

## Chapter 8: CONCLUSIONS AND RECOMMENDATIONS

The impedance-based health monitoring technique was applied to structures, simple and complex, ranging from metal to composite-concrete combinations. Concepts that directly applied to the technique itself, such as voltage levels, test wire length and effect of ambient conditions, were also studied.

Voltage levels used in the interrogation of PZT's and how these levels affect damage detection capabilities was studied. The issues dealt with were the sensing range of PZT's, damping effects and the appearance of the frequency response curves at various voltage levels. It was found that the use of low voltages (lower than 0.01 V) resulted in random variations in the impedance signature. With decrease in voltage (from 1.0 V, 0.5 and then to 0.1 V) the ability to detect damage also decreased. This reflects on the sensing area of the PZT: with decrease in voltage level, there is a corresponding decrease in the sensing area of the PZT. It was also determined that with change in damping, varying the voltage level did not have an observable impact on the ability to detect damage. It appears that with change in structural damping, change in voltage levels does not alter the ability to detect damage. However, it must be noted that the amount of change in damping that was induced in the experiment conducted is minimal for the structure in question. Hence, this result is not entirely conclusive. In conclusion, it can be stated that the use of very low voltages ( $< 0.01$  V) should be avoided. Increase in voltage level (within limits) increases the ability to detect damage.

The effect of the length of the test wire on damage detection capabilities was studied. Its effect on the frequency response was seen. From the frequency response charts it was found that there was a uniform vertical upward shift, for both the R and X functions, with increasing test wire length. This shift was more at the base of the curves than at the peaks. The critical aspect of the frequency response charts is that they establish that there is no change in the essential signature pattern of the curves. Damage

metric charts, based on both the 'R and X vs. Frequency' plots revealed that with increase in test wire length there is a decrease in the metric values. This implies that with increasing test wire length, the ability to detect damage decreases. However, the decrease in damage metric values is small; hence, for the test wire length considered (30 m) there is no real cause for concern. A line plot of damage metric values versus test wire length revealed an almost linear decrease of metric values with increase in test wire length. It can be concluded that although there is a decrease in the ability to detect damage with increasing test wire length, for wire lengths under 30 m, there is no real cause for concern. It is however suggested that to increase the sensitivity to detect damage, the test wire length must be kept as small as is practically possible.

A relatively complex truss structure is analyzed to determine the effects of external boundary conditions, ambience and other structural variations on the impedance-based health monitoring technique. The ambient conditions imposed are the addition of weight at two separate points on the structure, vibration of the structure and application of heat. The technique is able to distinguish 'damage' from normal, everyday structural and ambient variations, *to an extent*. It can be stated that external ambient conditions, *do* cause variations in the impedance signature. However, the impedance technique is able to distinguish and detect damage, *within limits*. A more complete understanding of the variation of the impedance signatures (with factors such as temperature), and application of signal processing methods would aid towards a more effective damage detection technique. It was also concluded that the measurements do vary over time, but the variation is relatively small (with reasonably small ambient variations); the measurements were found to be repeatable. The damage metric charts proved that the impedance technique could determine damage over time; when the baseline reading is taken at some point of time, and damage was inflicted to the structure at a much later time, the technique could be used to detect and determine this damage.

The effect of interrogating multiple piezoelectrics (multiplexing) to detect damage was investigated. An aluminum truss structure was used as the test rig. It was noted that multiplexing the PZT's did not compensate on the ability to detect damage. This method does however result in the loss of ability to predict the *location* of damage. Also, due to the averaging effect that occurs when the signals from all 4 PZT's are being analyzed at one time, there is a decrease in the sensitivity to detect damage. Hence, multiplexing the PZT's does decrease the ability to detect small changes in the structure. For maximum sensitivity and ability to detect damage, the PZT's should be interrogated individually. Analysis of the structure when the PZT's are multiplexed takes a fraction of the time when compared to them being individually interrogated. Hence, for applications with large structures, where the stress is on quick analysis, without too much weight on the location of the damage or small changes in the structure, multiplexing the PZT's is highly recommended.

A massive, circular, three inch thick steel steam header was analyzed to determine the applicability of the impedance-based health monitoring technique on large, dense structures. Practical issues such as positioning of the PZT's, optimal frequency range and the extent of damage that could be detected were the issues that were dealt with. It was concluded however, that no definite trend or pattern could be established in either the frequency response plots or the damage metric charts. From the analysis of the metric charts, no obvious advantage could be identified as to the positioning of the PZT on the flat versus the circular face. However, on comparison of the frequency response charts from the two PZT's, the PZT on the flat face appeared to have a more active impedance signature than the PZT on the circular face. The ability to detect the four levels of damage (drill 1 to 4) was studied using the damage metric charts. It was found that the results were not consistent and hence were inconclusive. There was however, a general trend of increase in metric values, with increase in the damage level for most of the frequency ranges. It must be noted that the test structure is a large, dense and an electrically continuous object. Even though the PZT's are mounted in the vicinity of the

damage, the extent of damage is so small (compared to the size of the test structure) that accurate determination of this damage is difficult. A more detailed study was done on the same header by Dominic Ciminello and Frederic Lalande [25] in an attempt to fully understand the mechanisms of health monitoring on this structure. However, this research also ended in inconclusive results. Health monitoring of such a massive structure, while it is in service, would indeed be a very difficult proposition. A more detailed experimental analysis would need to be done in order to arrive at any conclusive results.

In the demonstration at CERL, small, reinforced masonry walls were diagonally loaded to failure. Four identical masonry walls, each of them with a different type of composite reinforcement were considered. Each of the walls measured approximately 4'x4'. The structures were loaded in steps and PZT's were used to interrogate the structure at each stage to determine incipient damage (in particular, delamination effects).

The impedance-based health monitoring technique was used to detect real-time damage in composite reinforced concrete/masonry walls. The proof-of-concept demonstration provided an insight into the critical aspects of differentiating damage due to load and delamination. There is a marked difference between the signature pattern for the frequency response curve from the PZT's for loading and delamination. A complete change occurs in the signature pattern of the curve over the entire frequency range when the damage is due to delamination. Under loading effects however, the damage is distant as compared to delamination (which occurs right under the PZT's, between the composite material and the concrete surface) and hence there are only minor variations along the original (baseline) impedance curve.

The four masonry walls tested at CERL were successfully analyzed and the data collected from the PZT's was indicative of damage as and when it occurred. Data collected from the tests proved beyond a doubt the capability of this technology to detect imminent damage. The means used for the analysis of the data are frequency response

charts and damage metric charts (which are a quantitative summary of the frequency response charts). However, two factors proved to be a hitch in predicting damage *before* it was physically visible. The main reason was that the loading was carried out in discrete blocks. Hence, if damage occurred *while* the load was increased from one step to the next, it was detected *after* the crack was physically visible. The reason contributing to this effect was that the data acquisition system used has a minimum time requirement to obtain a set of readings from all the attached PZT's. The time required for a complete set of data to be acquired was more than the time taken to increase the load from one step to the next.

Twice during the testing, a PZT picked up damage to the structure while the load was being increased and the damage metric chart on the computer screen clearly indicated that there was delamination and hence imminent cracking in the wall. Seconds later, the crack would be physically visible. This is ample proof that if the load was increased in smaller steps (as would probably happen in real life applications) this technology would be very successful in picking up delamination between the composite material and the concrete surface, well in advance of cracks appearing in the wall.

Several conclusions and recommendations are arrived at:

In the case of health monitoring of the composite reinforced masonry structures a critical issue is the importance of delamination of the composite from the masonry surface to the health of the structure. The impedance technique can detect this kind of damage very well; however, in a real life application, delamination may not be the only cause for failure. The capability of this technique to detect such changes in the structure needs to be tested

The long term reliability and durability of the piezoelectrics and the effects of aging, fatigue and depoling in these actuators need investigation.

Issues related to the automation of the data acquisition process such as determination of the threshold level of critical damage in a given structure need to be further understood. The possibility of false alarms with the use of an automated software package and the inherent costs involved is also an issue that needs further investigation.

The key to the effective implementation of the impedance based health monitoring technique is the magnitude of the damage metric for a given change in the structural integrity. At this point, the magnitudes of the metric and change in structural properties are not correlated. An important question that needs to be dealt with is: 'For a given value of the damage metric, what is the extent of damage in the structure?'

The sensitivity of this technique to local changes is very useful in most cases; however, this effect does blind the sensor to any activity occurring at a distance. A good example of this is the composite-concrete combinations. The technique is extremely sensitive to the local change of delamination and is almost completely insensitive to any other changes. If the critical mode of failure for this structure was not delamination, effective implementation of this technique would then require more investigation.

In conclusion, this work provides an experimental study of the implementation issues related to the impedance-based health monitoring technique. The actual physics behind the phenomena still need extensive investigation.