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NCHRP IDEA Program

Smart Installation and Monitoring System for Large Anchor Bolts of Support Structures Made with 3D Printing Enhancement

Final Report for
NCHRP IDEA Project 196

Prepared by:
Dr. Jay Shen
Iowa State University

November 2022

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Prepared for

The NCHRP IDEA Program
Transportation Research Board
National Academies of Sciences, Engineering, and Medicine

by

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November 11, 2022

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Acknowledgement

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Glossary

RFRD	Radio frequency readout device
DTI	Direct Tension Indicator
PLA	Polylactic Acid
MnDOT	Minnesota Department of Transportation

EXECUTIVE SUMMARY

Anchor bolts, as a connection system used at the base of most highway support structures, commonly suffer from loosening effects that may impose high risk on collapse of these support structures. The current inspection method on loose anchor bolts only stops at the manual level. By punching the washers beneath the nuts with hammers, as shown in Figure S1 *(1)*, if the washer moves, then the bolts are considered loose.

FIGURE S1. Current "hammer pounding" inspection technique for loose anchor bolts

However, for each inspection team, there may be hundreds, or even thousands of structures using anchor bolts, with an average of more than 8 anchor bolts implemented at the base of each structure, the inspection work can be extremely time-consuming. Furthermore, when the washer moves under punching, the tension inside anchor bolts can be as low as less than 20% from the required value. In this case, the support structure can already have anchor bolts that have lost most of pretension from installation, thus, the stability of the supporting structures can be at great risk before inspection.

This project aims to develop a capacitance-based smart washer system that serves as an efficient way to monitor the tension inside the anchor bolts before the loose anchor bolts can cause severe stability issues. After several design trial and errors, the final prototype of the smart washer system consists of six components: a top direct tension indicator (DTI) washer, a middle smaller sized spacing washer, a bottom plain washer and a rubber ring as dielectric material, a couple of copper rings attached to top and bottom washers, and 3D printed polylactic acid (PLA) attachments as insulation layer, as shown in Figure S2.

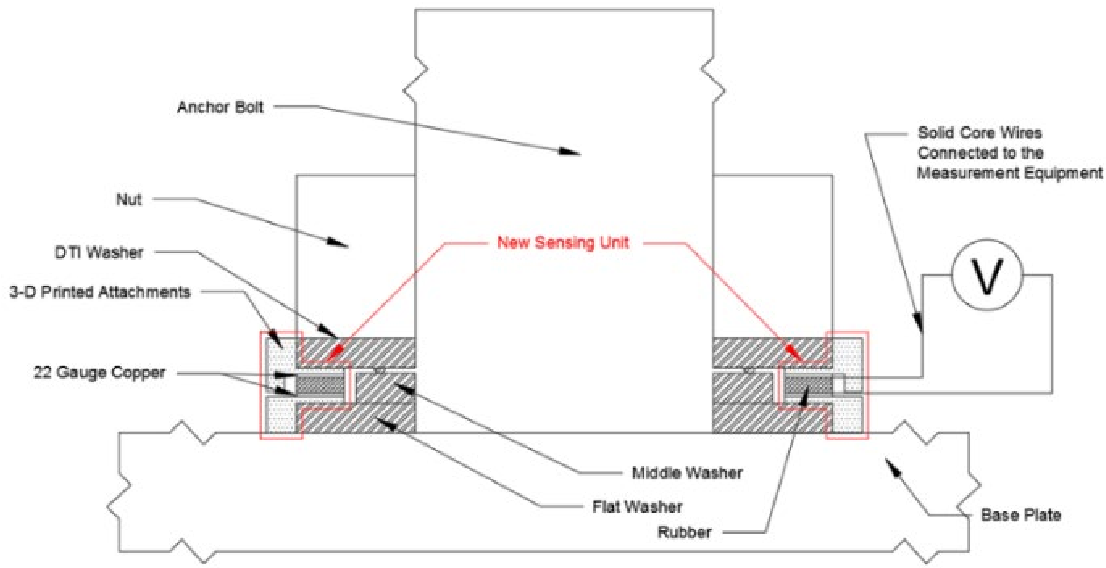

FIGURE S2. Design of smart washer system prototype

Stage 1 of the project was testing in the laboratory in order to develop a sensor prototype and a calibration curve to convert recorded capacitance values to tension inside anchor bolts. At first, several trial and errors were attempted on the design of the smart washer system, the first few designs revealed severe insulation problems, and after applying 3D printed attachments this issue was believed to be solved. The prototype of the sensing system was first tested on a single 2-1/2" diameter anchor bolt, by recording force, displacement and capacitance, a calibration curve on relationship between force and capacitance was established. Then the testing moved to the second part, the smart washer system was applied to a sign structure base specimen, to simulate the installation process of the anchor bolts with smart washer system. The first prototype was found to lack insulation and proved to have failed, then the second and final prototype with an addition of 3D printed PLA attachments improved the insulation. The final prototype was able to provide sufficient insulation to prevent the interruption from steel sign structure specimen, and stable readings of capacitance were able to be recorded and correlated to the calibration curves developed on single anchor bolt.

Stage 2 of the project was to monitor and assess the in-field performance of the smart washer system, by implementing the smart washer system on a sign structure specimen in the outdoor environment and monitoring the capacitance every week. During the monitoring period, it was found that the smart washer system can be greatly interrupted by the environment, especially during the rainy seasons. To mitigate the effect of the humidity, each measurement was performed at least 24 hours after raining and the humidity at each measurement was controlled at around or below 70%. Besides the change in the data capture strategy, a double-layered plastic waterproof cover was applied to the smart washer system to prevent water from damaging the sensor system. During the following 12 months of records, stable readings of capacitance were recorded, the waterproof cover was proven efficient. Given that the capacitor system can be easily interrupted by the environment, it was believed that modifications on outdoor use such as a durable cover that is able to keep all forms of water (even vapors) outside the sensor system and a proper data transmission system are still necessary before actual implementations.

From the results and observations of two stages of the project, the concept and prototype of the smart washer system have been proven efficient, and the sensor system was able to detect change of tension inside anchor bolts. With the proper modification for outdoor use to eliminate the environmental interruptions and data transmission system, this smart washer system can be a potential candidate for the inspection method on the anchor bolts.

IDEA PRODUCT

From testing and long-term monitoring results, the loss of tension in anchor bolts can be detected by the smart washer system, by reading the real-time capacitance from the smart washer system and convert into tension force values in the anchor bolts, the smart washer system can provide a direct indication on whether the anchor bolts are in need of re-tightening in the laboratory settings. With proper modifications the smart washer system has been shown that it has a high potential to be implemented in structures to detect loose anchor bolts without conventional manual "hammer punching" process.

CONCEPT AND INNOVATION

The core concept of the smart washer system is based on the mechanism of capacitors. With the change of distance between the two conductors, change of capacitance can be recorded. When reflected on the smart washer system, change of capacitance is the change of tension inside anchor bolts, when the tension starts to loose, the nut starts to rotate and move away from the base plate, then the gap between the washers increases, resulting in the reduction of capacitance value, once a significant capacitance reduction is observed, the loss of tension can be detected.

As for the innovations, conventional inspection techniques can only find the loose anchor bolts with less than 20% of the required tension applied, and inspection crew members are required to visit each support structure, so that the time and human labor cost can be a big issue, for example, the cost on traffic control when inspecting. Furthermore, almost all support structures are located close to highways, the risk on the safety of the inspection crew is also of big concern. However, from the testing and monitoring results of this project, the smart washer system has shown a potential to improve the conventional inspection techniques, laboratory testing has shown that the smart washer system was able to detect the change of tension force inside the anchor bolts, but long-term monitoring still needs to consider environmental interruptions and data transmission methods.

INVESTIGATION

1. STAGE 1: DEVELOPMENT OF PROTOTYPE

1.1. Original Concept

Since washer is an essential part of the anchor bolt connection, the research group proposed a smart washer system concept of implementing a parallel plate capacitive sensor to the washers, combining with a passive radio frequency readout device (RFRD) "tagboard" attached to the sensor system, and a handheld radio frequency (RF) reader. Instead of getting out of the car, the inspection crew can get an idea of the real-time tension situation of the anchor bolts (Figure 1.1).

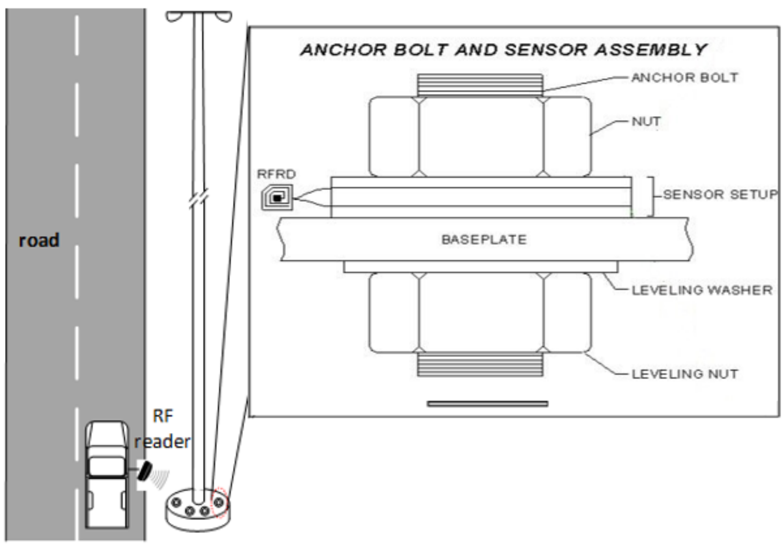

FIGURE 1.1. Original proposed smart washer system concept

The sensing principle of the smart washer system is based on the concept of parallel capacitor. The smart washer system consists of a direct tension indicator (DTI) washer and a plain flat washer, serving as two parallel plates, separated with an elastic insulated dielectric material. As the bolt is being tightened, the decrease of the gap between washers will lead to increase of capacitance. The relationship between capacitance and gap distance can be described in the equation below:

$$C = \frac{K\varepsilon_0 A}{d}$$

Where:

C is capacitance, K is the relative permittivity factor of the dielectric material, ε_0 is the dielectric constant, A is the area of the conductive surface, and d is the distance between two parallel plates.

The change of distance between washers will lead to a change of capacitance, this is the core concept that drives the entire sensor design. The decrease of the gap distance indicates that the washers are compressed during the tightening process, the pretension inside the anchor bolt also rises, which leads to the increase of the capacitance; the increase of the gap distance and indicates the sensor is decompressed, which means that the nut on top of the washers are going up, the anchor bolt is losing its pretension, ultimately indicating the anchor bolts become loose.

In the laboratory, performing tightening and loosening tests with smart washer system applied can correlate capacitance with pretension, from "fully-tightened" to "fully loose", thus, with any given capacitance value recorded, the corresponding pretension can be observed. In reality, when the inspection is performed, the status of the anchor bolts will be recorded and transmitted to the RF reader held by the inspection crew through the RFRD "tagboard", and the inspection crew can decide the "threshold" of pretension that the anchor bolts are in need of re-tightening.

1.2. Initial Design (I) and Evaluation

Based on the concept, the initial design was proposed by the research group, as shown in Figure 1.2. It consists of four major parts: top DTI washer, middle spacing washer, bottom flat washer, and memory foam or rubber was applied between top and bottom washers as dielectric material. All washers were painted with insulation coating to prevent short circuiting, as shown in Figure 1.3. It can be seen that the bottom surface of DTI washer, top surface of plain washer, and the entire middle washer were painted with blue insulation coating.

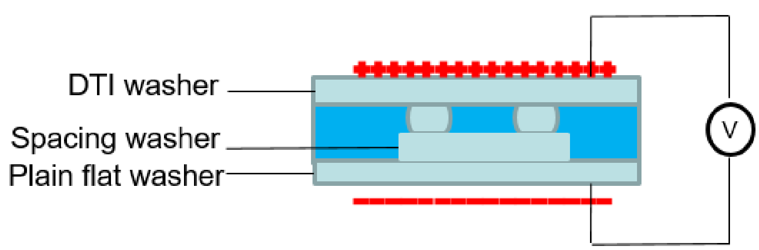

FIGURE 1.2. Initial Prototype Design of the Sensor

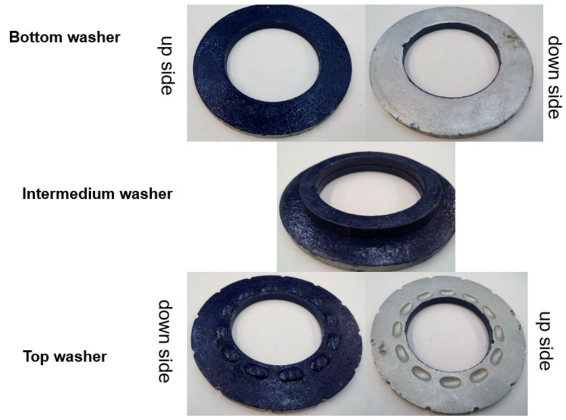

FIGURE 1.3. Application of insulation coating

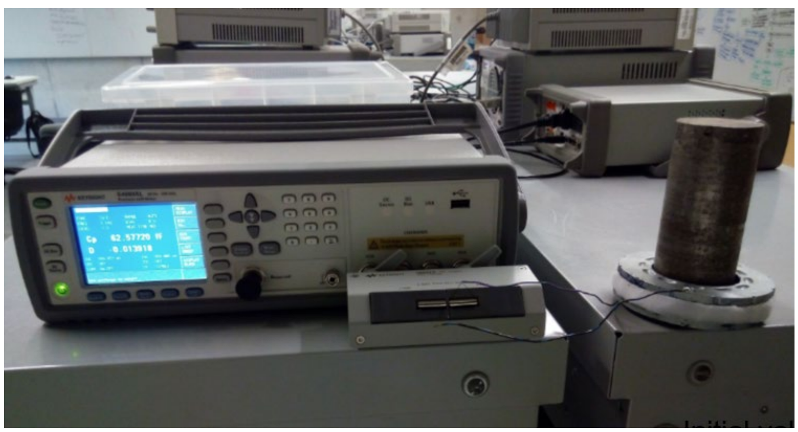

FIGURE 1.4. Laboratory initial evaluation setup

To evaluate this design, an initial evaluation was performed in the laboratory. Wires were soldered to top and bottom washers, and connected to the measurement equipment, with a steel rod placed inside the smart washer system simulating anchor bolt, as shown in Figure 1.4. By slowly compressing the sensor and recording the displacement, to see if the capacitance change can be detected as expected.

Figure 1.5 shows the result of the initial evaluation, notice that the capacitance change is the capacitance after deformation minus the initial value. All the values shown are the average of 5 different readings during the test. It can be seen that the results follow a linear trend for both rubber and memory foam capacitor. However, the rubber capacitor still shows a little bit higher capacitance compared with memory foam. The capacitance difference between rubber and memory foam at the same deformation is not too large; this is because the insulation material is added. Insulation significantly contributes to the total capacitance, and the insulation layer shows little change with the dielectric material.

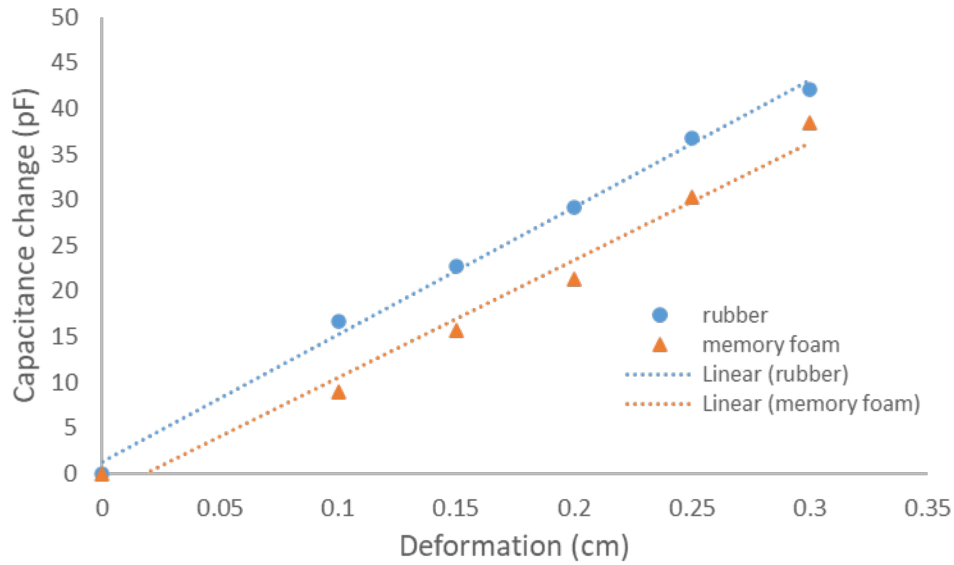

FIGURE 1.5. Initial evaluation results with different dielectric material applied

After achieving stable readings from initial evaluation, the sensor assembly was moved to a single anchor bolt setup on Skidmore Wilhelm system and tightening testing was performed, as shown in Figure 1.6.

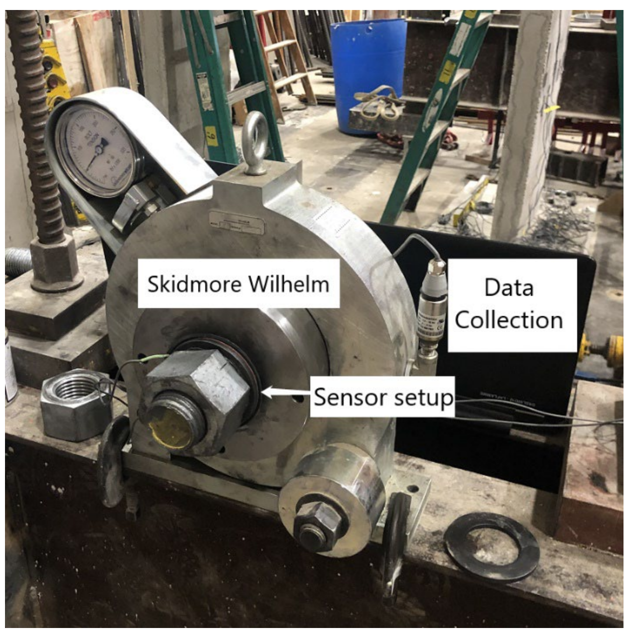

FIGURE 1.6. Tightening testing setup on single angle bolt

However, during the tightening testing, it was found that the capacitance reading was extremely unstable, as shown in Figure 1.7. As torque being applied to the anchor bolts, capacitance readings were several times larger than the results from initial evaluation, there were also “overload” readings observed over the course, indicating that there may be short circuit inside the capacitor. After taking the smart washer system off from the anchor bolt, it was found that the insulation coating was scratched off on the middle washer surface (Figure 1.8). This is because during the tightening process, the DTI washer moves close to the middle washer, when the protrusions start touching the middle washer, the rotation of nut was transferred to the DTI washer, causing frictions between the protrusions and middle washer, thus, as the tightening continues, the insulation coating was scratched off, and the wires were directly connected to the washers, the electrons could flow through scratched surface of the middle washer, causing short circuiting. It was believed that this loss of insulation coating eventually led to unstable reading of capacitor, as a result, an improved composite design was proposed, attempting to solve this insulation issue.

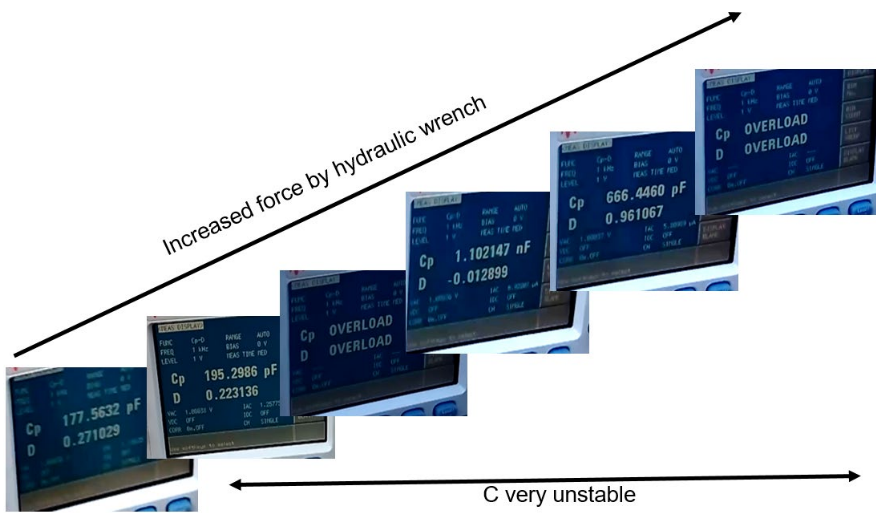

FIGURE 1.7. Unstable reading observed from tightening testing

FIGURE 1.8. Scratched insulation coating observed from tightening testing

1.3. Improved Composite Design (II) and Evaluation

To solve the issue of loss of insulation during tightening, the design has been changed with an addition of epoxy rings surrounding the top and bottom washer, as shown in Figure 1.9. Also, a layer of copper sheet was attached to the outer epoxy ring, to prevent wires from directly connecting the washers. However, during the tightening testing, the epoxy ring shattered as soon as torque started being applied to the sensor, causing the failure of the sensor. The research group immediately replaced epoxy with glass fiber reinforced polymer (GFRP) rings, but the bonding between GFRP rings and washers became the weakest part of the entire system. When anchor bolts were being tightened, bondage breakage was observed between the GFRP ring and the top washer, as shown in Figure 1.10, so that no matter how the anchor bolt was tightened, the capacitance was not able to change. This design was decided as a failure and a new improved design was proposed.

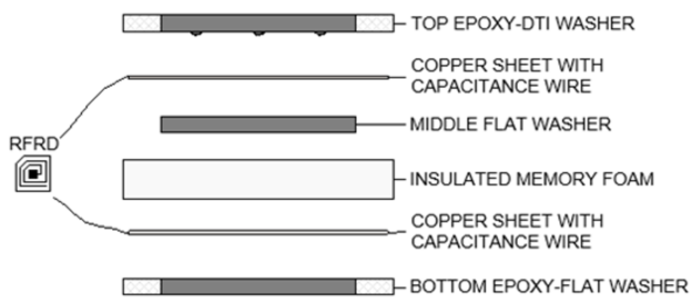

FIGURE 1.9. Improved composite design (II) scheme of smart washer system

FIGURE 1.10. Bonding breakage between GFRP ring and top washer

1.4. Improved Design (III) and Evaluation

After exploring possible options of design, the research group decided to improve the initial design (I) with additional insulation layers on the surface of washers, as shown in Figure 1.11 and 1.12. This design consists of three major parts: top layer, dielectric material and bottom layer. The top layer consists of a DTI washer, a 22-gauge copper ring and a 1/32" thick non-conductive GFRP ring between the washer and copper ring. The GFRP and copper rings are attached to the bottom surface of the DTI washer. The dielectric material is a 3/16" thick rubber ring. The bottom layer is formed with a flat washer, as well as the same GFRP and copper rings as the top layer. The GFRP and copper rings are attached to the top surface of the flat washer. A smaller-sized middle washer is placed on top of the flat washer to provide a surface for the DTI protrusions to make contact with.

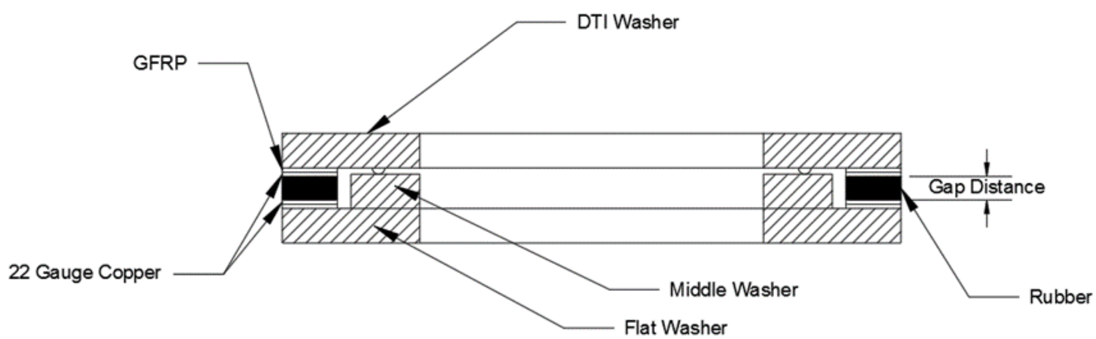

FIGURE 1.11. Cross-sectional view of improved design (III)

FIGURE 1.12. Components of the improved design (III)

The first testing performed on this design was similar to the initial evaluation in section 1.2, instead of applying the sensor to a steel rod in the laboratory, the sensor was directly applied to an anchor bolt at the base of a sign structure specimen, as shown in Figure 1.13. The sensor was connected to the capacitance measurement equipment and each measurement was taken for at least 120 seconds for a consecutive stable reading. A total of five measurements were taken, for each measurement, average capacitance was taken, as listed in Table 1.1.

FIGURE 1.13. Initial evaluation set up for improved design (III) on single anchor bolt

Trial	Capacitance, pF
1	48.06
2	48.61
3	46.99
4	46.72
5	48.64

TABLE 1.1. Initial Testing Results of Improved Design (III)

From the results, it can be seen that the capacitance readings were very close for each run, the difference between maximum and minimum reading was less than 2pF, and the average capacitance reading from the 5 trials was 47.8 pF, and the deviation was only 0.8 pF, indicating that the sensor was able to produce a stable capacitance when left sill on the anchor bolt.

Due to the lack of tightening equipment that can produce torque large enough to tighten the anchor bolts at the time, the tightening test on Skidmore Wilhelm was substituted with a compression testing on MTS testing system, the compression produced by MTS system was able to simulate the clamping force that was equivalent to the pretension applied to the anchor bolts. Figure 1.14 shows the setup of this test, sensor was placed between the loading cells of the MTS system, and connected to the data collection, MTS system could perform displacement-controlled testing so that the displacement was recorded by MTS system.

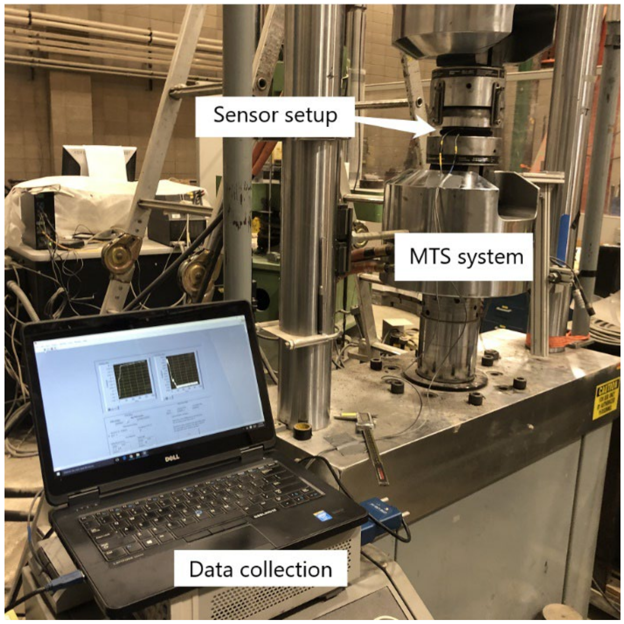

FIGURE 1.14. MTS testing setup

During the testing, it was found out that there was a fringing effect from the capacitor that had to be considered, since both heads of the loading cell were metal and conductive, once the sensors are charged, the fringing effect will lead the loading heads to become a second capacitor. The fringing effect is a boundary effect on the function of capacitance. When the capacitor is connected to power, the electrons inside the capacitor do not only vertically exist within the electric field, but they also exist around the field within a small range. In this case, outside the electric field is metal parts of the sign structure base, thus, the electrons can be conducted to these metal parts causing the incorrect readings on capacitance. This fringing effect was also unavoidable on the real anchor bolts since the entire sign structure base is made of metal. Even with insulation coating applied, the damage on the coating during the installation process could not solve the problem. Hence, adjustment factors were brought into the equation for capacitance-distance relationship.

$$C = N * \alpha * \frac{K\varepsilon_0 A}{d}$$

Where N is the number of the capacitor for measurement, which is taken as 1, and α is the fringing effect adjustment factor determined from the ratio between the width of the copper ring and the gap distance, which can be assumed as 1 in this case, when the width-gap ratio is 1 or larger, the adjustment factor, α is taken as 2.

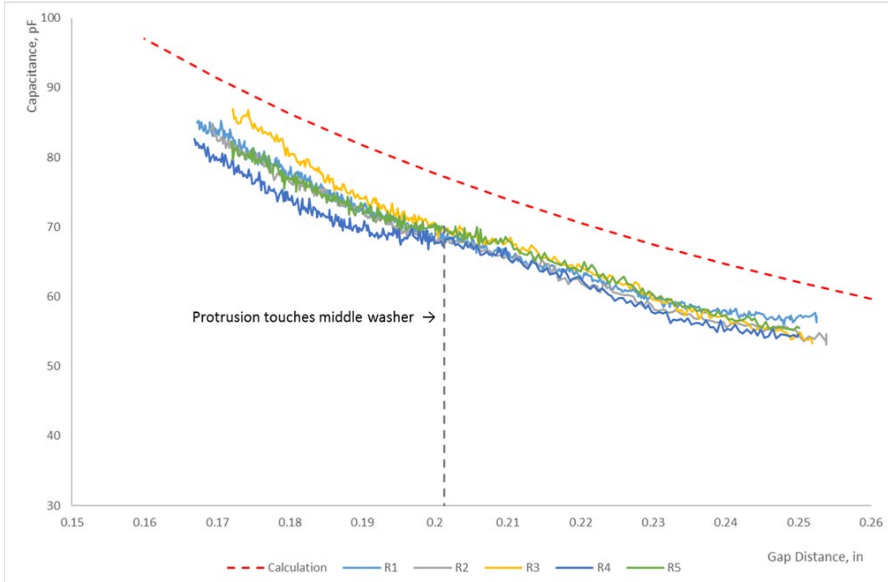

FIGURE 1.15. MTS testing results – capacitance vs. gap distance

As shown in Figure 1.15, it was observed that even with adjustments, the actual capacitance reading is still about 10% off of the calculation. The research group believes this is due to the limitation of manufacturing and the environment. However, trials on all five specimens show that the sensor follows the same trend before the protrusions touching the middle spacing washer, the curves vary a little after protrusions start to be flattened, but only within a 5% range. As the gap distance closes in between the top and bottom washers, the capacitance rises following the trend given by the calculations. Since the force was also recorded from the MTS testing, the force-capacitance curve could also be developed, as shown in Figure 1.16.

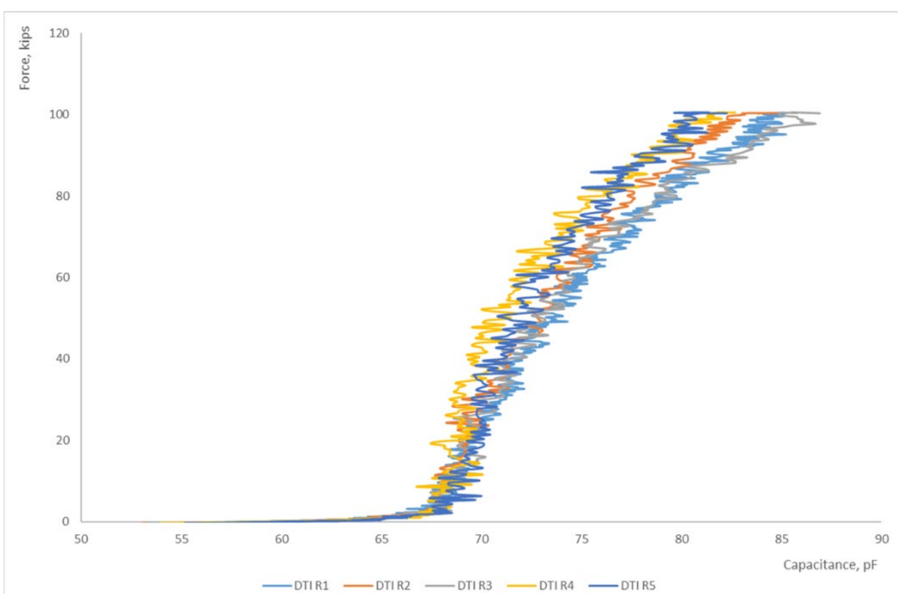

FIGURE 1.16. MTS testing results – force vs. capacitance

From Figure 1.16, it was observed that approximately for the first 10 kips loaded to the sensor, the capacitance increases rapidly, from 50 pF to 70 pF, and the trend of increase goes slower as the sensor was being loaded up to the 100 kips limit. This was because the protrusions started touching the middle spacing washer, since the testing is displacement controlled, to perform the same amount of displacement, the force required has to increase. When the protrusions start touching the middle washer, the capacitance reading was still affected, the research group believes this is from the imperfect insulation of the sensor, even with improved insulations, to get total insulation at the point was not realistic. Furthermore, after several loading-unloading cycles, another flaw in the design was observed.

When the sensor was loaded, the rubber was squeezed towards the outside of the sensor, thus creating extra straining on the wire, and the connection became very fragile and imposed risk of breakage during the loading process, this observation became a big concern on the durability of the sensor, as shown in Figure 1.17. The research group then replaced the stranded wires with solid core wires, and in this case, the connection was greatly strengthened and the risk of breakage at the wire connection was eliminated.

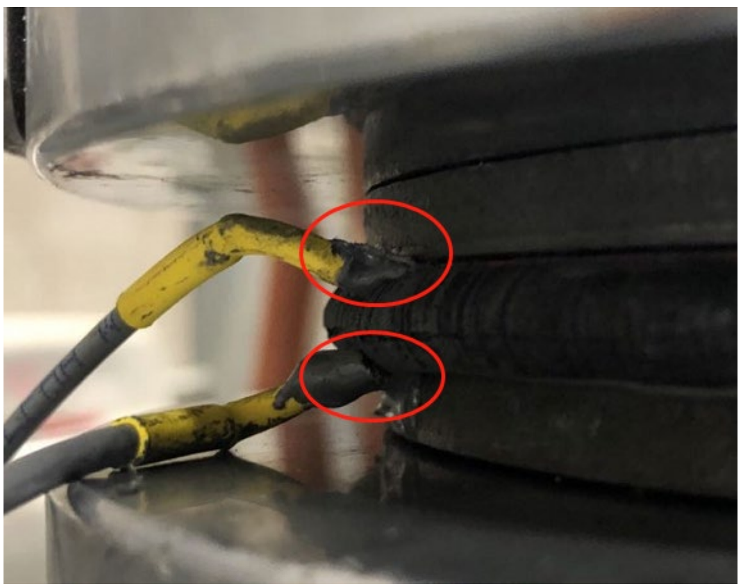

FIGURE 1.17. Straining of wires when sensor was loaded

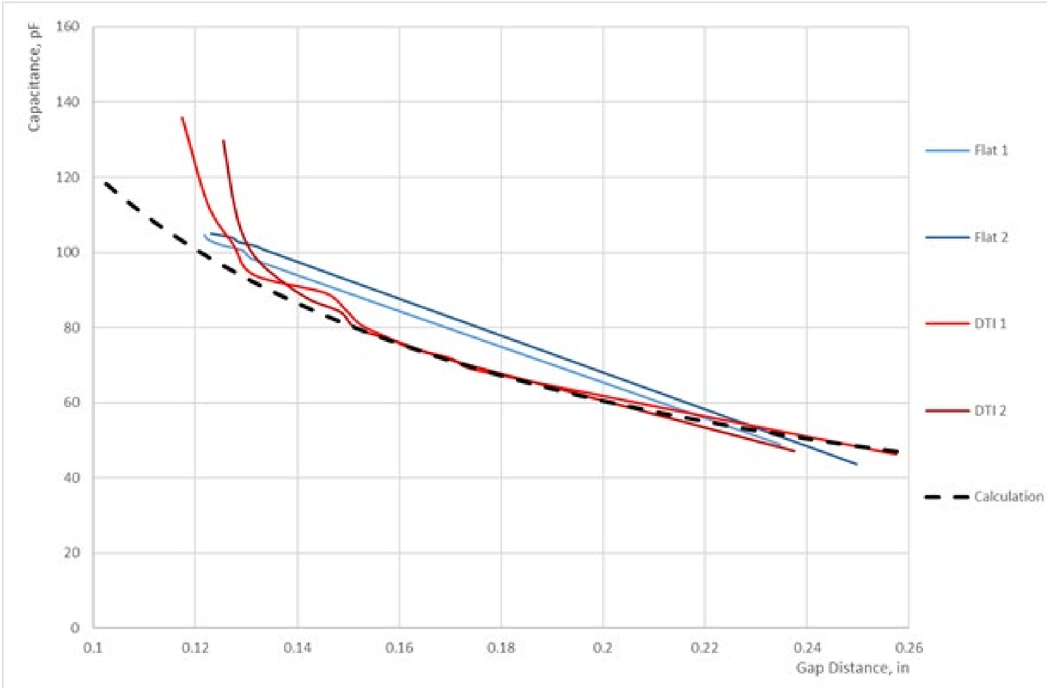

FIGURE 1.18. Skidmore Wilhelm testing results – capacitance vs. gap distance

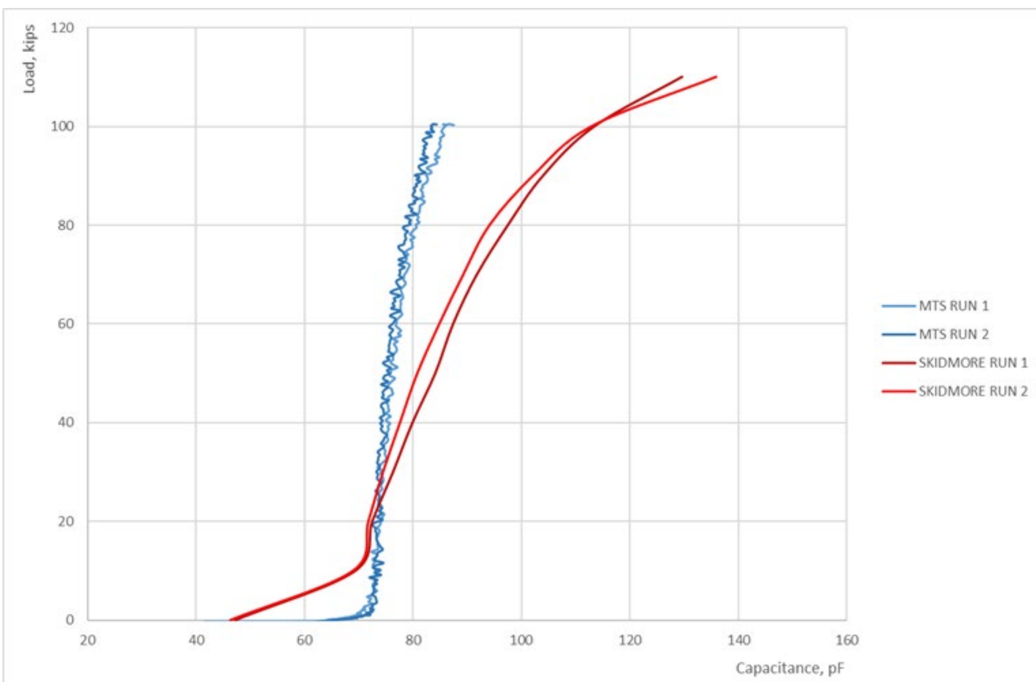

FIGURE 1.19. Load – capacitance Skidmore testing results vs. MTS testing results

After the arrival of the hydraulic wrench, the sensor was applied to the Skidmore Wilhelm system for tightening tests. Once the protrusions of DTI washers were flattened, those washers could not be reused, and the number of DTI washers were limited. The research group decided to use flat washers simultaneously for top washer during the tightening tests to observe if there was any difference.

Figure 1.18 plots the results from tightening tests on Skidmore Wilhelm system. It can be seen that the recorded data on sensors with DTI washers share a very close trend to the calculated theoretical value for most of the time. However, when the gap closes to about 0.14 inch, the capacitance reading increased and became higher than the calculated value. As for the sensor with flat washers as top washers, it was observed that the trend was more linear, but the recorded capacitance was higher than the theoretical value, this was because the flat washer does not have protrusions and no extra force was needed to overcome the resistance of the protrusions compared to the DTI washer. Comparing the results from MTS and Skidmore testing in Figure 1.19, the research group found that the different "second capacitor" formed by nut and base plate on Skidmore or by the heads of loading cell could affect the capacitance reading, causing different trends between the results.

Furthermore, when the sensors were applied to the sign structure specimen, the insulation problem started affecting the capacitance reading. After a small torque being applied to the anchor bolts, even with a tiny vibration on the specimen, the capacitance became unstable. As shown in Figure 1.20, on the computer, the left plot shows the real-time capacitance during the testing. Each peak was the time when a tiny vibration was applied to the specimen, the capacitance jumps from 60 pF to over 200 pF, and after the vibration, the capacitance managed to restore to the normal range. Due to the unstable capacitance performance on the specimen, the testing on the structural level for this design became unrealistic, and the sensor design needs further improvement.

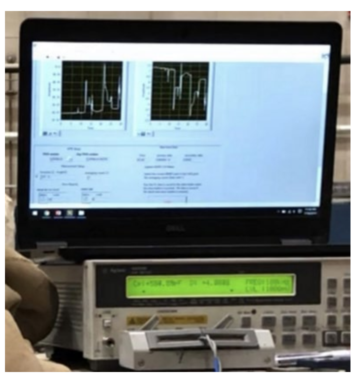

FIGURE 1.20. Unstable Capacitance Reading While Vibration Occurs on the Signpost

1.5. Design and Evaluation of RFRD “Tagboard”

Parallel to the development of the sensors, the development of “Tagboard” was also underway. The “Tagboard” design incorporates a linear voltage regulator and the original meandered inverted-F antenna for simplified lab testing. The antenna serves the purpose of allowing for wireless powering of the “Tagboard”. The addition of the linear regulator allows the “Tagboard” to operate from a lab power supply, or with added mobility, a 9V battery. A 3-pin jumper allows the selection of sourcing power from wireless energy harvesting or a DC supply. The microcontroller board is directly attached to the “Tagboard” through a set of female pin connectors. The board layout was altered slightly after PCB manufacturing to allow serial communication from the microcontroller to a host computer. This allows the user to access the measured raw data in real-time and save it to an output file. As a temporary benefit, this allows the microcontroller and measurement circuit to be powered from the host computer, so an additional power source is not needed. Figures 1.21, 1.22 and 1.23 show the schematic diagrams of the rectifier, measurement circuit and voltage regulator, respectively. Figure 1.24 shows the “TagBoard” layout.

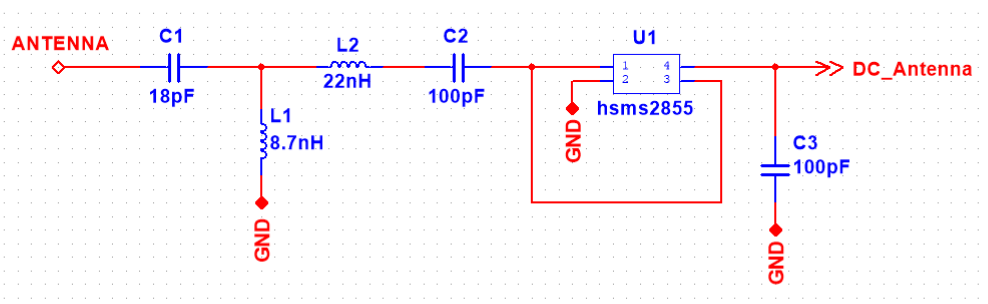

FIGURE 1.21. Rectifier circuit scheme

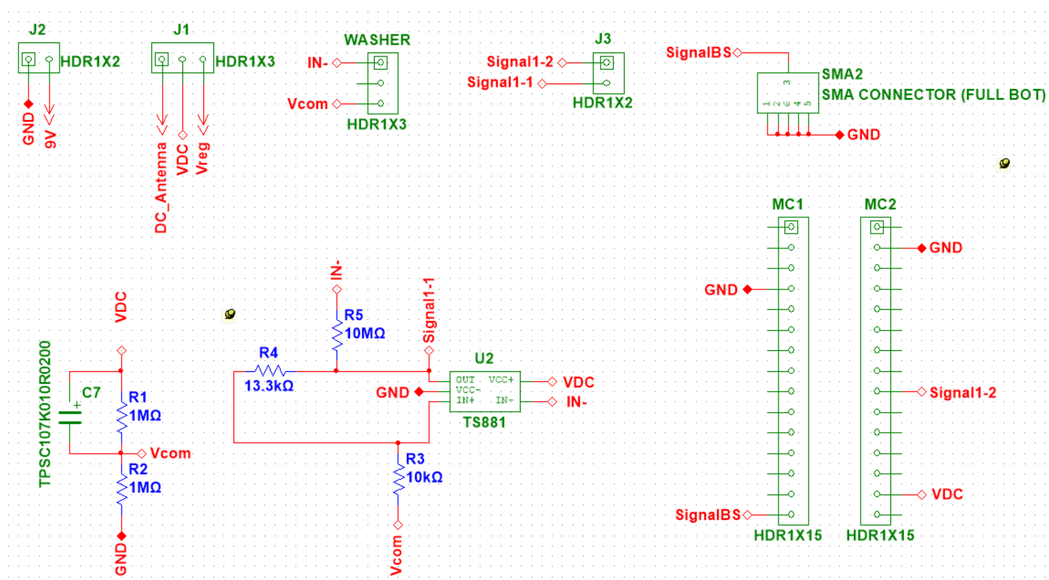

FIGURE 1.22. Measurement circuit & connectors

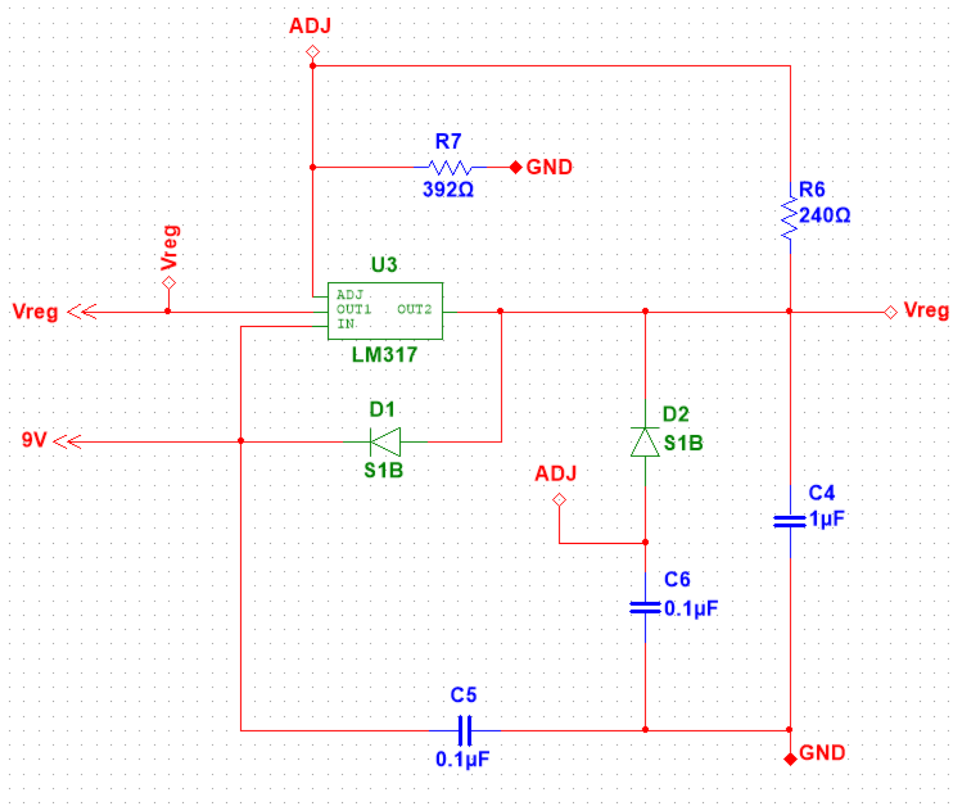

FIGURE 1.23. Voltage regulator circuit

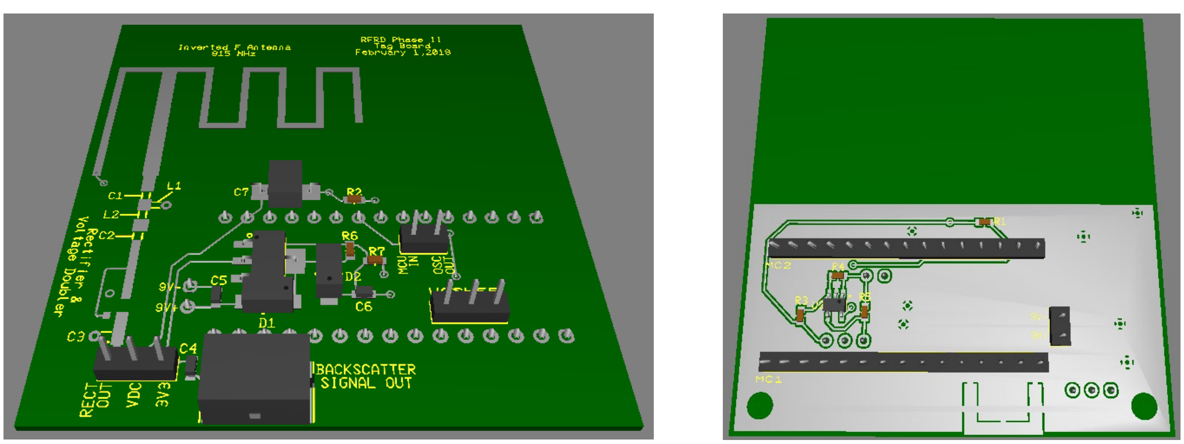

FIGURE 1.24. TagBoard layout: top side (left), bottom side (right)

After calibrations of the sensor, the “Tagboard” was introduced to the sensor system to replace the LCR meter as measurement equipment. At this stage, the “Tagboard” can be powered up by a 9V battery, as shown in Figure 1.25, or be programed to use the power from the laptop, where the laptop computer serves as both power source and output logger during the tests as shown in Figure 1.26.

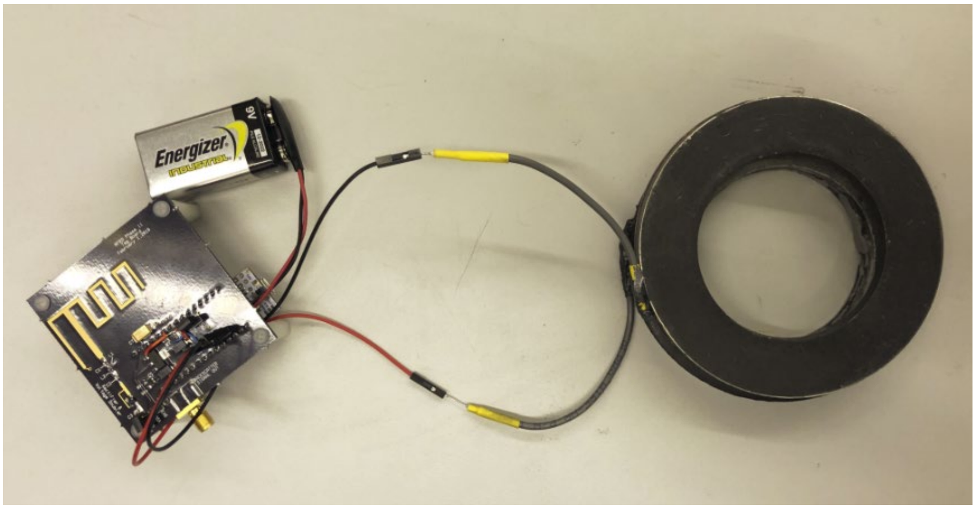

FIGURE 1.25. Sensor System with 9V Battery Power

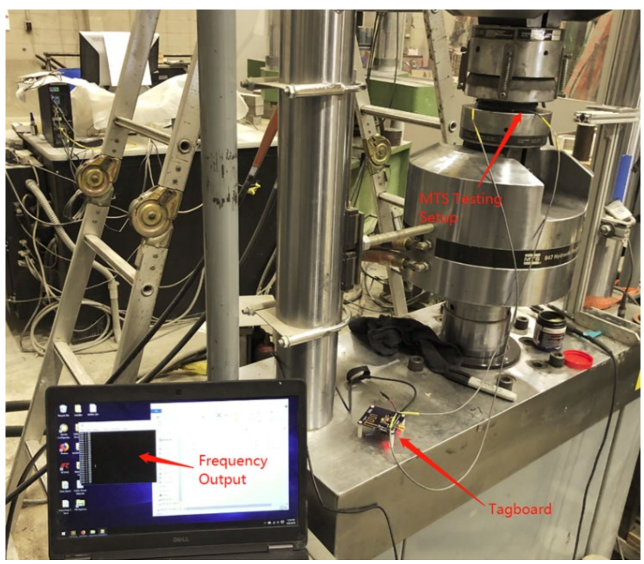

FIGURE 1.26. Sensor System with “Tagboard” During MTS testing

As shown in Figure 1.27, results from MTS tests show that “Tagboard” has an approximately constant residual capacitance, compared to the LCR Meter. The cause of this offset in results is believed to be when the grounded washer contacts metal (nut or baseplate), it forms another parallel capacitor, increasing the overall capacitance. Due to size and cost constraints, the measurement system in the

"Tagboard" was designed to measure capacitance differently than the LCR Meter, resulting in increased values.

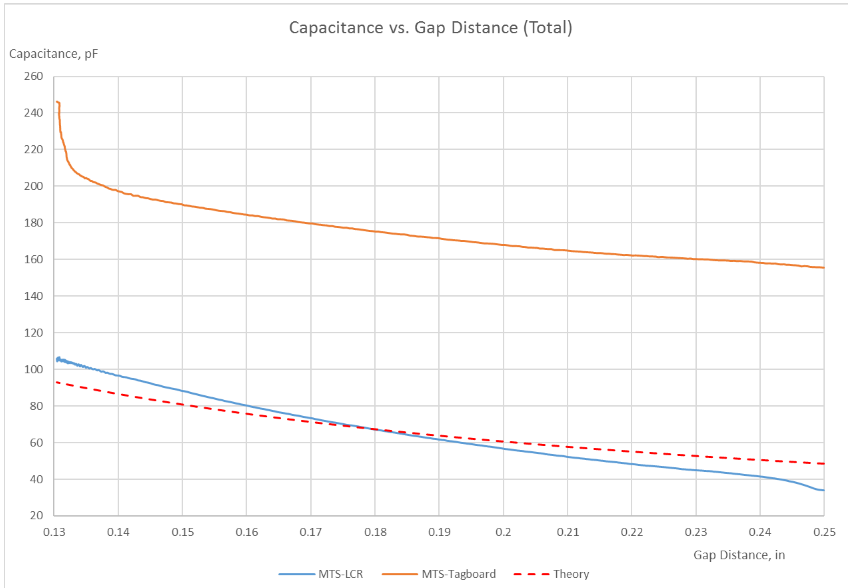

FIGURE 1.27. Comparison between Results from LCR and "Tagboard"

It was found that both the results from the LCR Meter and the "Tagboard" share the same trend, so the data was normalized as shown in Figure 1.28. The plot shows that the curve barely fit the theoretical calculation.

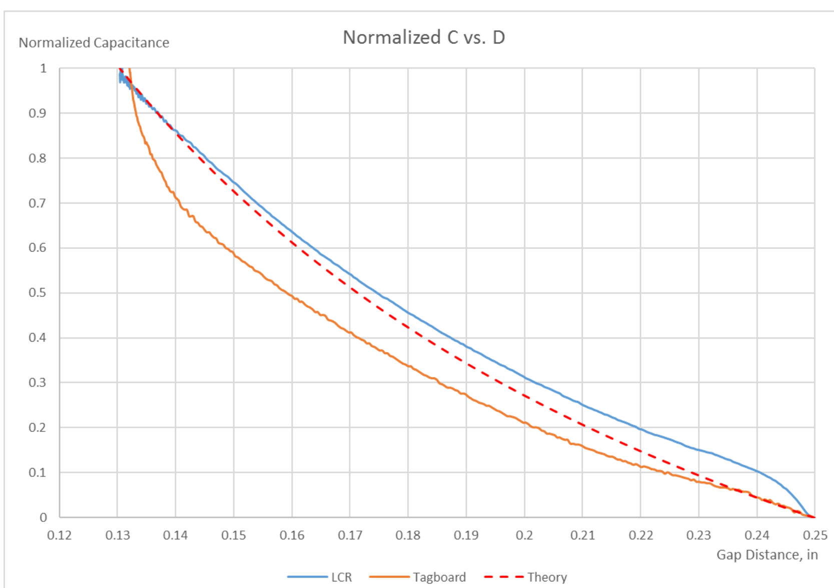

FIGURE 1.28. Normalized Capacitance VS. Gap Distance

When applied on Skidmore tension testing system, the research group could not get stable capacitance reading from the tests. More testing was also performed in an attempt to eliminate or stabilize the "Tagboard" performance, including testing with fixed capacitors. It is observed that the difference does not stay constant and changes along with the change in capacitance. The tests with fixed capacitors show that the "Tagboard" gave more than 15% error as the capacitance increases, even if the environment was strictly controlled (as shown in Table 1.2).

LCR Result, pF	68.20	101.00	148.00	218.70	327.00	1014.00
Tagboard Result, pF	61.67	89.00	129.00	188.00	280.00	858.00
Labeled Capacitance, pF	68.00	100.00	150.00	220.00	330.00	1000.00
LCR Error	0.29%	1.00%	1.33%	0.59%	0.91%	1.40%
Tagboard Error	9.31%	11.00%	14.00%	14.55%	15.15%	14.20%

TABLE 1.2. Comparison between Measurements of LCR Meter and "Tagboard" on Fixed Capacitor

Tests were also performed on the signpost specimen with the system to simulate the real on-site situation, the result is as shown in Table 1.3. When the sensor was plugged into "Tagboard" with the "TRBL" (top washer connected to the right port, bottom washer connected to the left port) set up, the capacitance measurement is not accurate, when switched to "TLBR" (top washer connected to the left port, bottom washer connected to the right port) set up, the measurement was relatively consistent, but the comparing with LCR, "Tagboard" gives an error over 20%.

Skidmore, Nut Touching Top		
	TLBR	TRBL
LCR (pF)	32.65	32.66
Tagboard(pF)	25.28	N/A
Pole, no Nut		
	TLBR	TRBL
LCR (pF)	31.75	31.67
Tagboard (pF)	25.35	76.62
Pole, with Nut		

	TLBR	TRBL
LCR (pF)	32.43	32.43
Tagboard (pF)	25.68	50.68
Sitting on Concrete		
	TLBR	TRBL
LCR (pF)	32.58	32.58
Tagboard (pF)	25.94	50.68

TABLE 1.3. Functionality Evaluation on "Tagboard"

Testing results with "Tagboard" applied to the sensor have shown that the current "Tagboard" was not able to accurately measure the capacitance from the sensor, and after consulting with the personnel in Electrical Engineering department, it was found that the design of the "Tagboard" was originally based on the wrong concept, and given that the project had changed the Principal Investigator after the failure in testing the "Tagboard", the focus of the project had been shifted to the development of a functional design of the sensor and the "Tagboard" development was abandoned.

1.6. Development and Evaluation of Sensor Design Using 3D-Printed Attachments

1.6.1. Introduction of 3D Printing technology

From testing results of previous section, it was found that the smart washer system was still affected by the lack of insulation, especially when applied to the sign structure specimen, the insulation issue caused from fringing effect had a great impact on the functionality of the sensor, leading to extremely unstable capacitance readings. To solve this problem, a design that used advanced 3D printing technology was considered. The idea of using 3D printing technology was first proposed during section 1.3 after the failure of the design with epoxy and GFRP rings attached around the washers, however, due to the limitation of resources at that time, 3D printing was not able to be implemented in designing. When the design in section 1.4 was found with severe insulation problems after testing on the sign structure specimen, 3D printing was again proposed to explore the possibility of solving the insulation problems.

In previous sections, all parts were sent to waterjet for cutting, such as the GFRP and rubber rings in sections 1.3 and 1.4, but waterjet was only able to do "cutouts", the research group would send several sheets of materials along with drawings, the waterjet could cut the desired shape out of the sheets. On the one hand, there would be inevitable waste of materials, on the other hand, the waterjet was only able to operate on a two-dimensional plane such as metal sheets, for example, if someone would like to make a one foot long I-shaped beam, it would be very hard for waterjet to cut out such a shape.

As for 3D printing, one of the most commonly used techniques is called “additive manufacturing”, instead of cutting materials out from a larger piece, additive manufacturing makes parts from nothing and wastes no material. Furthermore, the most commonly used materials on 3D printers are composite plastic polymers that are non-conductive. The printing mechanism of additive manufacturing is that, the material is first connected to the nozzle of the printer, then the heater inside the nozzle can heat up the material to the temperature that the material can melt, then the nozzle extrudes melted material onto the printing bed, the bed has lower temperature, once the material touches the printing bed, the difference between the nozzle and the printing bed can cool down the material to solidify again, with drawings made by the researchers and programmed into the printer, the printer would be able to print any parts with highly customized shapes. In this project, if an insulation cover was to be manufactured, using waterjet cutting, it would be very hard to achieve a shape of insulation prevention cover that could accommodate to the washers without blocking the room for wrench operation. The GFRP rings cut from the improved composite design had proven with bonding problems with washers even with industrial level adhesives. With 3D printing technology applied, the attachments would not have to be bonded with the washers, and the sides of the smart washer system could have an extra cover that was able to prevent short circuiting from fringing effects. Furthermore, the current widely used materials in 3D printing are non-conductive plastic polymers, this non-conductive property exactly suits the need of insulation. 3D printing can help build shapes that traditional manufacturing like waterjet cannot achieve and is very suitable for the need of an insulation attachments with customized shape requirements of this case.

1.6.2. Design of and Strength Evaluation of 3D-printed Attachments

Since the focus of this project had been shifted from developing a package of smart washer system and data transmission system to a functional design of smart washer system.

As shown in Figure 1.29, in addition to the improved design (III), 3D-printed attachments were introduced. In the top component of the sensor, the printed part serves the same goal as the GFRP ring from the previous design: to isolate the copper ring and the washer and provide sufficient insulation, plus a side cover that previous designs never had to mitigate or eliminate the evasion of electrons from the capacitor causing fringing effects or short circuiting. Similarly, for the bottom component, 3D-printed attachment replaces the GFRP ring from the previous design to provide insulation and covers bottom washer for better insulation. The core of this design is the extra cover on the outer side of the washers and the entire assembly, with a customized shaped outer insulation cover from 3D printing, electrons from the capacitor could be kept within the electric field to prevent short circuiting due to fringing effects when the sensor was loaded.

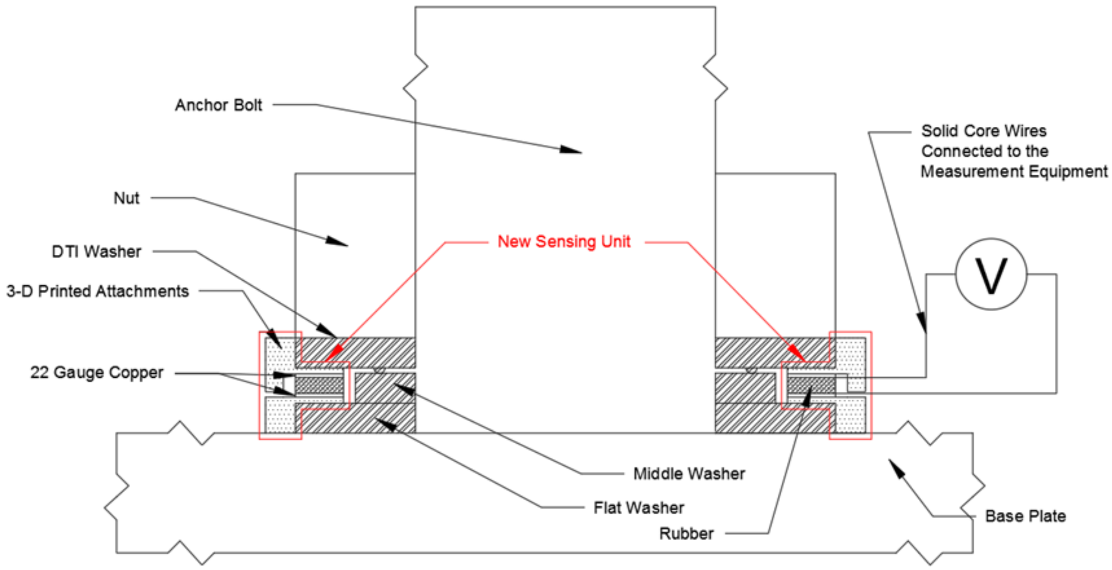

FIGURE 1.29. Cross-sectional view of design with 3D-printed attachments

When the design was settled, the research group started searching for proper materials to print, it was found that polylactic acid (PLA) was a great candidate. PLA material is non-conductive, cost-effective and has strong strength to endure the large clamping force brought from the anchor bolts. With the help from the Department of Industrial and Material Science Engineering, a few samples were printed for a strength test.

After assembling the smart washer system, without connecting to the capacitance measurement, the sensor was applied to the sign structure specimen, as shown in Figure 1.30. The anchor bolt on the specimen had a diameter of 2-1/2” and yielding strength of 55 ksi, which was the largest anchor bolt that commonly used in the highway support structures, and larger bolt diameter meant higher clamping force on the sensor, the research group believed if the attachments could survive the tightening of 2-1/2” diameter anchor bolts, it could also survive on smaller sizes. The bolt was tightened according to the newest specification provided by MnDOT, and to a pretension magnitude of 132 kips (60% of bolt yielding strength) with a 3300 ft-lb torque provided by the hydraulic wrench.

FIGURE 1.30. Strength test setup for 3D-printed attachments

After applying 3 loading cycles of tightening-loosening, the sample was taken off to observe the damage. From Figure 1.31, it could be observed that there was no visible damage on the 3D-printed attachments, and each component was still intact after the application of largest possible pretension inside the anchor bolts.

FIGURE 1.31. No visible damage observed on 3D-printed attachments after tightening-loosening tests

Since the tightening and loosening tests on the printed attachment samples have proven that PLA material was able to withstand the largest possible force introduced from tightening, the research group decided to use this material for the following tests with capacitance measurements connected. Several sets of attachments were printed inside the laboratory of Industrial and Material Science Engineering, using UPrint SE Plus 3D Printer (Figure 1.32) with an accuracy of 0.0003 inch (0.01 mm). During the printing process, the PLA was heated to a half liquid status (215 °C), then through the nozzle, a strip with 0.003-

inch diameter was extruded to the printing bed with a temperature of about 60 °C, and PLA was cooled down immediately after touching the printing bed because of the temperature difference and became solid again. The printer followed a layer-by-layer printing order, where the nozzle started extruded material from the bottom surface and gradually extruded material to the top surface, each layer was 0.003 inch thick, and this printing technique was previously mentioned as additive manufacturing. For each attachment printed, there were hundreds of layers printed, with such accuracy, the printed parts could preserve the desired shape as best as possible. Unlike traditional 3D printers, the printing work was performed in the constant temperature environment inside the UPrint SE Plus 3D Printer, so that the printing quality was guaranteed.

FIGURE 1.32. UPrint SE Plus 3D Printer

1.6.3. Laboratory Testing of 3D-printed Attachments

After the printing work was finished, sensors were assembled and prepared for the testing in the laboratory, as shown in Figure 1.33. At this stage, it was decided the testing was performed directly on the anchor bolts of sign structure specimen instead of on MTS system and Skidmore Wilhelm system, this is because the sign structure specimen can better represent the installation process performed in reality, and from previous design the sensor have stopped functioning on the sign structure specimen, if a stable reading could be recorded with this design, the insulation provided from 3D-printed attachments could be proven efficient.

FIGURE 1.33. Assembled sensor system with 3D-printed attachments

The first part of the testing was initial testing, the sensor was applied to the anchor bolts of the sign structure specimen, but with no pretension applied, the nut was rotated to exactly touching the DTI washer, as shown in Figure 1.34. A total of five sensor sets were tested, for each set, the capacitance measurement was connected to the sensor and left on for a consecutive 120 seconds of stable reading.

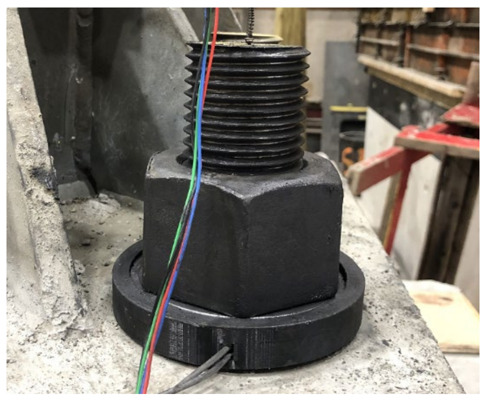

FIGURE 1.34. Initial testing setup for sensor with 3D-printed attachments

After finishing recording the capacitance for all five sets, average capacitance and error of each set were calculated, as tabulated in Table 1.4. It could be observed that all five sets of sensors were showing extremely close readings on capacitance, the error for each measurement was less than 0.3%, even with nut touching the top DTI washer, the sensor could produce stable readings on capacitance.

Set	Average Capacitance, pF	Error
1	31.18	0.23%
2	31.19	0.24%
3	31.21	0.26%
4	31.22	0.23%
5	31.25	0.23%

TABLE 1.4. Initial Testing Results of Sensor with 3D-Printed Attachments

Since the stable readings were observed from initial testing, the tightening and loosening tests were performed. The testing setup consists of sign structure specimen, sensor, capacitance measurement, Hytorc TX-8 hydraulic wrench, and DCDT calibration system for displacement measurement, as shown in Figure 1.35. To ensure that the sensing system only deform due to the pretension transferred from torque and the torque was applied appropriately, the hydraulic wrench was lifted by wood blocks.

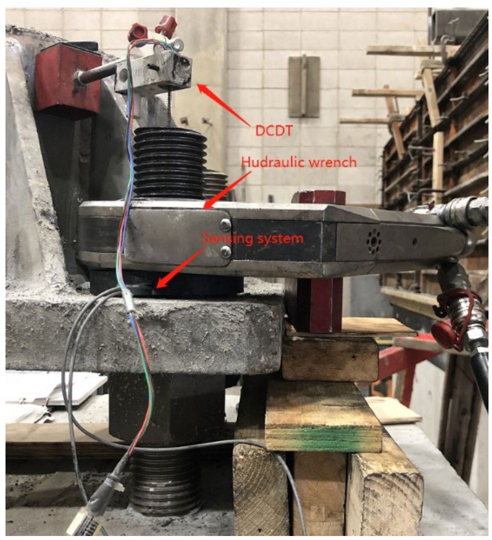

FIGURE 1.35. Tightening and loosening testing setup for sensor with 3D-printed attachments

Before each tightening/loosening procedure started, the measurement was turned on for at least 30 seconds of stable readings on capacitance, then after each tightening/loosening procedure was finished, another at least 30 seconds were measured to see if the capacitance had any change. Figure 1.36 below shows an example of the capacitance measurement during tightening/loosening. It can be observed that before and after tightening/loosening, the capacitance has a flat constant trend, then as the hydraulic wrench being activated, a small interruption on the capacitance reading is observed. The variation of capacitance was mostly within the range of ±5 pF and when tightening/loosening was finished and the hydraulic wrench stopped, the variation of capacitance stopped as well.

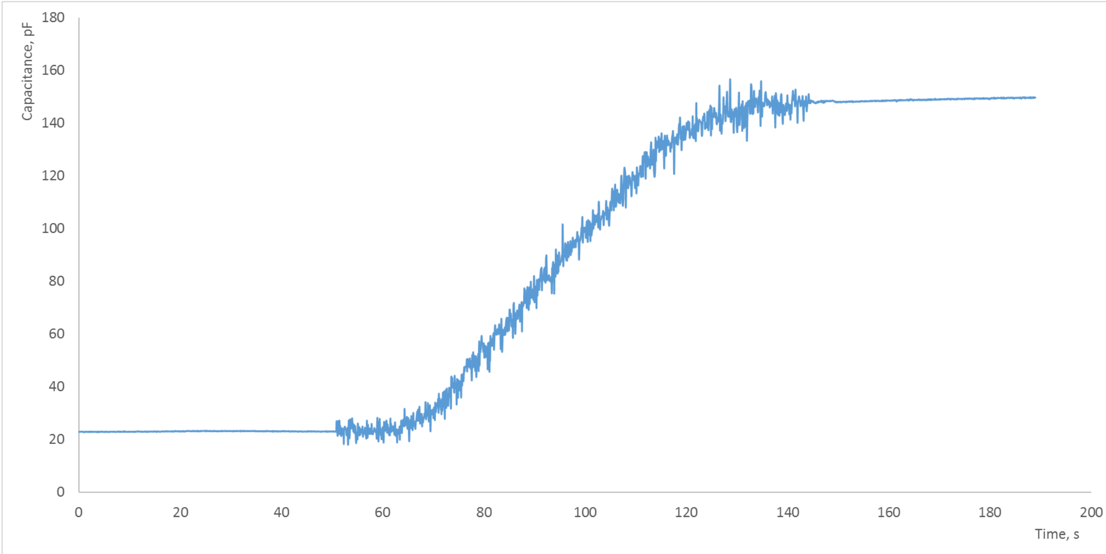

FIGURE 1.36. Example of time-capacitance relationship during tightening/loosening

Also, after the anchor bolts were fully tightened, the research group used a hammer to pound on the sign structure specimen, to see if the interruption of unstable reading of capacitance still exists (Figure 1.37). With the maximum possible force by human pounding on the specimen, the capacitance remained at a constant value with no visible change. Given that the previous design failed at this step due to the insulation issue, with the application of 3D-printed attachments, this issue of insulation was solved, proving that the efficiency of the 3D-printed attachments on insulation.

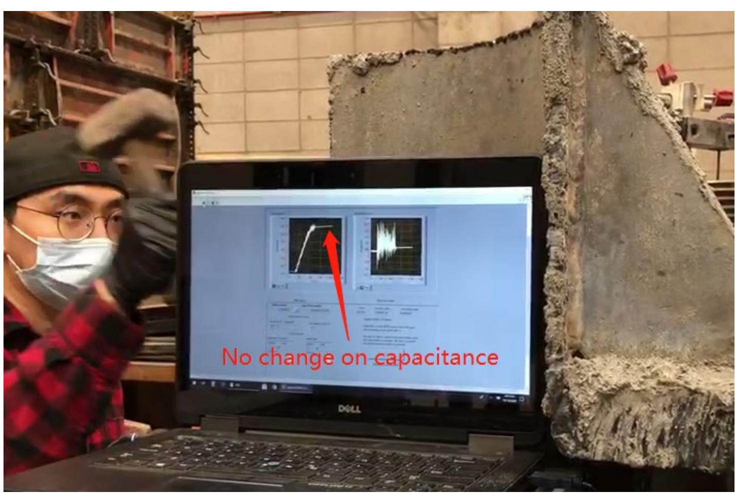

FIGURE 1.37. Testing on the sensor performance with vibrations introduced to the sign structure specimen after tightening

A total of 6 sets of sensors were tested in the tightening/loosening tests, the results are plotted in Figure 1.38 and 1.39. Looking at the plots, no matter tightening or loosening, each set of sensor was able to maintain the same trend, variation among sets were smaller for tightening tests than loosening tests. When the bolts are fully loose at no pretension, the capacitance was at about 30 pF, and when the bolts were fully-tightened at 132 kips, the capacitance was at around 140 pF. After collecting data from all 6 sets of tightening and loosening tests, a calibration curve for 2-1/2" diameter grade 55 anchor bolt was developed as shown in Figure 1.40. This calibration curve was able to provide a direct indication of the relationship between capacitance and pretension force inside the anchor bolts. For example, after installation, if a capacitance reading is around 140 pF, that would correlate to a fully-tightened status of pretension at around 132 kips, if after some time the capacitance drops to about 80 pF, which can be correlated to a pretension around 60 kips, indicating that the anchor bolt has lost around 50% of the pretension from installation.

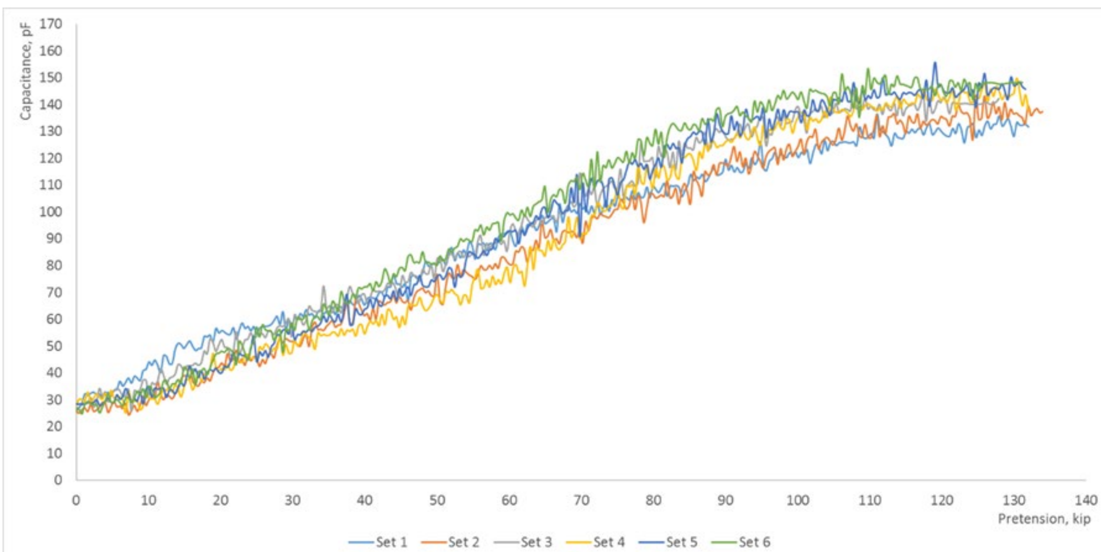

FIGURE 1.38. Capacitance-force relationship results from tightening tests

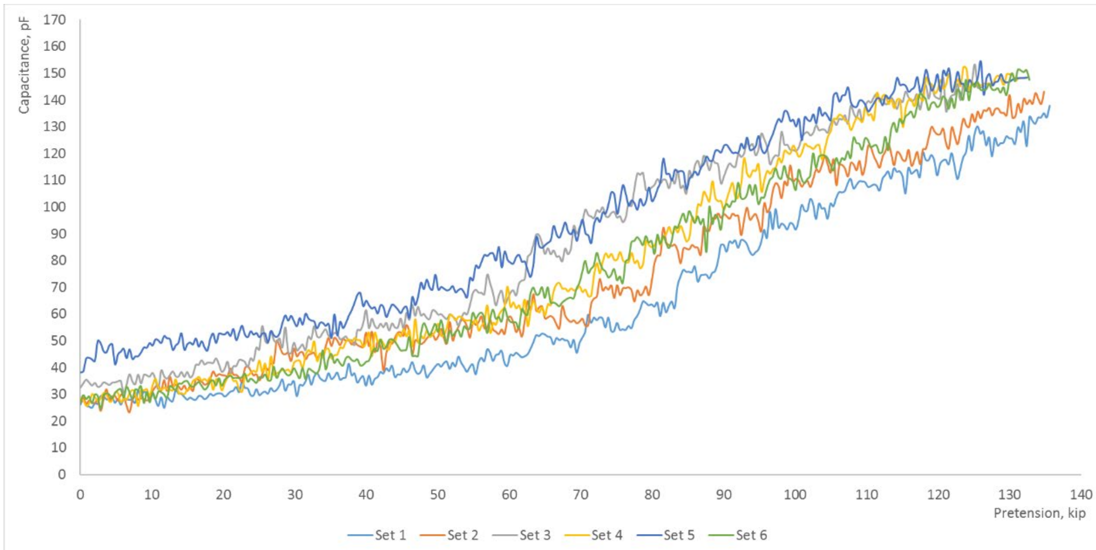

FIGURE 1.39. Capacitance-force relationship results from loosening tests

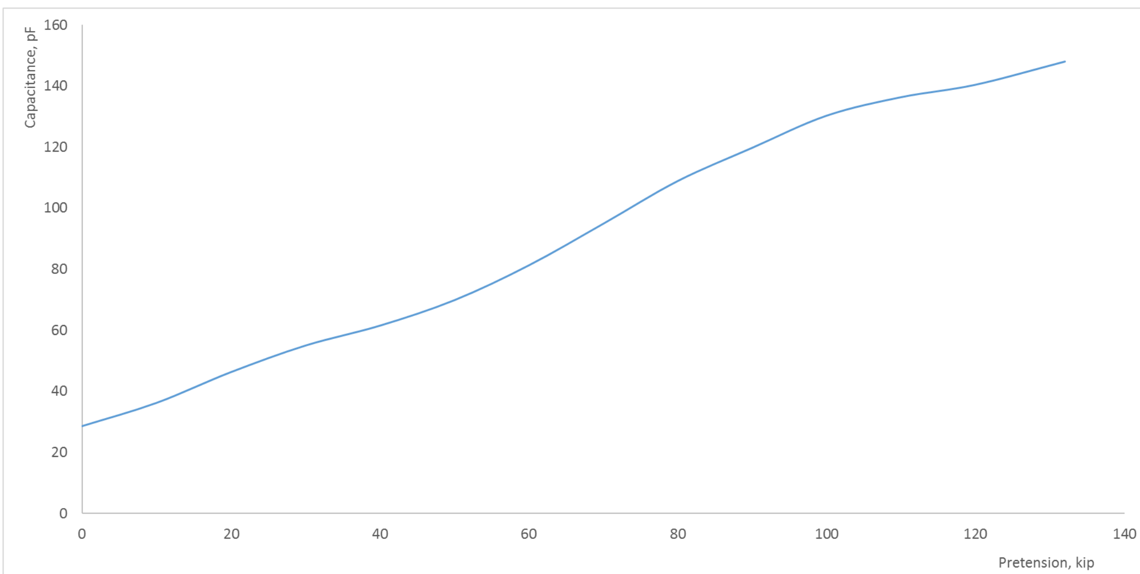

FIGURE 1.40. Calibration curve of 2-1/2" diameter grade 55 anchor bolts

Since MnDOT research *(2)* has found that there was an approximately 10% immediate loss of pretension in the first 48 hours after fully tightening the anchor bolts, the research group conducted a test to see if the loss of pretension could be detected by the sensing system. After tightening the anchor bolts to fully tightened, the capacitance was measured as an average of 141.44 pF, with an error of 0.26%. After 48 hours of tightening, the sensing system was reconnected to the capacitance measurement, the average capacitance was 132.86 pF with an error of 0.25%. The drop of capacitance was about 6%, which corresponds to the immediate loss of pretension. This observation agrees with findings in MnDOT research, and the sensor system was proven to be able to detect this change of pretension.

After completing the testing in the laboratory, the research group decided to take the specimen outside of the laboratory to perform a long-term monitoring test on the performance of sensor.

2. STAGE 2: LONG TERM MONITORING OF PERFORMANCE OF THE SMART WASHER SYSTEM

2.1. Preparation

With the development of the calibration curve in indoor laboratory testing, the project moved to stage 2: long term monitoring of performance of smart washer system. After moving the entire structure outside of the laboratory, the sensor system was again applied to the sign structure specimen, then the anchor bolt was tightened, due to the lack of tightening equipment at this stage, the anchor bolt was only able to be tightened to half of "fully tightened" value, then the capacitance was recorded with a consecutive 120 seconds of measurement. This reading of 76.86pF was recorded as "reference value" for the following monitoring. Based on the data collected throughout this stage from 12/18/2020 to 09/18/2022, the data was divided into three phases to be discussed.

2.2. First Phase of Monitoring (12/28/2020 - 07/10/2021)

When the preparation work was finished, the first phase monitoring of the performance of the sensing system started, as shown in Figure 2.1. Given that the measuring system was not able to be placed outdoor during the entire monitoring period, the measurement equipment was only connected to the sensing system at each visit. For each visit, the measurement equipment was connected through extension cords from the laboratory to sensor system for at least consecutive 120 seconds to acquire a steady reading, and not only the capacitance was recorded, but temperature at each measurement was also recorded as reference, since the capacitance can change along with temperature at a very small range. In this way, recording of temperature can help the research group observe the effect of temperature change on the sensor's on-site performance, and provides a reference that if the change of capacitance recorded is because of the temperature change or loss of tension inside the anchor bolts.

FIGURE 2.1. Long term monitoring setup of sensing system

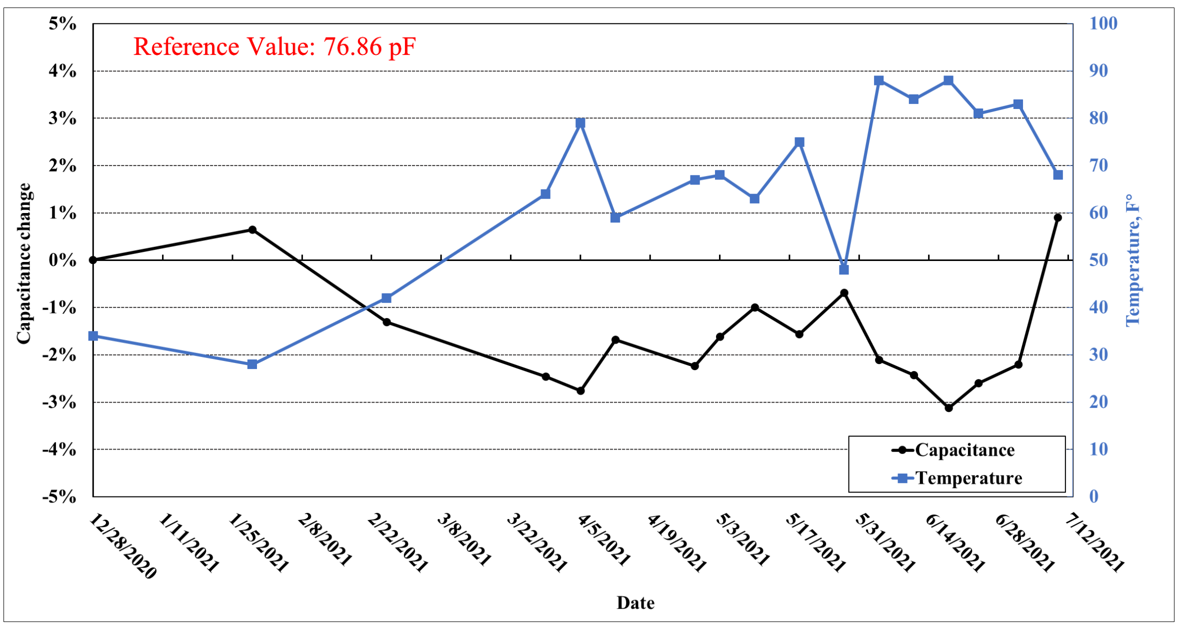

FIGURE 2.2. Results of phase I monitoring (12/28/2020-07/10/2021)

During the first 3 months of monitoring in this phase, the measurements were taken at a monthly basis, but for each year, there were only 12 sets of data collected, which could be less convincing and given the high sensitivity property of the capacitor found in the laboratory, if any abnormality took place between each measurement, the research group could not find it in time. As a result, the research group decided to shorten the measurement period to a weekly basis for a better understanding of the performance of the sensor system. With the temperature recorded during each visit, the results of the first phase of monitoring were plotted in Figure 2.2. It can be seen that the capacitance measurements were mostly concentrated within the range between -3% of the reference capacitance to +1% of the capacitance, which could be correlated with an absolute capacitance change of from -2.3 pF to +0.77 pF. From the plot, it was observed that from the end of December until the end of July, the temperature had risen, with higher temperature recorded, the capacitance tends to show a slight reduction. Also, one more thing that needs to be noticed is that the recorded temperatures were air temperatures, the actual temperature for the washer and anchor bolts can be different. For example, if the air temperature was recorded at 80 °F, the temperature of the specimen could be way higher than this, so that the capacitor may show some reduction in the measurements. This agrees with the property of the capacitor that higher temperatures tend to show reduction on capacitance. With the factor of temperature change being considered, there is no significant evidence on the change of capacitance, and in another words, the loss of tension.

2.3. Second Phase of Monitoring (7/10/2021 - 09/18/2021)

Starting from July 10, 2021, abnormal readings on the capacitance were recorded. During the visit of July 17, 2021, a sudden increase in the capacitance reading up to more than +25% of the original reference value was found (Figure 2.3). Research group found a set of abnormal record of capacitance since July 17,2021 because the arrival of the rainy season. Rainy weather was reported almost every day during that week, causing a higher conductivity for the capacitor, and a higher capacitance value due to high humidity in the air and the water in the gaps within the capacitor. The research group realized that the factor of humidity from the environment was not taken into consideration from the start of monitoring, the following measurements have recorded a reduced capacitance, and for each measurement, no visible water drop was made sure to be found on the surface of sign structure and sensor. To closely monitor the effect of humidity on the performance of the sensor, the research group had further shortened measurement period to every 3-4 days, or twice a week. Each measurement was made sure to be taken on sunny days at least 24 hours after the rain stopped and with no visible water observed on the surface of the specimen and the humidity was controlled at less than 70%. If constant raining or high humidity was reported for consecutive days, one or more measurements would be skipped until the water was dried out. During the following one and a half months of measurements, no more abnormal capacitance reading was observed, the capacitance went back to a relatively steady trend that was close to +5% from the original reference value. Starting from the measurement of 8/14/2021, the readings became stable again, and for the next few consecutive measurements, the capacitance stayed at around +5% from the reference value. Given that the capacitance was higher rather than lower than the reference value, which indicated that the tension inside the anchor bolts were not significantly lost, the research group decided to continue the monitoring plan to the third phase.

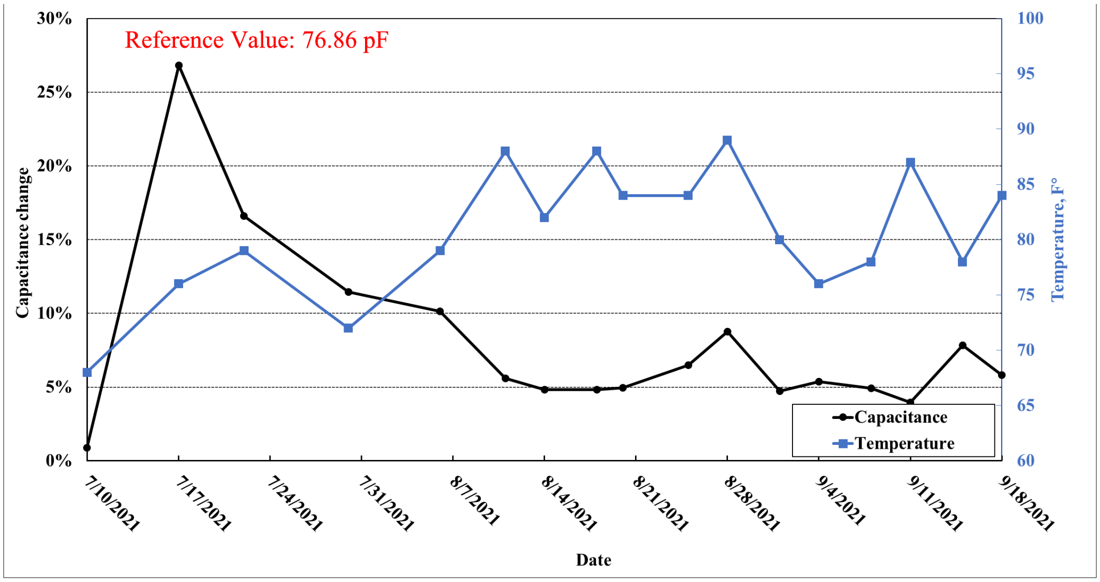

FIGURE 2.3. Results of phase II monitoring (12/28/2020-07/10/2021)

2.4. Third Phase of Monitoring (9/18/2021 - 09/18/2022)

Since it was found that the sensor could be easily affected by the water vapor in the air, or humidity, causing abnormal readings of capacitance. At the end of the second phase of monitoring, the research group had applied a double-layered plastic waterproof cover on the sensor and anchor bolt hoping to protect the sensor from interruption of environment (Figure 2.4). This plastic cover was made of tarps normally applied for laboratory equipment that were easily damaged by water when placed outside.

Every two months, a new set of plastic cover was applied before any possible damage on the cover could take place due to aging of plastic. For each measurement, the protection cover was taken off to see if any water drop existed on the inside of the cover. If water drops were found inside the cover, even if the humidity was lower than 70%, such as the condition shown in Figure 2.5, no measurement would be taken until the water completely dried out. With the change of measurement strategy mentioned previously, a complete 12-month worth of measurements were conducted twice a week, as shown in Figure 2.6. Compared with the reference value set on 12/28/2020, the measurements were mostly found within the range of +5% to +10% from the reference value, and no more abnormal reading of capacitance was observed, especially during the summer, heavy raining weathers no longer caused severe interruptions on the capacitance. After collecting a full year of data, the research group decided to re-calibrate the reference value. By taking the average capacitance records of the first month of the third phase, from 9/18/2022 to 10/18/2022, a new reference value was set, and the capacitance change along time was plotted in Figure 2.7. After re-calibrating the reference value, it was found that the capacitance change was concentrated within the interval of ±5%, and the capacitance followed the trend that increase of temperature would lead to slight reduction in capacitance, but the change was within 5% from the reference value.

FIGURE 2.4. Application of waterproof plastic cover on sensor and anchor bolt

FIGURE 2.5. Water drops observed inside the waterproof plastic cover

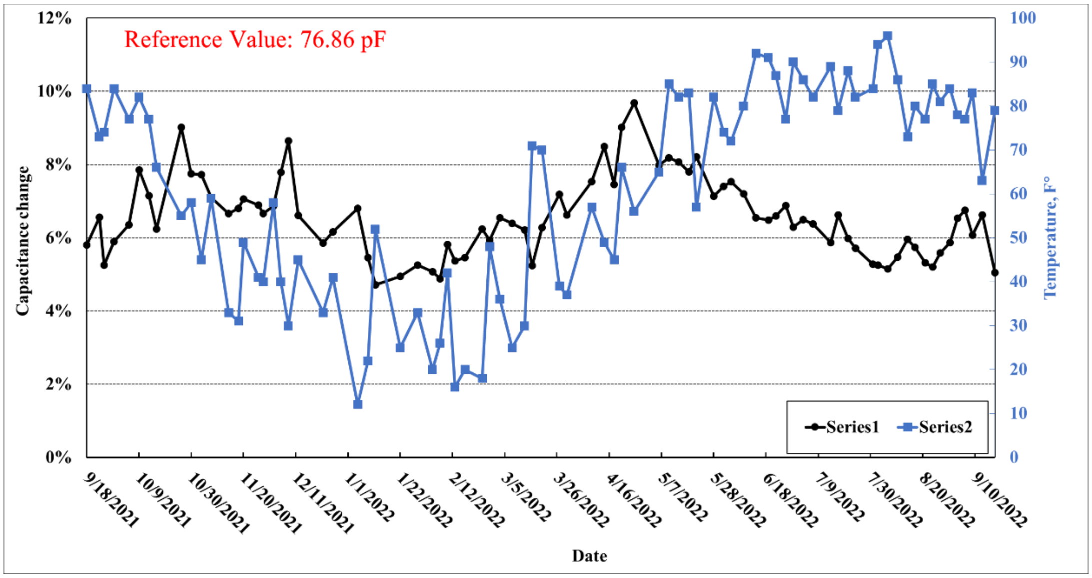

FIGURE 2.6. Results of phase III monitoring

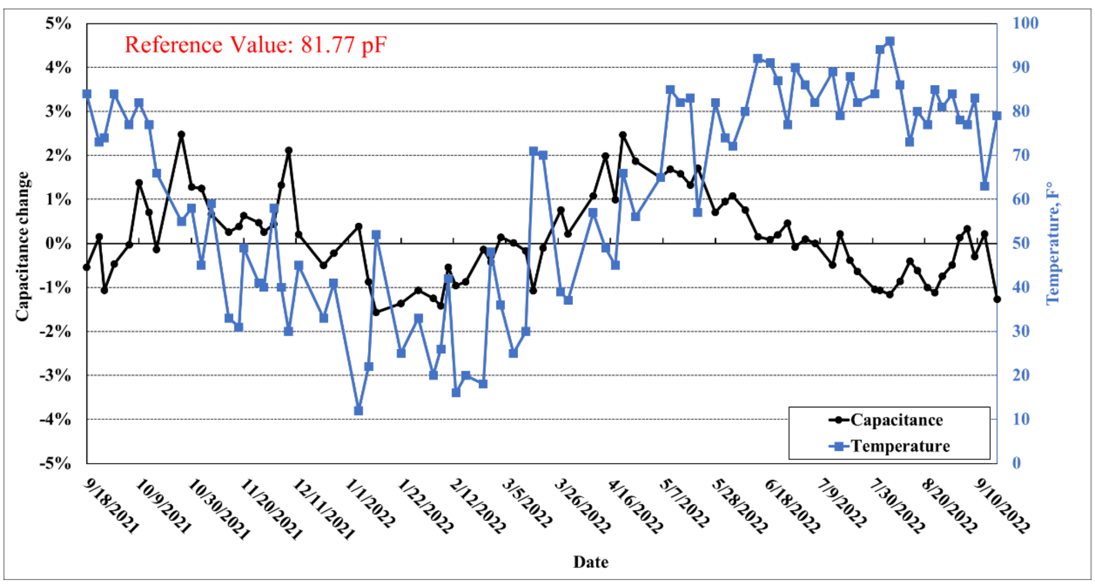

FIGURE 2.7. Results of the third phase of monitoring after adjusting the reference capacitance value

In summary, from the results of the third phase of monitoring, a set of relatively stable readings of capacitance was obtained, the application of the waterproof cover on the sensor and anchor bolt was able to mitigate the interruption from the environment, however, the cover was only a temporary measure and was changed every two months to be cautious. In reality, there is no way that a set of waterproof cover applied during monitoring would last for months or years, so that the research group was still skeptical that the sensor can be implemented on the anchor bolts of the real highway support structures until a proper, long-lasting waterproof cover can be developed as a part of package of the sensor system. Furthermore, the interruption from the environment is inevitable, and the property of a capacitor-based sensor is destined to be sensitive to the environment factors, no matter how the adjustments were made on the design or the package.

3. SUMMARY

This project presents the development of a capacitance-based smart washer system that serves as an efficient way to monitor the tension inside the anchor bolts before the loose anchor bolts can cause severe stability issues. The final prototype of the smart washer system was studied in two stages.

Stage 1 of the project tested the prototype in the in-door laboratory to develop a sensor prototype and a calibration curve to convert recorded capacitance values to tension inside anchor bolts. After a calibration curve on relationship between force and capacitance was successfully established, the smart washer system was applied to the base of a sign structure to simulate the installation process of the anchor bolts with smart washer system. The first prototype was found to lack insulation and proved to have failed, then the second and final prototype with an addition of 3D printed PLA attachments improved the insulation. The final prototype was able to provide sufficient insulation to prevent the interruption from steel sign structure specimen, and stable readings of capacitance were able to be recorded and correlated to the calibration curves developed on single anchor bolt.

Stage 2 of the project was to monitor and assess the in-field performance of the smart washer system, by implementing the smart washer system on a sign structure specimen in the outdoor environment. It was found that the smart washer system was sensitive to the environment, especially during the rainy seasons. After applying some simple protections on the system from water invasion, stable readings of capacitance were recorded. While the system can be implemented in the types of constructure with torque connections where there is no concern of environmental issues, it is recommended to introduce protection mechanism to prevent moistures from entering the system used in the structures exposed to the environment.

In conclusion, the concept and prototype of the smart washer system have been proven efficient, and the sensor system was able to detect change of tension inside anchor bolts. With the proper protection mechanism for outdoor use, this smart washer system can be an efficient tool for the inspecting and monitoring the anchor bolts in supporting structures for transportation as well as similar structures.

PLANS FOR IMPLEMENTATION

The smart washer system holds a potential on replacing the current inspection technique and provides a more accurate way to help decide the necessity for re-tightening. Minnesota Department of Transportation has expressed interest in implementing this system to the new support structures with anchor bolts at base.

This system can be feasible when connected to a wired or wireless transmission that can measure the capacitance, by observing the capacitance readings when the sensing unit is applied to the anchor bolts, the inspection crew can have an idea of the real-time status of the pretension inside the anchor bolts and be able to assess the condition and determine any potential maintenance or repair needs. Furthermore, the concept suits not only large diameter anchor bolts but also all kinds of bolted joints with proper modification.

The developed prototype was found to be able to reach expected performance under indoor environments. Once applied on-site, the limitations from the capacitor property and environmental interruptions have become a big concern and are critical to the performance of the smart washer system where environmental issues are of concern. It is suggested that a simple and efficient protection mechanism is developed by working with relevant professionals to prevent moisture from entering the smart washer system where environmental concerns are severe. It is recommended the invention is directly applied to other types of construction where torque connections are used and environmental issues are minimal such as building construction.

CONCLUSIONS

Based on the results from laboratory testing and long-term monitoring of the smart washer system during the two stages of the project, a few conclusions can be drawn as follows:

- The difficulty of developing the capacitive sensor was underestimated at the beginning of the project, since all the components of the anchor bolt connection were steel and highly conductive, it is not realistic to prevent the entire sensor system from being conductive. Also, the fringing effect was significant.
- The development of the data collection and transmission system that was originally proposed was based on the incorrect concept, leading to the inability of delivering a functional data collection and transmission system.
- Modified sensor design with 3D-printed attachments was developed to address the isolation issue in the original capacitive sensor system. The testing results have shown that the sensor was able to detect significant loss of tension inside the anchor bolts.
- The long-term monitoring results of the sensor system show that the sensor system is also sensitive to environmental conditions such as air moisture and temperature, especially the humidity, high humidity (over 80%) can potentially cause failure of capacitance measurement.
- For future research, if any, the focus should be on how to provide a trustworthy waterproof cover on the smart washer system to withstand the change of the environment, especially for the high-humidity areas.
- Due to the limitations of available equipment and specimens, only 2-1/2” diameter anchor bolts were tested and monitored, but the results have opened up the possibility that this smart washer system can be applied to all similar connections using pretensioned bolts, nuts and washers.

INVESTIGATORS' PROFILES

Dr. Jiehua Jay Shen: Principal investigator (2020-2022)

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APPENDIX: RESEARCH RESULTS

What WAS THE NEED?

As one of the most commonly used connection types on highway support structures such as sign posts, anchor bolts play a critical role in connecting the ground and the structure, and the current inspection techniques cannot efficiently detect the loose anchor bolts in time, so that the risk of severe consequences from loose anchor bolts can be in a great concern.

WHAT WAS OUR GOAL?

The goal of this project is to develop an efficient and durable monitoring system that can observe the real-time force conditions inside anchor bolts and help inspection crew to decide whether re-tightening of anchor bolts is necessary.

WHAT DID WE DO?

Two stages of work were performed in this project:

The first stage was to develop a feasible prototype that can be applied to anchor bolts and capture the loss of tension. The design started from the first initial design that exposed severe insulation issues to current design using 3D printed attachments that mitigated the insulation problems. Several steps of testing were performed, the sensing system was first left still when the nut was at the point of touching the top washer and no pretension was introduced. After stable readings were acquired, tightening and loosening testing of anchor bolts were performed, to observe the performance of the smart washer system under change of pretension inside anchor bolts. After testing in the laboratory, the smart washer system was able to detect significant tension loss in the anchor bolts and a calibration curve that correlated capacitance and tension for 2-1/2” grade 55 anchor bolt was developed.

FIGURE A1. Laboratory tightening/loosening testing setup (left) and long-term

monitoring setup (right) for smart washer system

The second stage of work was to monitor the on-site performance of smart washer system in a long-term duration. At least 12 months of measured data was collected on a frequency of twice a week. An extra waterproof protection cover was applied to help take stable readings of capacitance. With the recording of capacitance, temperature and humidity, interruption from environments were mitigated.

WHAT WAS THE OUTCOME?

From the work of stage 1, the designed prototype was able to detect the change of tension inside the anchor bolts with a tolerance of 10% at maximum. A calibration curve was established in the laboratory, so that the relationship between the bolt tension and capacitance reading can be correlated, and the work of stage 1 prepared the smart washer system for on-site monitoring of stage 2.

In the work of stage 2, it was found that the performance of the smart washer system can be greatly interrupted by environment, after attempts on mitigating the possible environmental interruptions, the smart washer system was able to produce a steady reading of capacitance, and during the course of monitoring, no significant loss of tension was observed, but the smart washer system still needs significant modifications before implementations in the field.

WHAT IS THE BENEFIT?

The key benefit of this project is to demonstrate that the smart washer system can help the inspection crew monitor the real-time status of the tension inside the anchor bolts. Also, the cost on each assembly can be significantly lower than the time and human labor using conventional inspection methods and using remote monitoring can be safer for the highway inspection crew. Based on the collected monitoring data, the smart washer system was able to output stable capacitance readings especially after applying extra waterproof cover and introduces possibility for future implementation. The inspection crew can make judgments on the thresholds of tension value that requires re-tightening, so that reducing the risk of consequences from loose anchor bolts. The results from this project have opened up possibilities that this system can be applied to all kinds of connections using bolts, with an addition of wired or wireless data transfer system, the inspection workload can be considerably reduced.