1, we believed that this property could be used to distinguish between healthy and damaged layers. We built two “identical cubes” and installed LED’s (for light generation) on one side of the cube and photo transistors on the other side to measure the transmitted light by each layer.

Verification of the Original Method

We cracked one of the cubes using a bullet. Then the glass plates, the LED’s and the photo transistors were placed inside a plastic box. An epoxy resin was used to prevent the contents of the box from moving . Unfortunately differences in resin flow and air bubbles made it quite difficult to distinguish between the healthy and the cracked cube based on the method described above. The differences in manufacturing variability in adding the resin caused the method to fail. Our method wasn’t sufficiently robust to accommodate slight variations in manufacturing. In order to overcome this difficulty we decided we needed to develop a new method which met the following criteria:

- A method that is less sensitive to manufacturing variability in building the cube.
- Doesn’t require strict manufacturing tolerances or an “ideal part”.
- Requires very little data collection and computation.
- All computer components could fit in a 6 mm space which can be inserted between the armor plates and the plastic cube containing the armor plates. (The plastic cube is inserted inside a steel box in a later procedure).
- The method should be robust.
- The data analysis should be quick and easy to use and interpret.

Figure 3 a Top View of a healthy Armor Sample

3b Top View of a damaged Armor Sample

The following diagram shows the hardware configuration

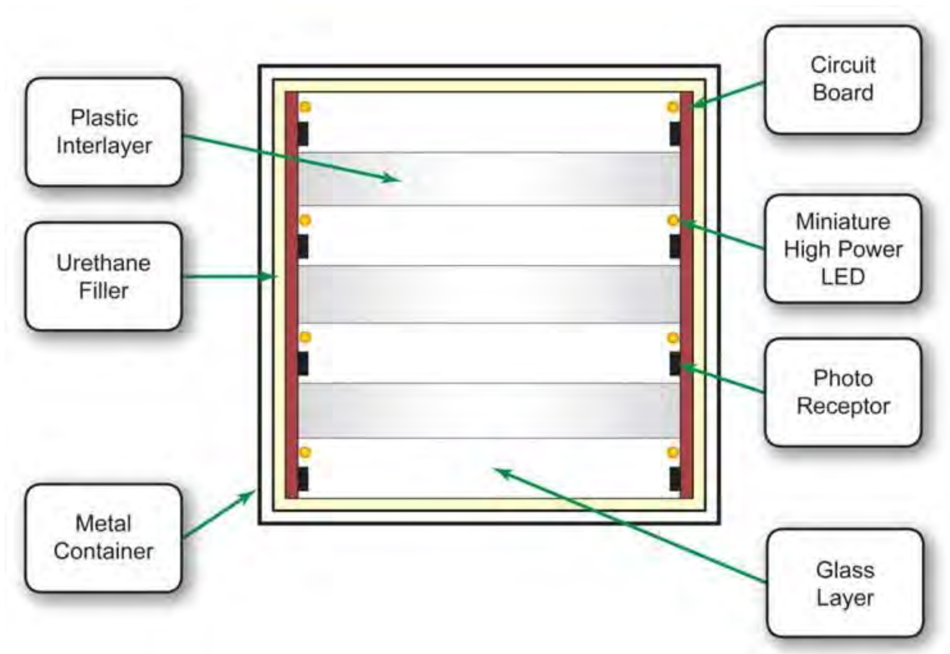

Figure 4 Hardware configuration of the inspection system

As shown in Figure 4 the cube has 4 glass layers, and these glass layers are separated from each other by plastic inner layers. The entire cube is encased in a plastic box. A Urethane filler is used to prevent the glass layers from movement in the box. The plastic container is then encased in a steel container. The circuit board needs to fit in the 6 mm space between the glass plates and the plastic box.

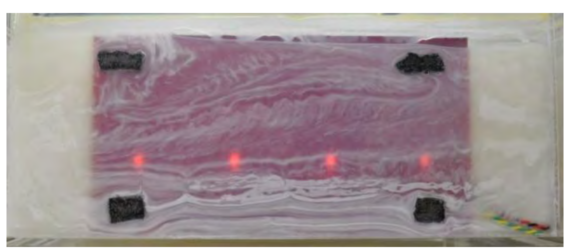

Figure 5 Image of the circuit board (side view)

Figure 5 shows a side view of the circuit board which is only a few millimeters thick and has been inserted inside the cube. Four LED's in one layer are lit, and they are clearly visible in this view.

Description of the Data Collection Apparatus and its Use

The cube contains two identical circuit boards which are placed on opposite sides of the cube. Each circuit board is aligned with the glass plates so that it has four LED transmitters and four phototransistors per layer. The LED's on one board transmit light that is received by the phototransistors on the board on the opposite side. By using two boards we have redundancy built into the system so that if a LED or phototransistor is defective on one side of the board we have an identical device on the opposite side. Note: the spectrum of the LED's was analyzed and shown to present a significant change from damaged to undamaged sample. The color of the LED's can be changed and tailored for various glass recipes.

Let us consider how the data is collected for layer 1 for one side of the cube. The other layers on the other side are similar. The first LED in layer 1 is turned on and the readings of the 4 phototransistors in layer 1 on the opposite side are collected by a 10 bit a/d converter and stored in computer memory. This process is then repeated for the other 3 LED's in layer 1. So we obtain 16 readings for layer 1 from one side of the cube, and similarly 16 readings from the other side of the cube. Since each board has 4 layers we collect 64 readings from each board, for a total of 128 readings from a single test of the board. Because there is some random noise in each reading, a procedure is needed to remove this variability. One way to remove this noise and account for differences due to environmental changes is to create a database that will capture the status of the cube when it is known to be healthy (after manufacture and before it is fielded).

How the Database is Created

We need to create a database of measurements taken when the cube is know to be undamaged (right after manufacture) to use as a reference. These measurements are the light intensities as read by the a/d converter. We measure the cube repeatedly and take the average of the 32 readings over time and store the averages in 32 variables, 4 variables per layer, 4 layers per board, and a total of two boards. We also compute the 32 standard deviations for these variables. We repeat the testing under various ambient conditions to determine the average value for each variable, and the deviation in each variable. It may happen that we get a standard deviation of 0, since the phototransistors only produce values between (0-1023) because they are read by a 10 bit a/d converter. In this case or whenever the standard deviation is less than 1, we arbitrarily set it to 1. This set of 32 averages and 32 standard deviations is then stored in the cube in a non-volatile memory chip. If a phototransistor or LED is damaged during construction of the cube, this fact will implicitly be stored in the cube database, because it will automatically effect the averages and standard deviations associated with that particular phototransistor or LED.

Determining Cube Health

At some time in the future we wish to check if the cube is damaged, and to what extent. We test the cube once and we get 32 variables. We define a metric as follows: let $1\_ave_{i,j}$ represent the average of a photo sensor where i is the layer number $1 \le i \le 4$ and j is the sensor number, $1 \le j \le 4$. $1\_ave_{i,j}$ represents the averages for sensor board 1, while a similar variable $2\_ave_{i,j}$ represents the averages for sensor board 2. Now compute the metric value at i,j for all i,j pairs for board 1 as follows,

$m_{i,j} = |(1\_ave_{i,j} - x_{i,j})/1\_sdev_{i,j})|$ where $1\_sdev_{i,j}$ is the standard deviation associated with $1\_ave_{i,j}$ as computed above and | | is the absolute value of the variable. We can compute the max deviation for layer 1 as follows: for each layer from 1<=i<=4. max1,i = max(mi,1, mi,2, mi,3, mi,4), and we can compute max2,i in an analogous manner. If either max1,i or max2,i is greater than a threshold value we say that layer i is damaged. In practice a threshold value of 30.5, has distinguished between healthy and damaged layers. The next section shows how to calculate the threshold.

Calculation of the Threshold to Distinguish between Healthy and Damaged Armor Layers

The calculation of the threshold that is used by the metric to distinguish between healthy and damaged armor layers is quite straightforward.

- First we compute the maximum metric value obtained for healthy armor layers. To obtain this value it is necessary to have a reasonable sample of undamaged armor cubes (10 or more) to get a good estimate for this value.
- Next we compute the minimum metric value for damaged armor layers, using 10 or more cubes with damaged layers.
- The threshold is then set to be the average of the two values above, i.e. a value half way between the maximum and minimum values.

From our limited data, we only have two cubes one damaged and one healthy, we got the following values $max_{healthy}$=6.0 and min $_{damaged}$ =55.0 which gives a threshold of 30.5.

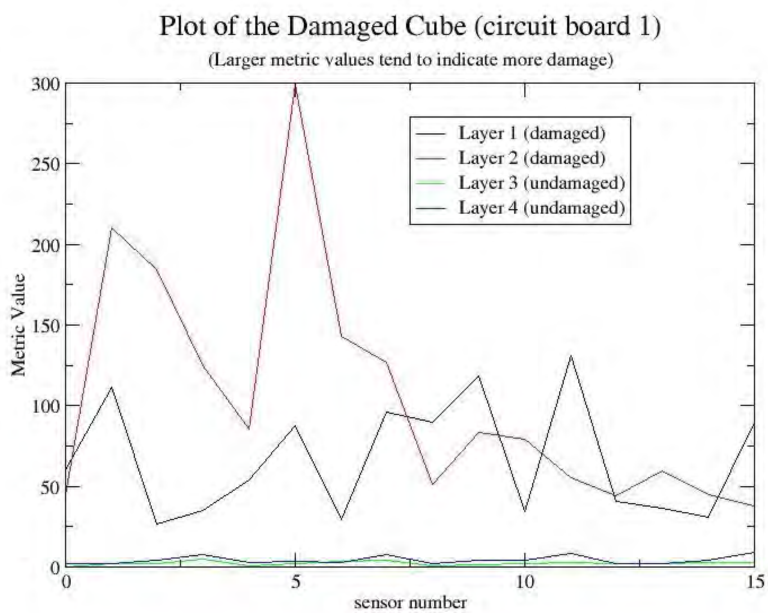

Figure 6 Plot of the Damaged Cube

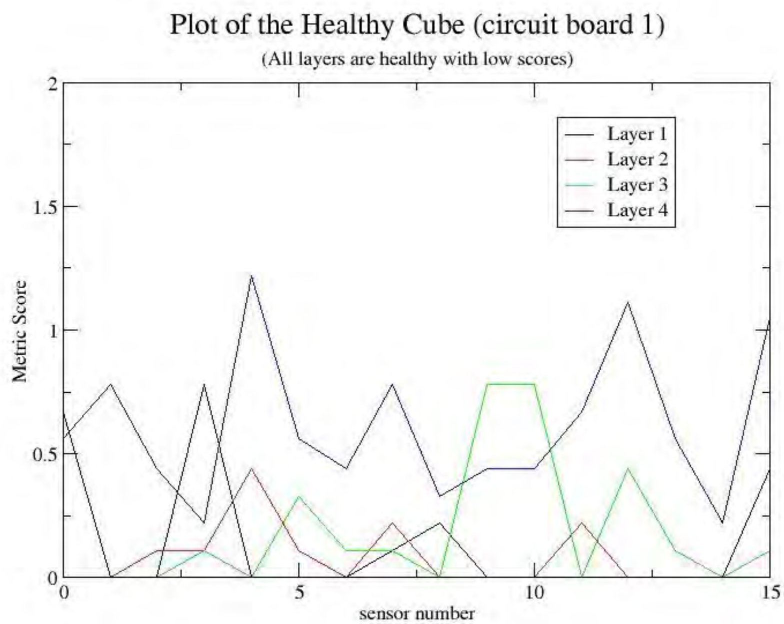

Figure 7 Plot of the Healthy Cube (circuit board 1)

Figure 6 shows the metric values for the damaged cube. Since there are 4 LED's per layer and 4 photo transistors we have a total of 16 readings per layer. Layers 1 and 2 have significantly high readings than layers 3 and 4. This is due to the fact that the cube was hit with a ballistic round which penetrated the top two layers, but had little effect on the bottom two layers. Figure 7 looks somewhat similar to Figure 6 in terms of variability, but there is more than two orders of magnitude difference in the scales on the two graphs. (Figure 6 has a scale of 0 300, while Figure 7 has a scale of 0 to 2). A comparison of Figures 7 and 8 shows that the values from circuit board 1 and 2 are quite similar. The scores from circuit board 1 and 2 are not identical because of slight differences in the positions of the LED's and phototransistors on the two boards.

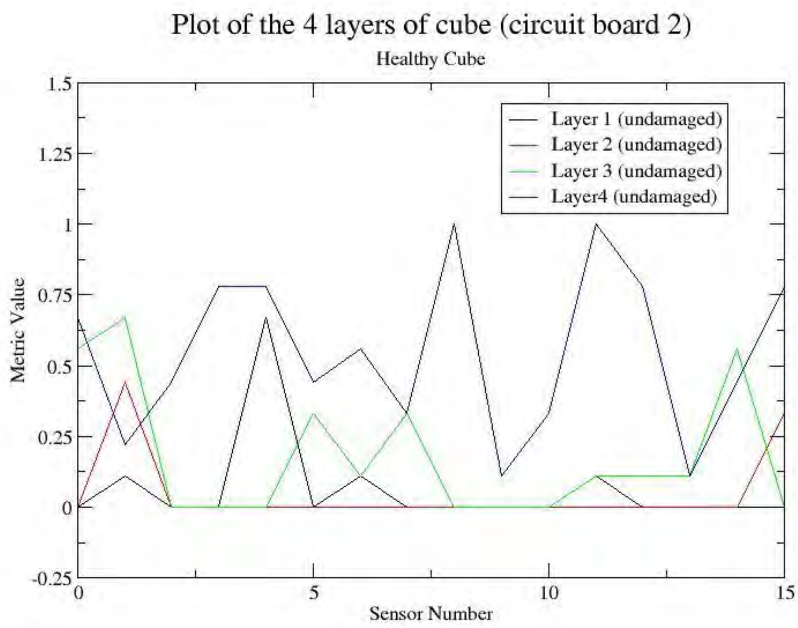

Figure 8 Plot of the Healthy Cube (circuit board 2)

Results of Testing Two Cubes (one circuit board)
Cube 1 (before and after Damage)
Cube 2 (Two Repetitions) (

Cube 1 (before damage)

Layer Number	Metric Score
1	1.72
2	1.53
3	2.09
4	2.16

Cube 2 (trial 1)

Layer Number	Metric Score
1	0.89
2	0.56
3	0.67
4	1.22

Cube 1 (after damage)

Layer Number	Metric Score
1	205.88
2	299.74
3	4.35
4	5.35

Cube 2 (trial 2)

Layer Number	Metric Score
1	0.89
2	0.67
3	0.89
4	1.44

1

Figure 9 Comparing the Healthy and Damaged Cube Scores (Two Repetitions)

Based on the threshold of 30.5, it is clear that Cube 2 is healthy, and Cube 1 is damaged. In addition, only the first two layers of Cube1 are damaged based on the layer scores. One of the design requirements for our system was that the output should be easy to interpret. To achieve that goal a graphical interface was designed for the system so that it would be quick and easy to determine the health of each cube layer.

Figure 10a System Output from a Healthy Armor Cube

Figure 10b System Output from a Damaged Armor Cube

Figure 9 shows that the system is quite repeatable for the healthy cube. It also shows that the damage to the upper two layers of the damaged cube has caused some change in the values of the lower two layers that weren't damaged. Figures 10a and 10 b show the difference between a healthy and a damaged cube. In Figure 10a all four layers of the cube are green which indicates that the entire cube is healthy. In Figure 10b the top two layers are red which indicates they have been damaged. The bottom two layers are green so they are considered healthy.

Conclusion

An embedded, nondestructive apparatus and methodology has been developed for armor composed of glass layers. The method and apparatus was developed because the only previous method of inspection required the use of a high power X-ray machine. It was expensive and usually not available in the war theater. The method presented in this paper uses off the shelf components and a rather simple algorithm which doesn't require extensive computation. LED's are used for light generation and photo transistors to measure the amount of light transmitted. The apparatus is installed when the armor is manufactured before it is encased in a steel box. The system output is presented in a simple easy to use format which tells the user if the armor cube is healthy or damaged. If damage has occurred, the user is informed of which layers in the cube are damaged. In this case, the spectrum of light was in the visible band, though it need not be since there exist infrared photodetectors.

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