# Investigation of Retroreflective Sheeting Materials Response to Induced Strain While Mounted to Common Civil Substrates for Use as Passive Strain Sensors for Structural Health Monitoring

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**ABSTRACT**

Retroreflective sheeting materials (RRSM) are used for various applications in engineering, although primarily for traffic signs and roadway markings. There are several ASTM standard types of RRSM that have required values of retroreflection to ensure safe usage. Retroreflectivity (RR) is the portion of light returned to the light source measured in candelas per lux per square meter, as measured using a retroreflectometer. As load is applied to RRSM, the retroreflection changes, and many have a reasonably linear relationship to the material's strain (ε), thus, opening the possibility for using RRSM as a passive strain sensor for structural health monitoring that is low cost, practical, and innovative. Material sensitivity (retroreflectivity divided by strain) is the most important factor when evaluating various standard RRSM types for potential use as passive strain sensors. Previous work has showed that a manufacturer, designated "B"'s standard Type VIII (designated B-TVIII) material has the highest retroreflective sensitivity to induced strain, making it the best candidate for passive sensing. Other materials are also candidates, such as manufacturer "A"'s Type XI white (A-TXIW). To continue to evaluate RRSM's potential to be used as a sensor, an understanding of the material's behavior while adhered to common civil substrates, such as concrete and steel, is necessary. RRSM was mounted to steel and cyclically loaded in tension to examine the RR versus microstrain (µm) relationship, assess mounting procedures and compare results to previous tension tests of the bare materials. Initial results show that the RR-µm relationship of the material tested alone in tension differs from the same relationship when it is adhered to a steel specimen. Several factors were considered, such as surface preparation, RRSM length and adhesion materials to understand why the relationship differs. Through testing, it became apparent that temperature may have an effect on the results and temperature vs RR of B-TVIII and A-TXIW were evaluated and it was determined that the retroreflectivity of the material is lower at lower temperatures.

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## INTRODUCTION

Retroreflective Sheeting Materials (RRSM) are flexible reflective fabric like materials that are made for various applications, but primarily for traffic signs and roadway markings. ASTM D4956, "Standard Specification for Retroreflective Sheeting for Traffic Control" [1] defines standards for 11 types of sheeting material. They are produced by various manufacturers [2]. RRSMs are comprised of several layers, including an adhesive backing so that with proper surface preparation it can be adhered to steel, aluminum, or concrete. Higher grade materials with higher baseline values of retroreflectivity (RR) have a prismatic reflecting layer. Figure 1 shows a schematic cross-section of a typical RRSM with a prismatic reflecting layer.

The Federal Highway Administration (FHWA) Manual on Uniform Traffic Control Devices (MUTCD) [3] requires all public agencies to maintain minimum levels of sign retroreflectivity. To establish compliance, agencies can measure retroreflectivity of a sign using a handheld retroreflectometer, which when held against the material measures the amount of light returned to the source in candelas-per-lux-per-square meter. Many Departments of Transportation (DOTs) make their own traffic signs and are required to periodically measure the retroreflectivity of their signs thus they have access to and familiarity with retroreflectometers and RRSM.

As load is applied to RRSM, the retroreflectivity changes in intensity and as a consequence, RRSM has the potential to be used as a passive strain sensor for structural health monitoring (SHM) [4]. The installation, strain measurement and technology of these sensors are straightforward and inexpensive. The potential applications of these sensors include monitoring dead load induced on bridge super and substructures, observing crack growth in reinforced and prestressed concrete members, residual stress measurements and other circumstances that would benefit from static strain measurements. To implement RRSM on a structure, an understanding of how the materials adhere, and behave while adhered, to common civil substrates is necessary.

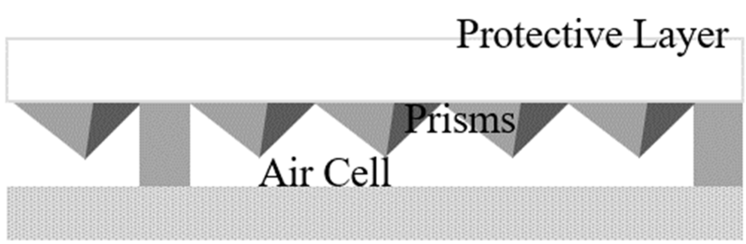
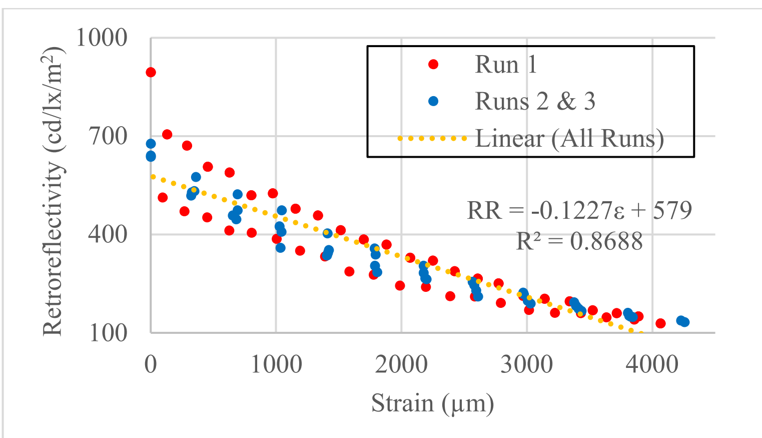


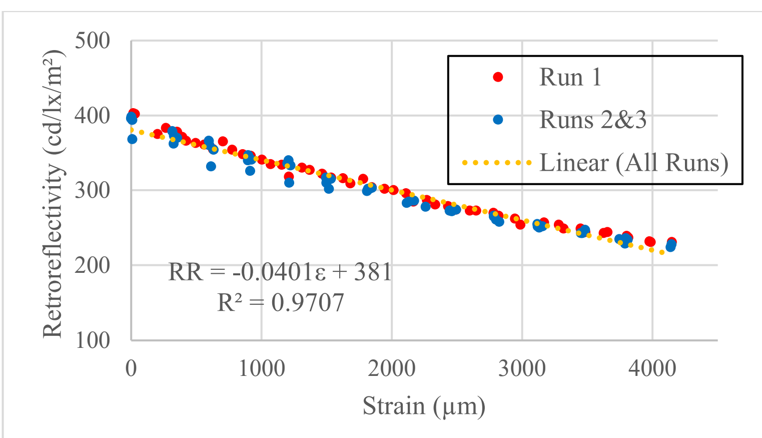

Figure 1. RRSM Composition with Prismatic Layer

## BARE MATERIAL RESPONSE

Previous investigation has shown that certain types of RRSM have a reasonably linear relationship between induced strain and retroreflectivity. These specific materials are likely better candidates to be used as passive strain sensors for SHM as they have higher retroreflective-microstrain sensitivity, low degradation with cyclic loading and high values of strain to failure [4]. The most sensitive identified was a Type VIII material produced by manufacturer "B," based on tension tests of the bare materials. That material is identified here as "B-TVIII." Another potentially good candidate for a passive strain sensor is a white Type XI material produced by manufacturer "A", designated "A-TXIW". The results of cyclic tension tests of these two materials are shown in Figure 2. Retroreflectivity, measured in candelas per lux per square meter, is plotted versus microstrain in the figures for materials B-TVIII and A-TXIW. Sensitivity of all loading and unloading cycles of the bare material tests for all specimens of B-TVIII is -0.1098 and $R^2$ is 0.931. This material has the highest retroreflective sensitivity to strain. Material A-TXIW has an average sensitivity for all cycles of all specimens of -0.0417 and $R^2$ of 0.945. These plots display all data points collected for that specimen as well as the linear regression, equation and $R^2$ value for all loading and unloading cycles.




(a) B-TVIII




(b) A-TXIW

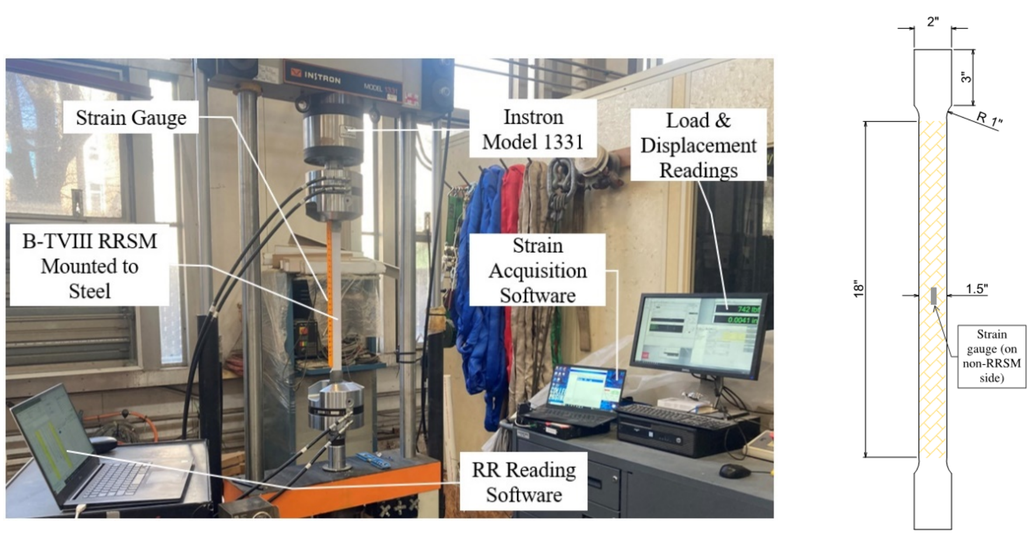
Figure 2. Bare Material Test Results

Sensitivity to strain is the most important variable to consider when evaluating these materials for their use as passive strain sensors. Of all bare materials tested, B-TVIII has the highest retroreflective sensitivity to strain, therefore continued testing on B-TVIII is crucial. Other materials, such as A-TXIW, are not as sensitive, but have tightly correlated, linear relationships between RR and strain, making them candidates to be used as passive sensors and continued experimentation is ongoing.

## TENSION TEST PROCEDURE: RRSM MOUNTED TO STEEL

Thus far, only testing of bare RRSM has been performed, but to be used as a strain sensor, the RR-µm relationship while mounted to a substrate needs to be understood. In this work, strips of B-TVIII RRSM were cut and mounted to ¼" thick A36 steel "dogbone" specimens and tested in tension in an Instron 1331 Test Frame. A sketch of the steel shape as well as a photo of the test set up are shown in figure 3.

Initially, to prepare the surface prior to mounting the RRSM, the steel was sanded using 220 grit sandpaper and cleaned with acetone. The RRSM was cut to be 1.5" by 18" so that it would fit the gage of the steel specimen, the backing was removed to expose the adhesive layer and the RRSM was rolled onto the steel using a rubber roller. The specimen was loaded in tension to 10,000 lb, pausing every 500 lb to take retroreflective readings. It was then unloaded to 0 lb, also pausing every 500 lb. This was repeated for a total of 3 loading and unloading cycles, similar to the bare material tension tests [4]. To determine the retroreflective sensitivity to microstrain, RR readings were recorded along the length of the specimen and those within the center 15" of the specimen were used to evaluate the RR-µm relationship while mounted to a steel substrate.

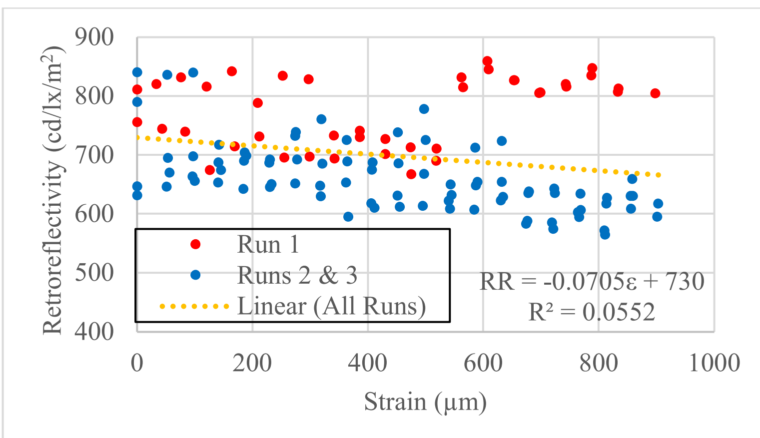



(a) Test Set Up (b) Specimen Dimensions

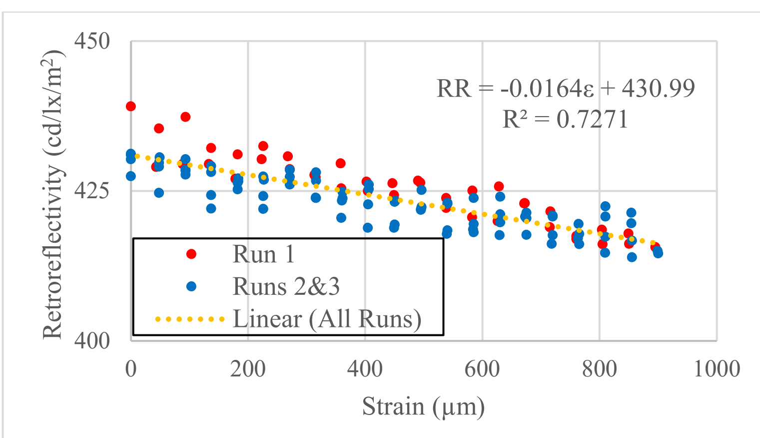
Figure 3. Instron 1331 Tension Test

## TENSION TEST RESULTS: RRSM MOUNTED TO STEEL

Initial results showed that the material behaved much differently when mounted to steel than when the bare material was tested in tension. Sensitivity of all loading and unloading cycles of B-TVIII mounted to steel was -0.0705 and $R^2$ was 0.055. For A-TXIW, RR sensitivity to microstrain while mounted to steel was -0.016 with an $R^2$ value of 0.727. Both materials displayed a decrease in strain sensitivity and correlation when mounted to the substrate. A-TXIW still displayed a linear relationship with a high correlation, while the RR-µm relationship of B-TVIII is considerably more scattered while mounted to steel than the bare material. Figure 4 shows RR vs µm relationships of B-TVIII and A-TXIW materials mounted to steel. The plots of these materials display all data points collected for that specimen as well as the linear regression, equation and $R^2$ value for all loading and unloading cycles. The range of RR measured during the mounted specimen tests was approximately 300 cd/lx/m$^2$ for B-TVIII and 50 cd/lx/m$^2$, therefore different scales were used for the y-axes. When the bare material was tested in tension, the maximum microstrain was approximately 4,000 µε while the maximum microstrain for the mounted tested was limited to approximately 1,000 µε, below the yield strain of steel.




(a) B-TVIII




(b) A-TXIW

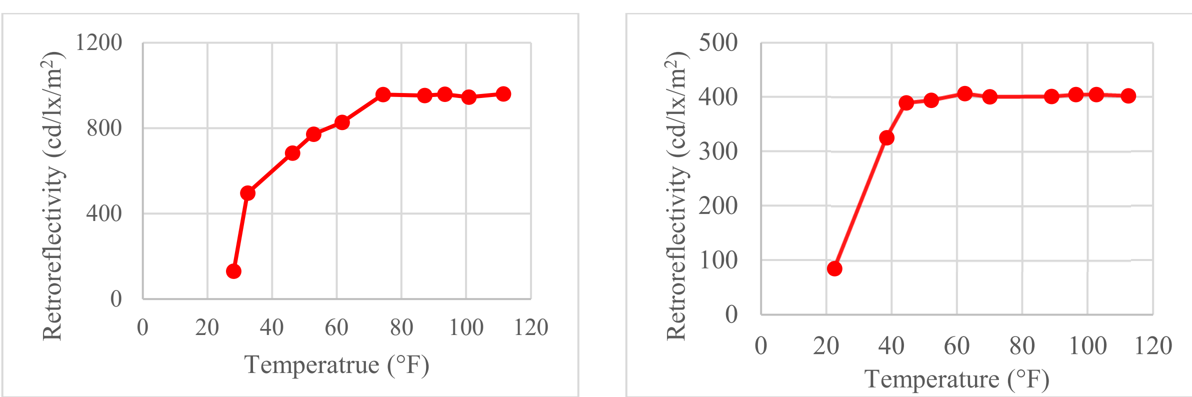
Figure 4. Tension Test Results: RRSM Mounted to Steel

Compared to the tension test results of the bare material, the steel mounted specimens were less sensitive, and had weaker correlations. The lower sensitivity and lack of correlation, particularly in material B-TVIII, led to changes in the testing and surface preparation procedures for tests of the materials mounted to steel. This included using an epoxy coating after sanding and cleaning the steel to improve adhesion, increasing the length of the RRSM so that it was in the grips of the Instron Test Frame rather than just along the gage length of the steel, and putting a line level and gasket material on the retroreflectometer to ensure that no external light affected the RR readings. Overall, these efforts did not improve the RR-µm relationship of the RRSM mounted to steel.

The RRSM-on-steel tension tests of materials B-TVIII and A-TXIW were performed in the months of November – March in a large high bay laboratory with imprecise temperature control. Temperature readings were not taken during the steel mounted tests, but it occurred to the authors that changes in temperature could be affecting the results. Consequently, preliminary tests of the material's RR response to temperature were performed to determine if laboratory temperature could have an impact on the RR-µm relationship and be a contributing factor as to why the material was responding differently than when it was tested alone in tension.

## TEMPERATURE TESTING OF RRSM

Tests were conducted to measure the change in retroreflectivity of the RRSM as a function of the temperature of the material. Temperature evaluation of RRSM was performed using a one square foot piece of material. The material was not mounted for this test. At approximately 10° Fahrenheit intervals, from about 30°F to 110°F, 10 retroreflective readings were taken over the surface of the specimen and averaged. Temperature readings were taken using an infrared thermometer at each interval. The material was cooled and warmed by placing it in a freezer, and then allowed to warm up to room temperature as RR measurements were taken, then placing it in an oven, then allowed to cool down as RR measurements were taken. Figure 5 shows results of the temperature test for materials B-TVIII and A-TXIW. Scales for retroreflectivity vary for each material as their baseline readings differ.




(a) B-TVIII (b) A-TXIW

Figure 5. Material RR vs Temperature Plots

B-TVIII's and A-TXIW's retroreflectivity are affected by temperature. For material B-TVIII, from approximately 30°F to 70°F, RR of the material is lower than its baseline reading (room temperature reading) and increases with increasing temperature. At approximately 70°F, there is an inflection point where the RR of the material plateaus, indicating that at lower temperatures the retroreflectivity of B-TVIII is also lower. For material A-TXIW, the temperature response is similar, but the point at which the retroreflectivity beings to plateau at approximately 40°F, rather than 70°F as it is in B-TVIII.

These temperature test results suggest that results from the tension tests performed on the material mounted to steel in the non-temperature-controlled environment could have poor correlation between RR and microstrain due to the laboratory conditions, rather than adhesion to the substrate. A-TXIW has a more correlated relationship between RR and µm when mounted to steel than B-TVIII and based on the temperature testing of the two materials, laboratory temperature during those tests is likely a contributing factor.

## CONCLUSIONS AND FUTURE WORK

RRSM has the potential to be used as a passive strain sensor for SHM based on its retroreflective-microstrain relationship. To evaluate how it will respond when applied to transportation infrastructure as a sensor, an understanding of the material's adhesion and its RR-microstrain relationship while adhered to common civil substrates is necessary. From tension testing of material B-TVIII while mounted to steel, it is apparent that the material behaves differently than when it is tested in tension on its own. Many adhesion methods were evaluated, and none led to well correlated relationships between retroreflectivity and microstrain as the bare material tests did. Temperature could be a contributing factor to these results as B-TVIII's RR values are lower at lower temperatures. Future work will include continued temperature testing of various material types to determine temperature effects. Tension tests with RRSM mounted to steel are ongoing and future testing will include temperature readings.

## REFERENCES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4. Hannah M. Power, Harry W. Shenton III, *Passive strain sensing for structural health monitoring using retroreflective sheeting materials*, Measurement, Volume 214, 2023, 112763, ISSN 0263-2241, https://doi.org/10.1016/j.measurement.2023.112763.