Temperature Effects on Rail Anchor Slip Force – Year 2

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16. Abstract

Rail anchors are integral to the rail industry due to their effectiveness in improving track stability, enhancing track resistance to longitudinal movement, and preventing thermal-related track failures. The resistance to longitudinal movement allows for maintaining Rail Neutral Temperature (RNT). Temperatures outside the RNT range can lead to derailments and other catastrophic failures. Despite the positive impact rail anchors have in the rail industry, research on the interaction between rail and anchors remains minimal. In this study, utilizing a modified Track Panel Pull Test (TPPT) setup, the interaction of rail and anchor is analyzed with varying temperatures under cyclic loading. Temperatures range from below freezing to extremely hot temperatures, with a range from -10°C (14°F) to 78°C (172°F). Furthermore, displacement-controlled testing procedures were utilized to obtain consistent slip forces, or longitudinal resistances, for specified displacements of the anchors. Temperature affects longitudinal resistance differently for different anchor types. Specifically, resistance consistently increases as temperature increases, but the magnitude of this effect varies by anchor design. From hot to cold temperatures, there was a 38%, 34%, and 32% drop in longitudinal resistance for Anchors X, Y, and Z, respectively.

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List of Abbreviations

AAR	Association of American Railroads
CWR	Continuous Welded Rail
RNT	Rail Neutral Temperature
TPPT	Track Panel Pull Test
USDOT	U.S. Department of Transportation
UTCRS	University Transportation Center for Railway Safety

Disclaimer

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1. Introduction

Continuous Welded Rail (CWR) track stability poses a significant challenge for the modern railway industry. CWR systems offer smoother ride quality and reduced maintenance costs, however, suffer from thermal-related failures more often compared to traditional rail (Rodriguez et al., 2024). This is due to the thermal contraction and expansion of the rail, which can lead to track buckling and rail pull-apart (Kish and Samavedam, 2013). Thermal-related failures have the potential to cause catastrophic derailments, disrupt major operations, and in turn, cause significant financial loss. The increasing costs and hazards associated with derailments underscore the urgency of thoroughly understanding the factors that ensure track stability is adequate.

The rail industry depends on two critical parameters to respond to such challenges normally, which are lateral and longitudinal resistance of the track. Markine and Esveld (1998) performed research using the LONGIN program to study the longitudinal and lateral behavior of CWR tracks. The LONGIN software uses three types of numerical models that analyze longitudinal creep, lateral displacements, and longitudinal displacements. Xiao et al. (2018) performed a full-scale experimental study on ballasted track to evaluate service performance and longitudinal resistance. Their study demonstrated that ballast beds lose compactness gradually due to repeated longitudinal movement caused by the reciprocated movement of the track frame.

Likewise, Jing et al. (2020) carried out field tests on ties with and without end anchors to analyze changes in lateral resistance. Jing et al. (2020) determined that using end anchors on each tie more effectively increases lateral resistance compared to increasing shoulder ballast height. Research on calculating magnitude and distribution of longitudinal fastener loads was performed by Trizotto et al. (2021). Loads caused by passing trains were assessed with a verified method in both the rail and the fastening system.

A full-scale experimental study conducted by Liu et al. (2021) examined how temperature and humidity conditions affect both the longitudinal and lateral resistances of ballast beds in ballasted tracks. They found that lower temperatures and drier environments lead to reduced ballast bed resistance whereas higher temperatures and humid environments increase it. Furthermore, they found that resistance is highly sensitive to temperature variations. In another study, Nobakht et al. (2022) experimentally and numerically studied how vertical loads affect the longitudinal resistance of ballasted railway tracks. The experimental portion involved testing the longitudinal resistance of a track with five concrete ties under various vertical loads. The numerical portion involved a three-dimensional model, using ABAQUS software, which demonstrated a nonlinear relationship between the longitudinal track stiffness and vertical load.

Alizadeh et al. (2022 and 2023) also conducted both experimental and numerical studies on the longitudinal resistance of ballasted railway tracks. However, instead of concrete ties, their focus was wooden and steel ties. A study by Potvin et al. (2023) reviewed crucial factors that influence longitudinal track resistance, which highlighted that accurate measurements of longitudinal resistance could result in fewer components breaking, and in turn, more efficient CWR repairs after rail breaks or destressing procedures. Finally, Dersch et al. (2023) studied a full-scale experiment evaluating how tie type, fastening system, shoulder width, ballast condition, and crib ballast height affect the longitudinal resistance of CWR tracks.

This work expands upon prior work conducted by Rahmaninezhad et al. (2024), where a modified Track Panel Pull Test (TPPT) was developed to study anchor performance and interaction with the rail. This study expands the scope by also investigating the effects of temperature on longitudinal resistance, anchor performance, and the interaction between the anchor and the rail. While Liu et al. (2021) showed that ballast bed resistance is sensitive to temperature changes, Choi et al. (2025) found that temperature fluctuations in CWR rail fractures have a profound impact, further reinforcing the need to understand the thermal-mechanical behavior of CWR systems, including the behavior of the rail anchor itself. This study explores the role of temperature effects on longitudinal resistance of rail anchors, which is fundamental to the maintenance of a stable Rail Neutral Temperature (RNT).

2. Summary

This report presents the second-year findings from a research project focused on the effects of temperature on the longitudinal resistance of rail anchors within a CWR system. The research builds upon previous work, where a full-scale modified TPPT was designed and fabricated by researchers at the University Transportation Center for Railway Safety (UTCRS). The primary objective of the second year was to utilize the TPPT to study the impact of varying temperatures on rail-anchor performance.

The report includes sections on test apparatus, instrumentation, measurements, and methodology used during experiments. The results reveal critical insight into the behavior of rail anchors under different thermal conditions, such as a direct correlation between reduced temperature and reduced longitudinal resistance. This finding demonstrates the importance of temperature-related maintenance for railway safety, as it suggests that the performance of rail anchors is sensitive to environmental temperature.

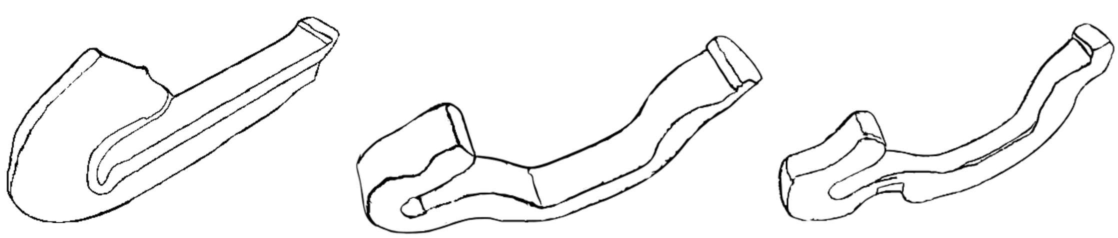
Although the findings offer a deeper understanding of temperature effects on rail anchor performance, the data collected during this research are specific to the modified TPPT test apparatus. Therefore, the findings should not be generalized across different systems. Further research will expand the study to include more anchor types, a wider range of temperatures, and long-term cyclic testing to gain a further understanding of the long-term thermal effects.

3. Modified TPPT Setup, Instrumentation, and Anchors

3.1 Anchor Types

This study evaluates three types of anchors: Type X, Type Y, and Type Z (**Figure 1**). These anchors were selected based on their distinct geometrical and structural characteristics, as well as their capacity to resist longitudinal loads. The performance of these anchors is also impacted by their design dimensions and material composition. As detailed in **Figure 1** and **Table 1**, the dimensions of each anchor were recorded prior to testing. Specifically, internal width and clamping height were recorded.

Installation of the anchors was performed following standard field methods, involving each anchor being driven onto the rail using a sledgehammer. Additionally, to maintain consistency, a single designated operator was assigned for anchor comparisons to mitigate the variability inherent to manual installation.



(a) **(b)** **(c)**

Figure 1. Anchors: (a) Type X, (b) Type Y, and (c) Type Z

3.1.1 Anchor Dimensions

Physical properties of each anchor are characterized by two key dimensions: clamping height and internal width. Illustrated in **Figure 2**, these critical parameters are essential for understanding the fit and load distribution of each anchor. Measurements of these dimensions were taken using a dial caliper with a resolution of 0.001 inches.

Measurement procedures for the clamping height, which grips the top and bottom of the foot, consider the physical properties of the anchor. The caliper was translated along the surfaces between the clamping height to obtain the minimum value. The internal width, which spans the base of the rail, or the width of the foot, exhibits less variation across measurements and is the more straightforward dimension to measure.

The relative importance of the aforementioned parameters and their relation to slip force are a subject of ongoing investigation. Preliminary data indicates a negative correlation between clamping height and peak load, suggesting that a smaller clamping height may contribute to higher longitudinal resistance.

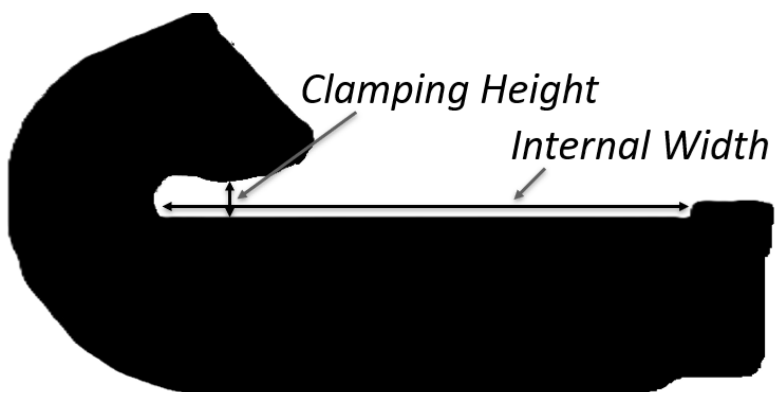


Figure 2. Schematic section of anchors

Table 1. Anchor dimensions before testing

Anchor Type	Internal Width (inch)	Clamping Height (inch)
X	6.10	0.60
Y	6.20	0.55
Z	6.10	0.50

3.2 Test Apparatus Setup

The modified TPPT setup at the UTCRS is composed of a rail, hydraulic system, instrumentation, and safety measures. **Figure 3** shows the physical layout and configuration of the test apparatus. The design and subsequent modifications constituted a significant portion of the first year of this project; the goal was to create a solid foundation for evaluating slip force performance. For the second year of research, the setup was modified to analyze the effects of temperature on slip force.

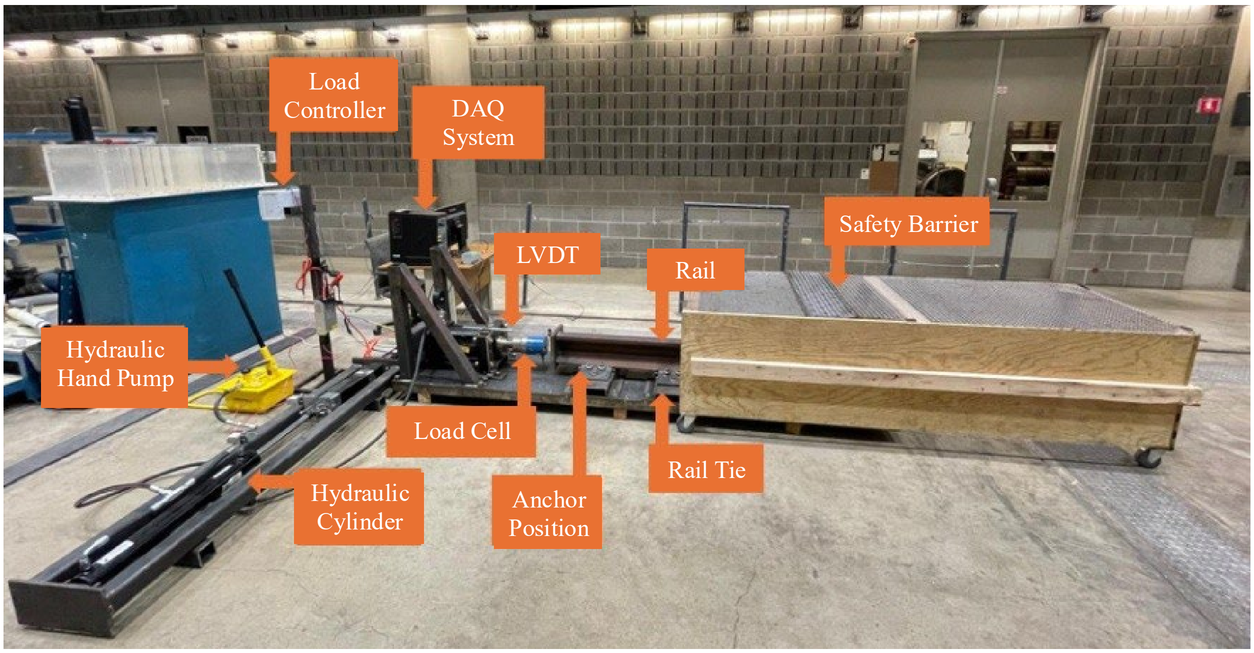


Figure 3. Modified TPPT setup

3.2.1 Dimensions

The overall footprint of the test setup was 10 feet by 9 feet. Specifically, the track and rail section occupied a 10-foot by 3-foot area, while the auxiliary section measured 9 feet by 2 feet. The original version of the setup had a smaller footprint due to an upright configuration of the load controller, as depicted in **Figure 4**; however, the auxiliary hydraulic cylinder was placed horizontally, as shown in **Figure 3**, due to necessary modifications made to increase the load capacity. A short rail segment measuring 26 inches (approximately 2.2 feet) was still utilized in this year's study. This segment length was chosen to ensure sufficient contact with the load cell and proper weight distribution across the rail tie.

Figure 4. Early TPPT setup before modifications

3.2.2 Base Plate and C-Shape Steel Channel

In place of traditional ballast and ties, a thick steel base plate and a C-shaped steel channel are used. The hardened steel setup effectively simulates ballast and ties with significantly higher stiffness and rigidity, allowing for precise evaluation by isolating the effect of anchor performance. To enhance rigidity and eliminate anchor rotation, a steel plate was welded to the channel between the C-shaped steel channel and the anchor. The steel setup enables the isolation of the effect of rail anchors, decoupling their performance from other factors, such as anchor rotation. **Figure 5** shows the contact between the steel plate and the anchor during testing.

Figure 5. Rail, tie, and anchor

3.2.3 Load Controller

The load controller, built by researchers at UTCRS, provides a consistent load rate for the system by regulating the voltage to the jackscrew motor, which allows direct management of the rate of extension of the jackscrew (**Figure 3**). The jackscrew works in series with the primary and secondary auxiliary hydraulic cylinder. The original auxiliary cylinder and jackscrew were smaller and deemed insufficient, therefore, they were replaced with a larger-scale system.

3.2.4 Hydraulic Cylinders

The test setup utilizes two hydraulic cylinders in series to apply a load to the system (**Figure 3**). The main cylinder serves as the primary mechanism for generating load from the hydraulic circuit, making direct contact with the rail's horizontal polar moment of inertia. The auxiliary cylinder is in series with the main cylinder and jackscrew, ensuring accurate and adjustable loading for controlled experimental conditions.

3.2.5 Hydraulic Pump

The manual hydraulic pump is primarily used to preload the rail to maximize the stroke length of the auxiliary cylinder. The hydraulic pump has an oil capacity of 453 cubic inches and operates at a maximum pressure of 10,000 psi.

3.2.6 Safety Barrier

A safety barrier, constructed of 1-inch-thick plywood on the sides and a top section of carbon steel expanded sheet, encloses the portion of the setup containing the rail and anchor to ensure user protection and to mitigate risk in the event of a catastrophic failure during testing.

3.2.7 Anchor Installation

The rail anchors are installed by a dedicated operator using the standard field method, which involves driving them onto the rail with a sledgehammer. The use of a designated operator is crucial to ensure consistency in the experimental results.

3.2.8 Thermal Control

To evaluate the temperature effects on longitudinal resistance, thermal conditioning for hot and cold temperatures was applied to the test setup. For elevated temperatures, two BRISKHEAT HSTAT301002 heating tapes were secured to each side of the rail using magnets, as shown in **Figure 6**. The heating tape measures 24 inches in overall length, 3 inches in overall width, and 1/8-inch thick, and capable of operating temperatures up to 424.4°F (218°C). For lower temperatures, the rail segment was chilled with a standard freezer overnight to achieve thermal equilibrium before testing. The freezer is capable of temperatures as low as -4°F (-20°C).

Figure 6. Side view of the rail with heating tape secured by magnets.

3.3 Instrumentation

3.3.1 Load Cell Sensor

A load cell was utilized to continuously monitor and record the load applied longitudinally to the rail segment throughout testing, and to effectively capture load behavior as shown in **Figure 7**. Additionally, the load cell captures the maximum load exerted on the system through the rail-anchor interaction, which is critical for evaluating the longitudinal performance of the anchor. The load cell was attached to the end of the hydraulic cylinder, axially aligned with the rail to accurately measure the longitudinal resistance. Peak load and the subsequent return to a near-zero load state were recorded in each cycle during testing.

3.3.2 Linear Variable Differential Transducer Sensor

A linear variable differential transducer (LVDT) was used to measure the displacement of the rail relative to its initial position during testing, as shown in **Figure 7**. The position of the LVDT was moved to align with the polar moment of inertia at the end of the rail during single-tie rail testing; however, since no significant errors were detected, the tests conducted with the double-tie rail and four-tie rail were performed with the LVDT positioned in its original position. The original and current position of the LVDT is placed above the hydraulic cylinder's frame, extending to the rail. The LVDT provided the displacement data used to generate the load versus displacement figures for each test cycle. The LVDT also enabled control of the displacement, crucial for the data of this report. Precision in displacement measurement was ensured by using a high sampling rate (15 Hz) while testing.

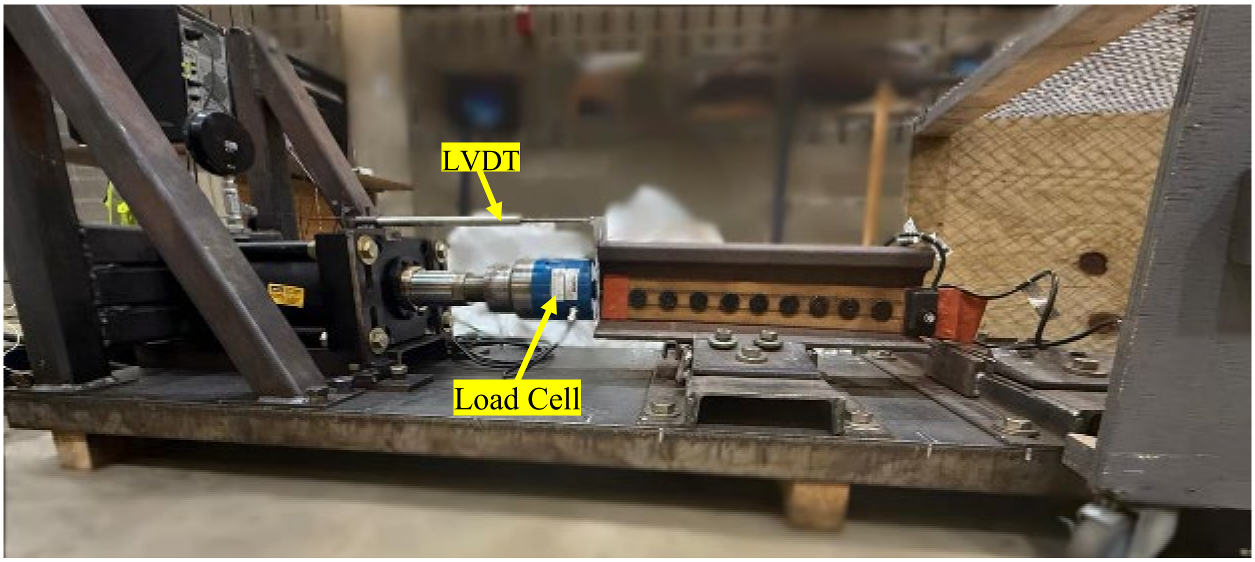


Figure 7. Position of the load cell and LVDT.

4. Test Refinement and Workshop Guidance

In collaboration with MxV Rail and BNSF Railway, the testing methodology was refined through consultations with their engineers. This year's on-site visit served to review and confirm the integrity and execution of the ongoing research. The visit included a presentation of preliminary data, followed by a live demonstration of the testing procedures.

The primary focus of the demonstration was the temperature-based testing methodology. The application of the heat pads and the protocol for using the freezer were demonstrated and discussed. Additionally, proper installation of anchors to ensure consistency and adherence to best practices established in the field was reaffirmed. Valuable practical insight was provided by the engineers, validating the current test protocols and deepening the understanding of how anchors behave in rail revenue service.

These consultations were critical to maintaining the reliability and validity of the research, ensuring that the study is aligned with industry standards.

Figure 8. Training workshop on 3/24/25.

5. Results and Discussions

5.1 Test Procedures

Each cycle began with preloading the rail by manually pumping the hand pump until 5,000 lbs were exerted on to the rail. The 5,000 lbs preload may not be reached during the first cycle due to the anchor settling. Next, the load controller applied load at a constant rate of 10,000 lbs/min until the desired maximum displacement of 0.2 inches was achieved for each cycle, at which point the load was removed. By controlling the specified displacement of each cycle, the amount of loading for each cycle gradually increased as the tests progressed. Towards the end of the 15th cycle, the load steadied out and did not exhibit a significant change.

5.2 Key Findings

The primary findings from the thermal cyclic testing and its implications for track stability and maintenance are discussed in this section. The data was collected from approximately 15 cycles of testing per anchor type at each of the different temperature setpoints (cold, ambient, and hot) which highlighted the significance of temperature effects on rail anchor performance.

5.2.1 Effect of Temperature on Longitudinal Resistance

A significant relationship between temperature and longitudinal resistance was demonstrated by the data. The results show that as temperature increased, the peak load recorded also increased. Conversely, lower temperatures corresponded to lower longitudinal resistance. The behavior is likely due to thermal expansion and contraction of the rail, which is hypothesized to directly impact the clamping force provided by the anchor.

5.2.2 Impact of Cyclic Loading

Testing revealed that cyclic loading significantly affected anchor performance. Each cycle degrades the anchor performance with a clear distinction in the load versus displacement curve, showing a loss of longitudinal resistance. Although the load returns to zero after it is released at the end of the test cycle, a residual displacement of the rail remains, indicating a gradual permanent slip of the anchor. The results show that anchors lose grip over time due to repetitive mechanical and thermal stress, even without a constant load.

5.3 Discussion of Results

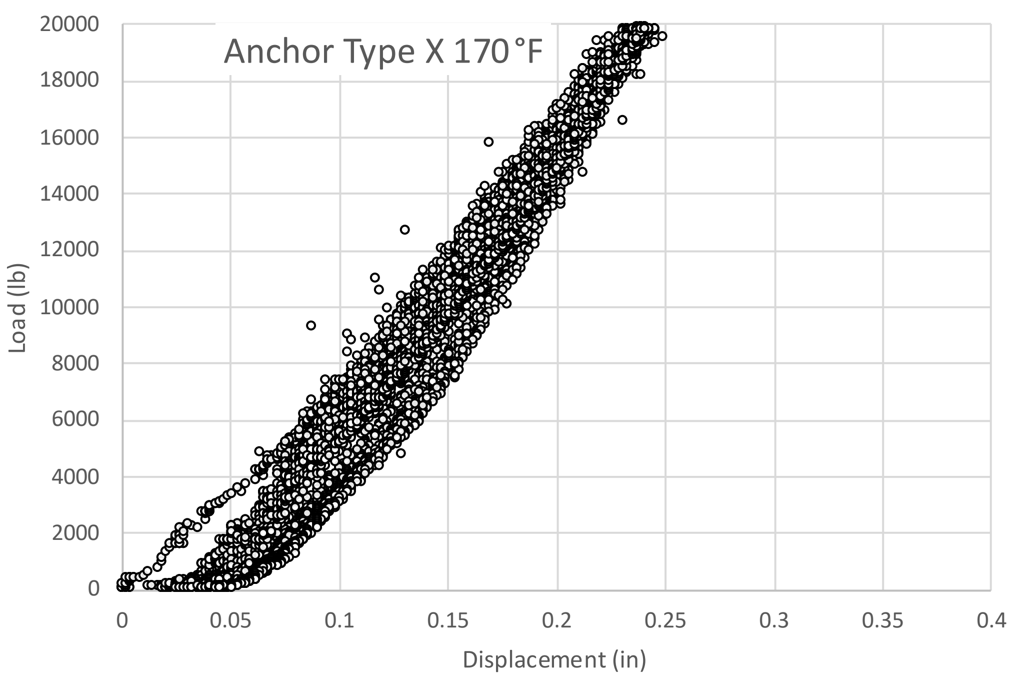
The findings have direct implications for railway maintenance and safety. The need for specific maintenance during cold weather is validated by the results, which demonstrate a decreasing longitudinal resistance of rail anchors at low temperatures. Furthermore, the occurrence of permanent displacement during cyclic loading highlights the importance of anchor long-term durability and the ability to maintain resistance in addition to initial clamping force.

Load versus displacement curves for the three anchor types, X, Y, and Z, are shown in **Figure 9**, **Figure 10**, and **Figure 11**, respectively. The results are not intended for comparison between different anchor types, should not be considered for specification benchmarks, and pertain only to this specific test setup. The results serve as an analysis of load-displacement behavior and illustrate how temperature affects the performance of rail anchors.

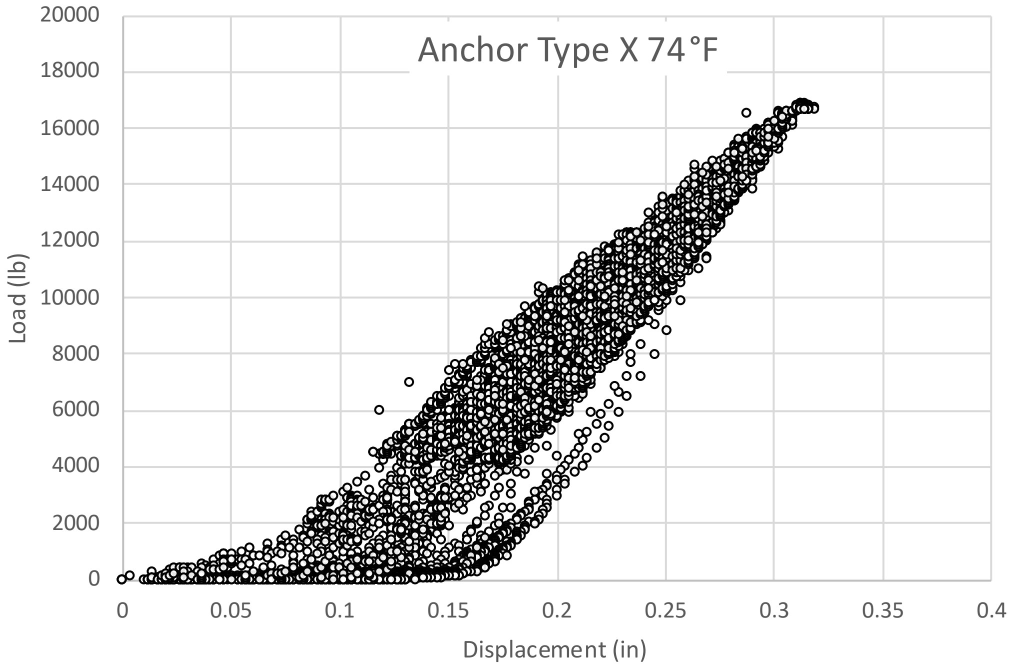
Each anchor exhibited a different maximum load within the 15 test cycles at the various temperatures. Each anchor type displayed a consistent behavior in which cold temperatures exhibited the lowest slip forces. Conversely, the anchors at higher temperatures had a higher peak slip force. The three test temperature ranges are referred to as hot (164-172°F), ambient (74-75°F), and cold (14-61°F). Anchor type X (**Figure 9**) produced maximum loads of 19,900 lbs, 16,800 lbs, and 11,400 lbs for the hot (170°F), ambient (74°F), and cold (14-50°F) tests, respectively. Anchor type Y (**Figure 10**) produced maximum loads of 17,300 lbs, 14,600 lbs, and 11,500 lbs for the hot (164°F), ambient (75°F), and cold (14-61°F) tests, respectively. Finally, anchor type Z (**Figure 11**) produced maximum loads of 14,500 lbs, 13,300 lbs and 9,700 lbs for the hot (172°F), ambient (74°F), and cold (18-36°F) tests, respectively.

A 9%, 16%, and 8% drop in longitudinal resistance for Anchors X, Y, and Z, respectively, were observed when comparing the hot and ambient temperature conditions. In addition, there was a 33%, 22%, and 27% decrease in longitudinal resistance for Anchors X, Y, and Z, respectively, when comparing ambient temperature conditions to cold temperature conditions.

The maximum displacement for anchor type X was 0.34 inches, 0.25 inches, and 0.22 inches (**Figure 9**), for the hot, ambient, and cold tests, respectively. Anchor type Y experienced maximum displacements of 0.34 inches, 0.40 inches, and 0.29 inches (**Figure 10**), for the hot, ambient, and cold tests, respectively. Lastly, the maximum longitudinal displacement for anchor type Z was 0.26 inches, 0.29 inches, and 0.23 inches for the hot, ambient and cold tests (**Figure 11**), respectively. No direct correlation between maximum load and maximum displacement during testing could be discerned. Higher temperatures positively correlate with increased anchor capacity, as thermal expansion enhances the clamping force and creates a beneficial increase in resistance.



(a)



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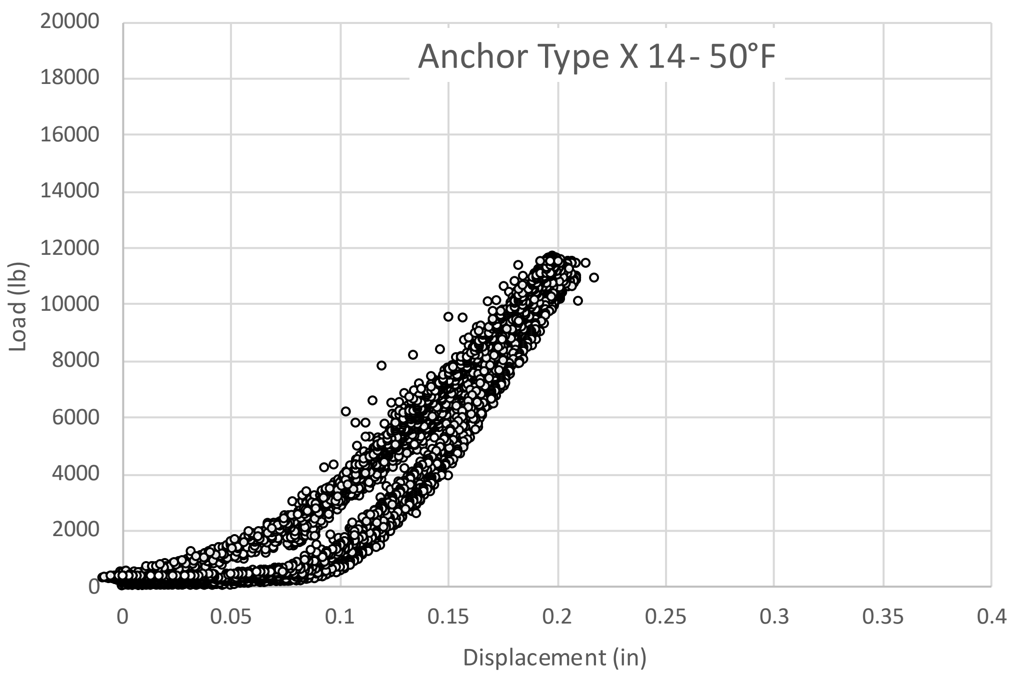
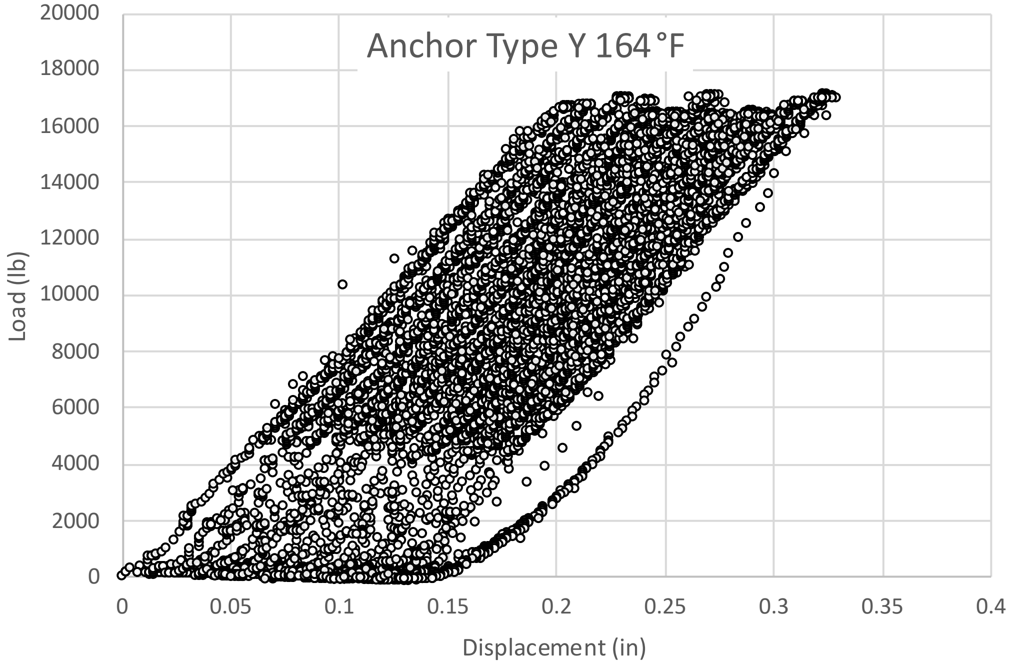


(c)

Figure 9. Anchor Type X Results: (a) Hot, (b) Ambient, and (c) Cold.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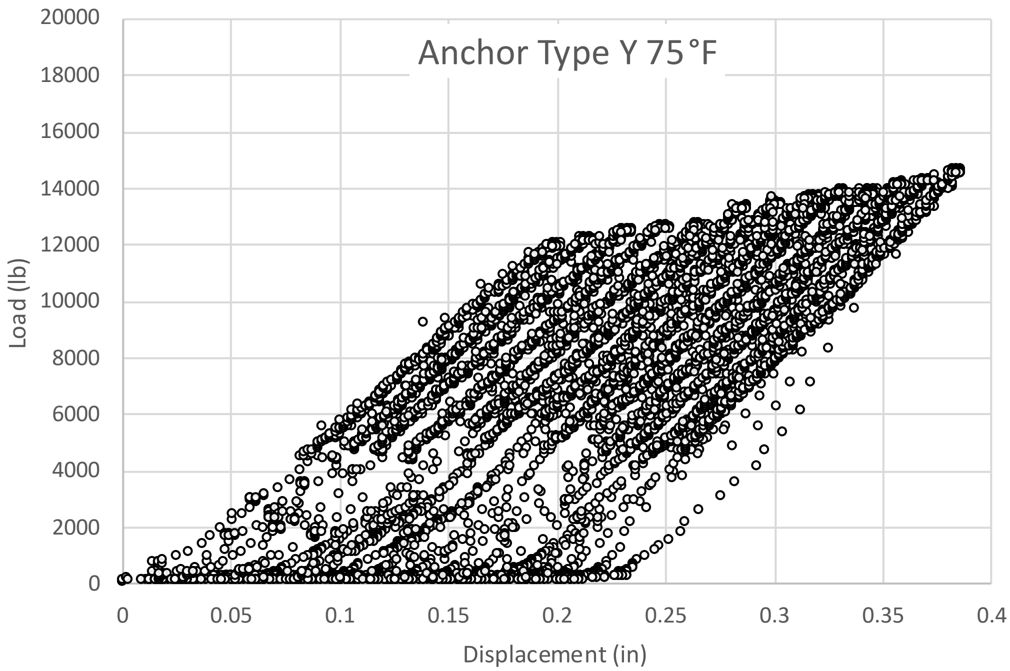
Load (lb)
Displacement (in)
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4

(a)


Anchor Type Y 75 °F
Load (lb)
Displacement (in)
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18000
16000
14000
12000
10000
8000
6000
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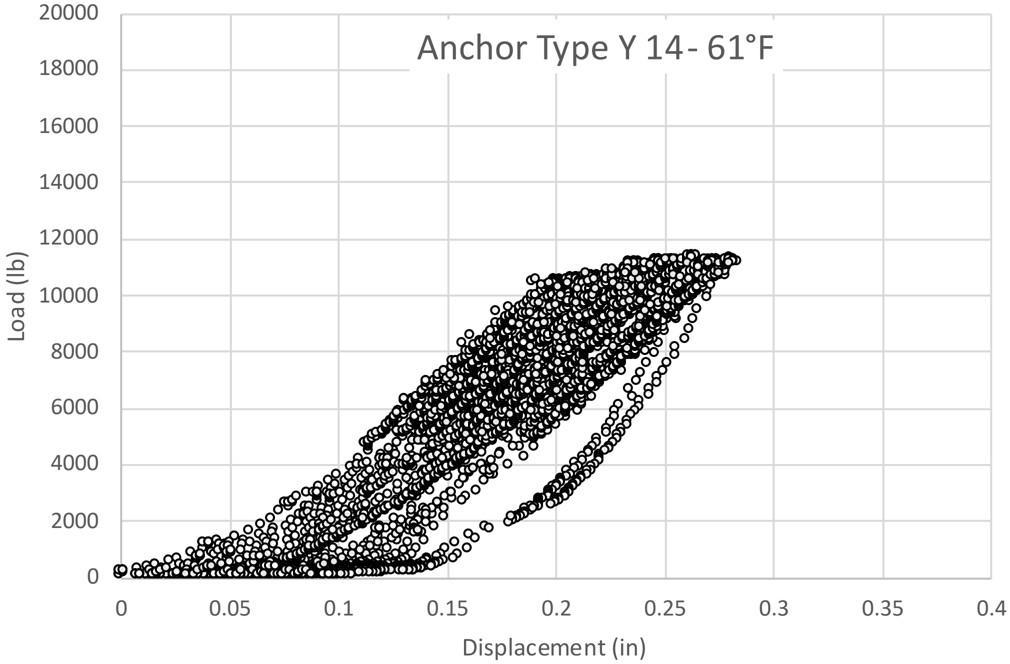
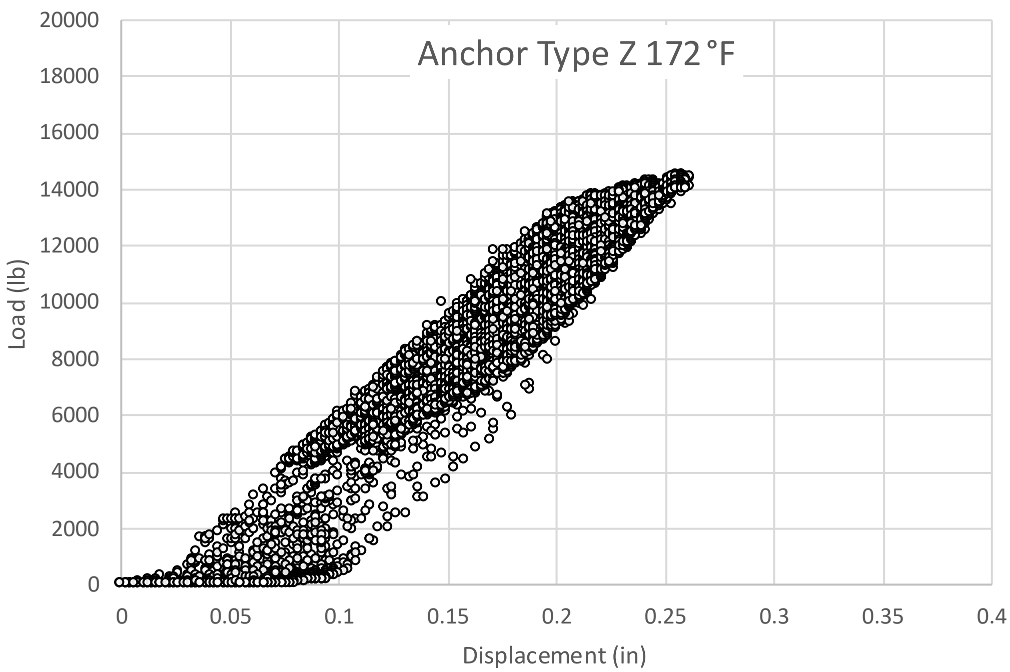
(b)



(c)

Figure 10. Anchor Type Y Results: (a) Hot, (b) Ambient, and (c) Cold.



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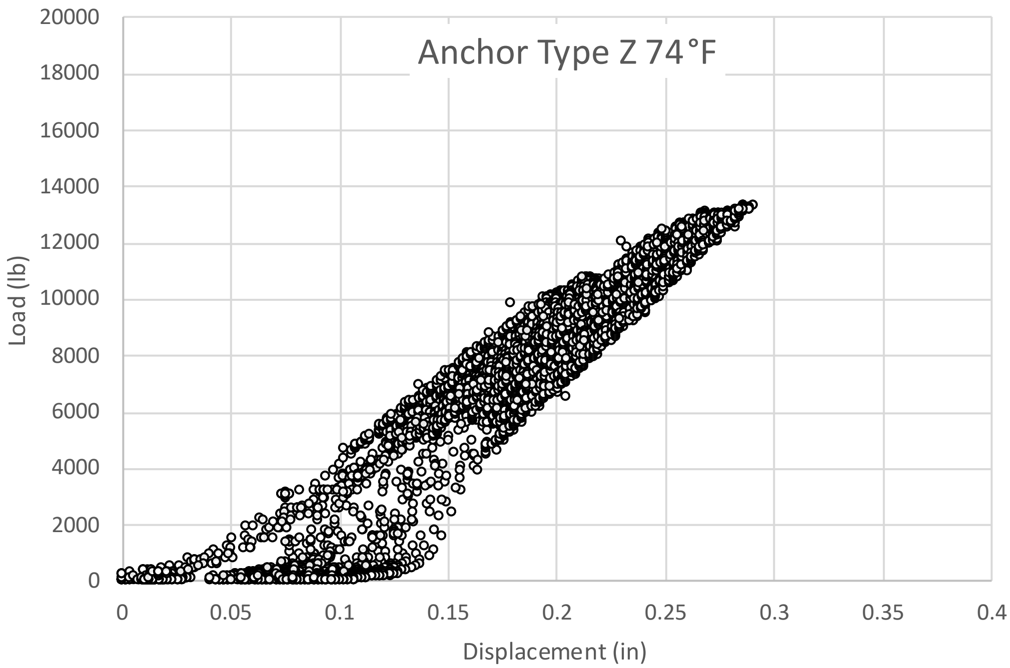

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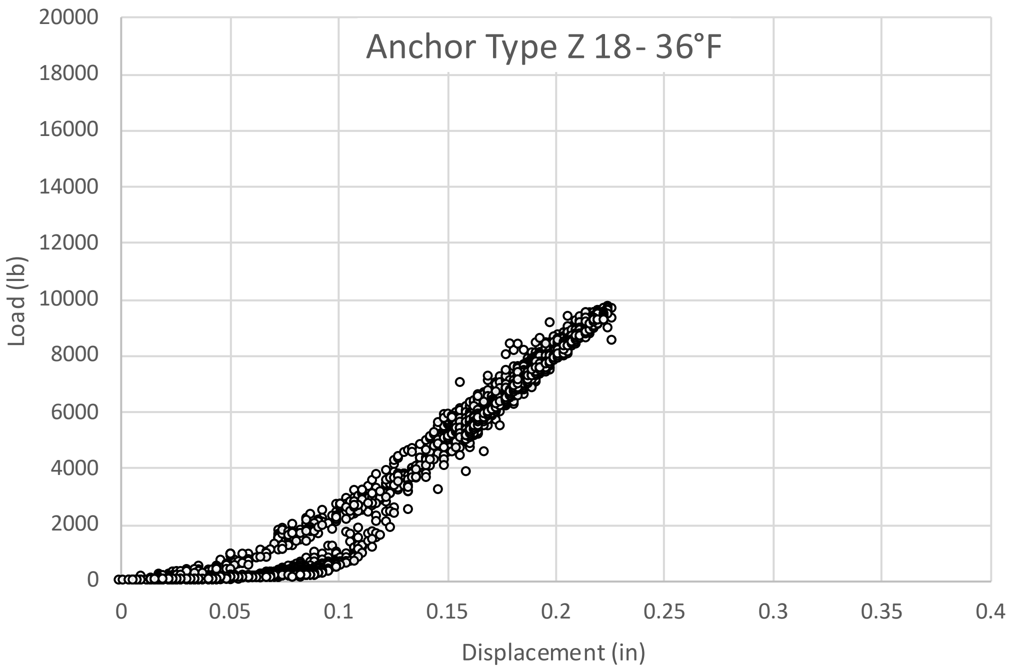

(c)

Figure 11. Anchor Type Z Results: (a) Hot, (b) Ambient, and (c) Cold.

6. Conclusions

The primary focus of the study was to evaluate the temperature effects on the longitudinal resistance of rail anchors utilized on Continuous Welded Rail (CWR) systems. A portion of the project was to modify the previous test setup to simulate temperature changes and assess the performance of three anchors with varying designs. Each anchor was tested at three different temperature ranges, hot (164-172°F), ambient (74-75°F), and cold (14-61°F), resulting in approximately 45 tests per anchor type. The behavior of each anchor type at the various temperatures was analyzed to examine changes in longitudinal resistance.

The results included in this report are specific to this test setup and are preliminary; therefore, they are not suitable for specification benchmarks or comparisons. The data shows that lower temperatures result in a noticeable drop in longitudinal resistance; conversely, the longitudinal resistance has a smaller increase but is still positive as temperature increases. This indicates that rail anchors resist more load at higher temperatures. A 9%, 16%, and 8% drop in longitudinal resistance for Anchor X, Y, and Z, respectively, were observed when comparing the hot and ambient temperature conditions. In addition, there was a 33%, 22%, and 27% decrease in longitudinal resistance for Anchor X, Y, and Z, respectively, when comparing ambient temperature conditions to cold temperature conditions. Finally, there is a 38%, 34%, and 32% drop in longitudinal resistance for Anchor X, Y, and Z, respectively, when comparing the hot and cold conditions.

The displacement behavior shows a weaker correlation than the longitudinal resistance response under varying temperature conditions after cyclic loading. Anchor X shows a 31% maximum displacement increase from cold to ambient temperature and a 27% maximum displacement decrease from ambient to hot temperatures. Anchor Y shows a 27% maximum displacement increase from cold to ambient temperatures, however, there is a 16% drop in maximum displacement from ambient to hot temperatures. Anchor Z has a 23% increase in displacement from cold to ambient temperature but shows a 13% drop from ambient to hot temperatures. The cold tests consistently showed the least amount of maximum displacement after the 15^{th} cycle. This suggests that although load capacity increases with temperature, displacement response may depend on other anchor geometry and material properties.

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