Chapter 15
The Great Train Disaster of 2025: Isolating Sensitive Equipment from Rail-Induced Vibration

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Abstract Ground-borne vibrations from railroads are often assessed for their impacts on human comfort and vibration-sensitive equipment in nearby structures, but in rare cases, there is vibration-sensitive equipment located directly on the tracks and supporting structure itself. One such example is known as an Impedance Bond (Bond), which is a crucial component in railway signaling systems, particularly on electrified railways. It allows traction current to flow through the rails while simultaneously blocking the flow of alternating current (AC) used for signaling, ensuring both traction and signaling systems can operate independently and safely on the same track. Bonds typically have vibration criteria, which, due to the circuit boards in them that contain several delicate components, can be very strict at frequencies much higher than are usually considered for human comfort or typical vibration-sensitive equipment.

This paper describes a project on a major commuter rail line in the United States where several Bonds were failing repeatedly at a discrete number of locations on the system. Extensive measurements and investigation determined that that a combination of locally poor track conditions and inadequately designed isolation systems were responsible. Several new isolation systems were considered, as well as track quality improvements in order to eliminate the repeated failures that were causing significant issues with the operations of the rail network.

Keywords Vibration Serviceability · Ground-borne Vibration · Vibration Isolation · Vibration Measurements · Model Validation · Dynamic Loading

Introduction

Impedance Bonds (Bonds) (example shown in Figure 1) are crucial components in railway signaling systems, particularly on electrified railways. It allows traction current to flow through the rails while simultaneously blocking the flow of alternating current (AC) used for signaling, ensuring both traction and signaling systems can operate independently and safely on the same track. These components are typically installed within the track gauge and are subjected to vibrations from passing trains, the intensity of which is influenced by local track conditions and mounting configurations, which usually include local vibration isolation systems. These isolation systems, which are provided by the Bond supplier as part of the overall system, are typically 3/8" neoprene pads that sit between the Bond the mounting frame below. Critically, the Bonds have bolts that penetrate the isolation pad that end with washers and nuts on the lower side of the mounting frame, which provides a destructive short-circuiting of the isolation system. The effects of this deficient mounting configuration will become evident throughout the course of this paper.

This paper describes a project on a major commuter rail line in the United States where several Bonds were failing repeatedly at a discrete number of locations on the system. An extensive testing regiment was conducted to understand the failure mechanisms of the Bonds, which also included microscopic investigation of the internal components to determine how each failed.

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Fig. 1 Typical Impedance Bond

Vibration Criteria

Impedance Bonds are intended to be designed in accordance with the vibration protocol specified in the American Railway Engineering and Maintenance-of-Way Association (AREMA) Communications & Signals (C&S) Manual [1], which serves as the basis for their conformance and acceptance testing. This protocol involves a sinusoidal vibration sweep characterized by a constant amplitude of 0.2 inches for frequencies between 5 Hz and 20 Hz, and a constant acceleration of 4.2 g for frequencies above 20 Hz up to 200 Hz (see Figure 2), along with a 10 g shock limit lasting 0.11 milliseconds. The assessment criteria are denoted as Class A Roadbed which is applicable to the equipment located on a track.

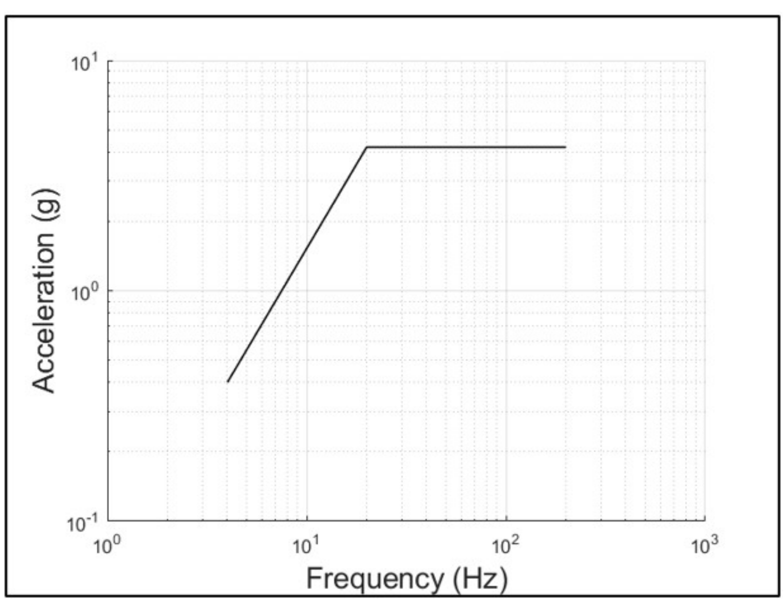


Fig. 2 AREMA Class A Vibration Assessment Criteria

Initial Testing

Initial testing was conducted at the location of one of the Bonds that had been failing repeatedly. The purpose of the testing was to measure the vibrations experienced on frame below the Bond, as well as the Bond itself (which was intended to be isolated by 3/8" thick neoprene pad). These measurements were then compared to the AREMA criteria to determine if those acceptance levels were being exceeded. The efficacy of the isolation system was also calculated. The following conclusions were drawn from the initial testing:

- Consistently high-magnitude energy content at high frequencies between 700 Hz and 1000 Hz were measured. See Figure 3 for one-third frequency content in the vertical direction atop the Bond. These high magnitude forces at these high frequencies are generated by the wheel-rail interaction, particularly when the trains are running at high speed. It is noted that significant rail corrugation was observed at the failure location. The existence of rail corrugation and high speed of the train pass-bys could be attributed to these high vibration levels at these frequencies.
- It should be noted that measurements were taken at frequencies considerably higher than the 200 Hz upper limit of the AREMA criteria. As can be seen in Figure 3, the levels of the accelerations above 200 Hz are an order of magnitude higher than those below 200 Hz, which points to a potential deficiency in the criteria limits used by AREMA.

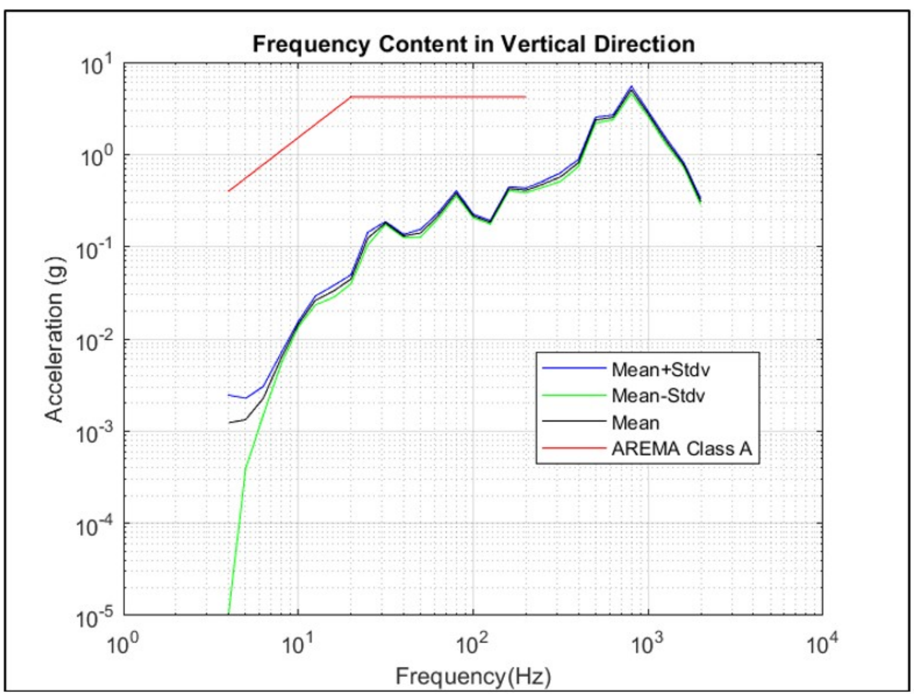


Fig. 3 Frequency Content of the Measured Vertical Vibration Data on the Bond

- Measurements showed that the vibrations on the Bond were in order of approximately 40% of the levels on the frame below, indicating that the 3/8" thick neoprene isolators are not effective in mitigating vibration (as properly installed isolation systems should provide 90%+ isolation efficiency). As such, the Bond is exposed to repeated high-level stress reversals which increases the possibility of fatigue failure. It is our opinion that the failure of the Bond is related to fatigue failure due to these high magnitude forces at these frequencies.
- In order to assess the impact of train speed on the high frequency vibration levels, it was then recommended to perform additional controlled tests at a variety of speeds during the data acquisition period.

Speed Effects Testing

Further testing was then conducted at the same location as described in Section 3, but with the train passing at predetermined speeds in order to explore these velocity-related effects. The following conclusions were drawn from this subsequent testing:

- The overall vertical vibration levels at different speed limits are presented in Figure 4. The corresponding one-third octave frequencies are also presented in Figure 4.
- As expected, the vibration levels increased with the speed of the train pass-by. The highest vibration levels were observed due to train pass-by at 55 mph.
- Up to 200 Hz, the energy contents are similar, irrespective of train speed, indicating that the vibration response of the Bonds is governed by the substructure stiffness at these frequencies. Above 200 Hz, the energy contents increased with the speed of the train. As noted in the initial testing, the energy contents at the high frequencies are related to wheel-rail interaction at speeds 35 mph and above. The high amplitudes of vibration at these frequencies are directly related to existing rail corrugation at the subject site.
- To corroborate this, another measurement location was selected along the track where the train can speed up to 35 mph. The measured vibration levels are plotted in Figure 5. As noted, at this location the vibration levels between 700

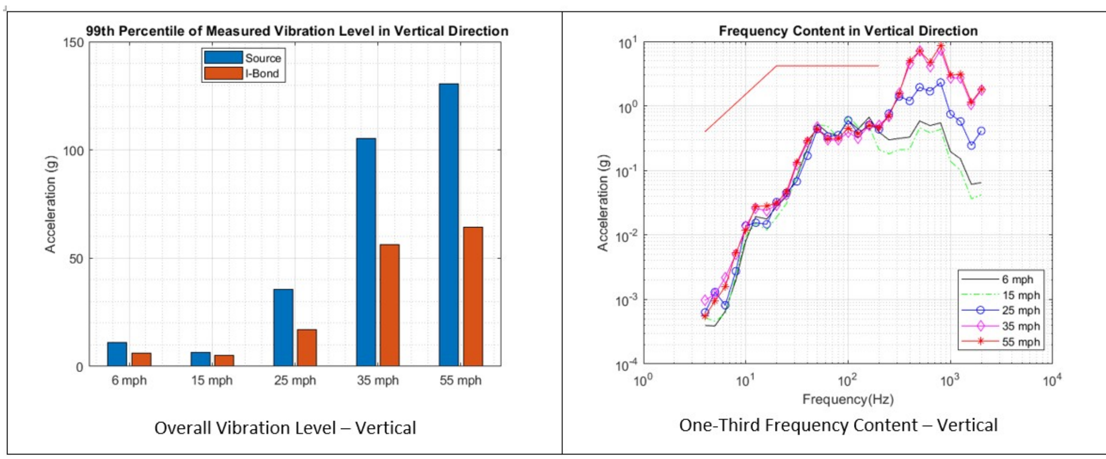


Fig. 4 Vibration as a Function of Train Speed

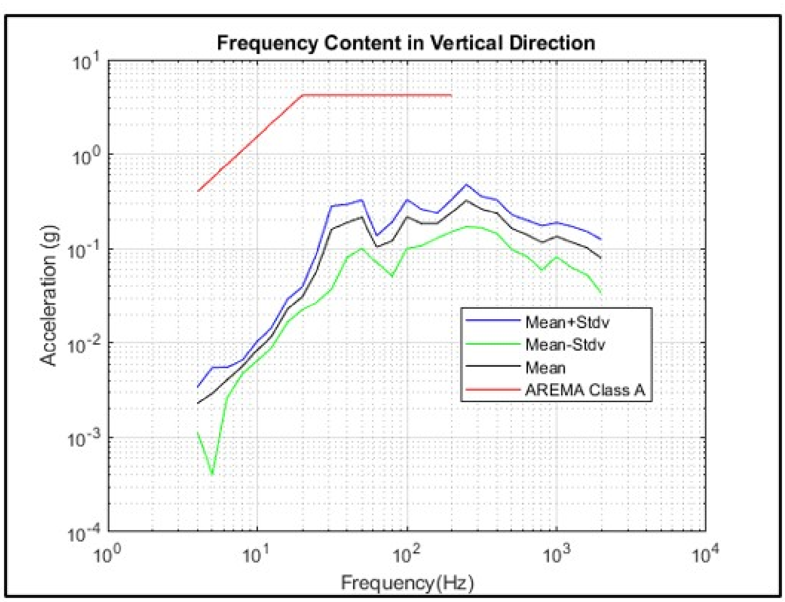


Fig. 5 Measured Vibration Levels at Location – without Rail Corrugation

and 1000 Hz are measured to be 0.4 g compared to a maximum vibration level of 10g where there is significant rail corrugation (Figure 4).

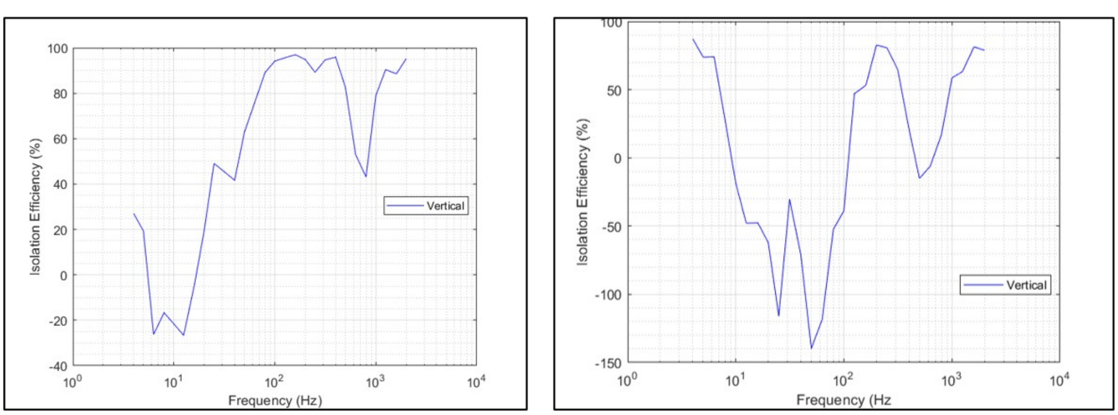
- The existing isolation details with 3/8” thick neoprene pad were also reviewed. Based on the assessment, an axial force of approximately 5000 lbs was predicted at the location of the bolts. This is expected to exceed the elastic load range of the 3/8” thick isolators. Therefore, in the vicinity of the bolts, the neoprene isolator is acting as a rigid connection, allowing transfer of vibration from the rail track to the Bonds. Also, it is noted that the bolts are not entirely resiliently decoupled. Thus, the currently installed isolators are not effective in mitigating vibration transfer to the Bond.
- Based on the conclusion that the existing isolation system was deficiently designed and installed, additional testing was then conducted to determine the efficacy of an alternative system, which was based on wire-rope isolators (example shown in Figure 6).

Fig. 6 Wire Rope Isolator Example

Wire Rope Isolator Testing

Testing was then conducted at a number of locations to determine the relative effects between using the existing neoprene pad isolation system and proposed wire rope isolators. The following conclusions were drawn from this subsequent testing:

- A typical isolation curve for wire rope isolator and 3/8” thick neoprene isolators are presented in Figure 7. Note that positive values in Figure 7 show effective isolation while negative values indicate amplification of vibration. Based on



Vibration Isolation with Wire Rope Isolator

Vibration Isolation with 3/8” thick Neoprene Pad

Fig. 7 Comparison of Vibration Isolation Between Wire Rope Isolator and 3/8” Thick Neoprene Isolator the assessment, isolation efficiency in the vertical direction is the governing factor for overall isolation performance, and as such, the details for lateral and longitudinal directions are not included in this paper.

- There is no isolation up to approximately 100 Hz with 3/8” thick neoprene pads. The isolation efficiency is also negative between 300 Hz and 500 Hz indicating that the neoprene configuration is not effective in isolating vibration at these frequencies.
- In the case of wire rope isolators, there is no significant isolation up to approximately 50 Hz. Above 50 Hz, the performance of wire rope isolator is significantly better than 3/8” thick neoprene pads. Overall, the isolation performance of wire rope isolators was significantly better than that of neoprene pads. The vertical isolation efficiency, averaged over different measurement locations is presented in Figure 8.

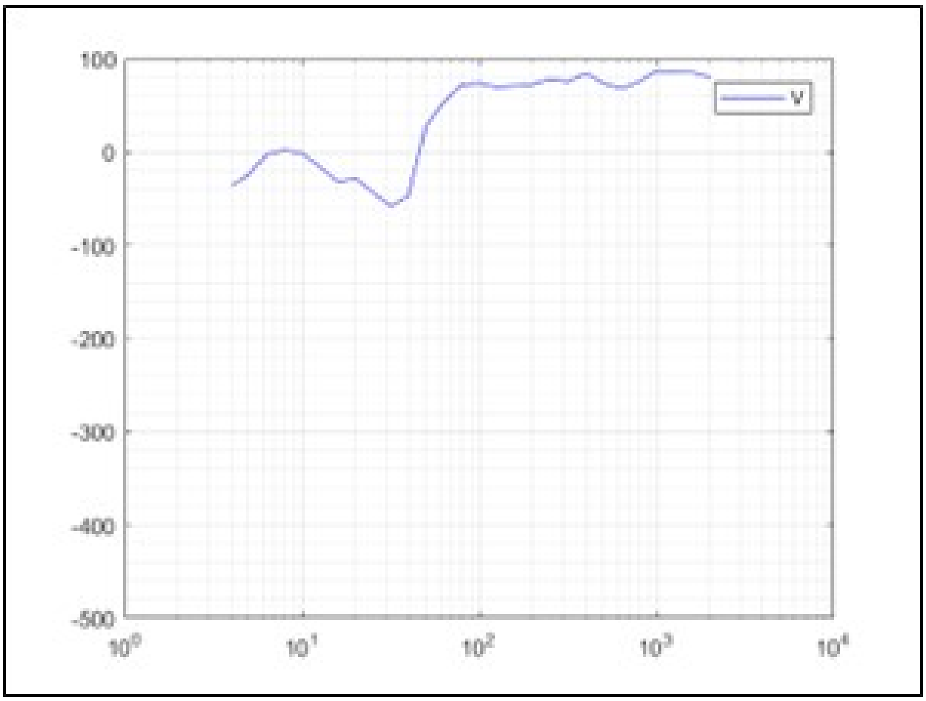
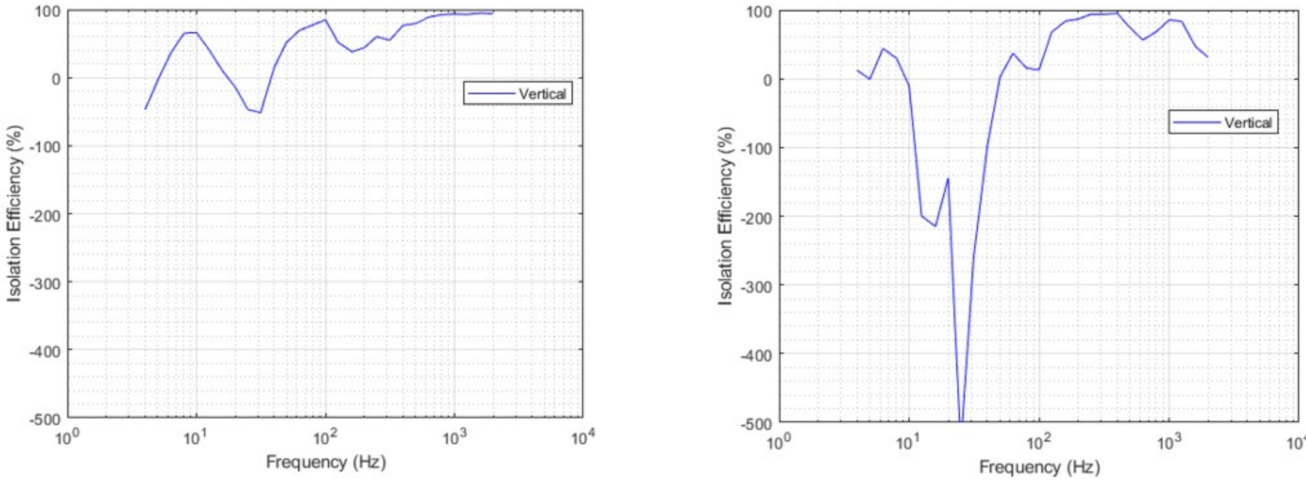


Fig. 8 Average Vertical Isolation Efficiency of Wire Rope Isolators

- It should be noted that an additional potential isolation short-circuiting path may be present in the system through the electrical cables that connect the Bonds to the tracks (which can be seen in Figure 1). It was decided to conduct additional measurements at one location to quantify vibration transfer through the electrical cable connection. At this locationn, the measurements were first conducted with the cable connections to the Bonds (typical installation). In the second setup, vibration levels were measured at the Bonds without these cable connections in place.
- Figure 9 provides a comparison of the isolation efficiency of these setups, which confirmed that vibration transfer through the cable connection was minimal. As noted previously, efficiency in the vertical direction governs the isolation design under the operating conditions.
- Based on the product data sheet for the wire rope isolator, the dominant frequency of the wire rope isolator is calculated to be 10 Hz. However, during the field testing, the dominant frequency was measured to be 20 Hz with two additional peaks at 30 and 32 Hz.
- In an effort to understand the discrepancy between theoretical and measured frequencies, the load-deflection curve and measured vibration levels were further examined.
  - At the frame below the Bonds, the root mean square (RMS) vertical vibration level was measured to be approximately 3g. This would roughly translate to 9 lbs force with a maximum RMS displacement of 0.04 mm.



Wire Rope Isolator – with cable connection

Wire Rope Isolator – without cable connection

Fig. 9 Typical Isolation Performance with Wire Rope Isolator With and Without Cable

  - As per the force-displacement curve, this falls within the initial region of the curve where stiffness is higher than the presented value in the product data sheet. With the higher stiffness values, the frequency of the as-built system is expected to be higher than 10 Hz.

- It was requested that the vendor of the wire rope isolator, provide more information on the load-deflection curve in the region of low amplitude displacement. The data provided was then extrapolated to estimate the stiffness of the wire rope isolator under the operating load regime. See Figure 10.

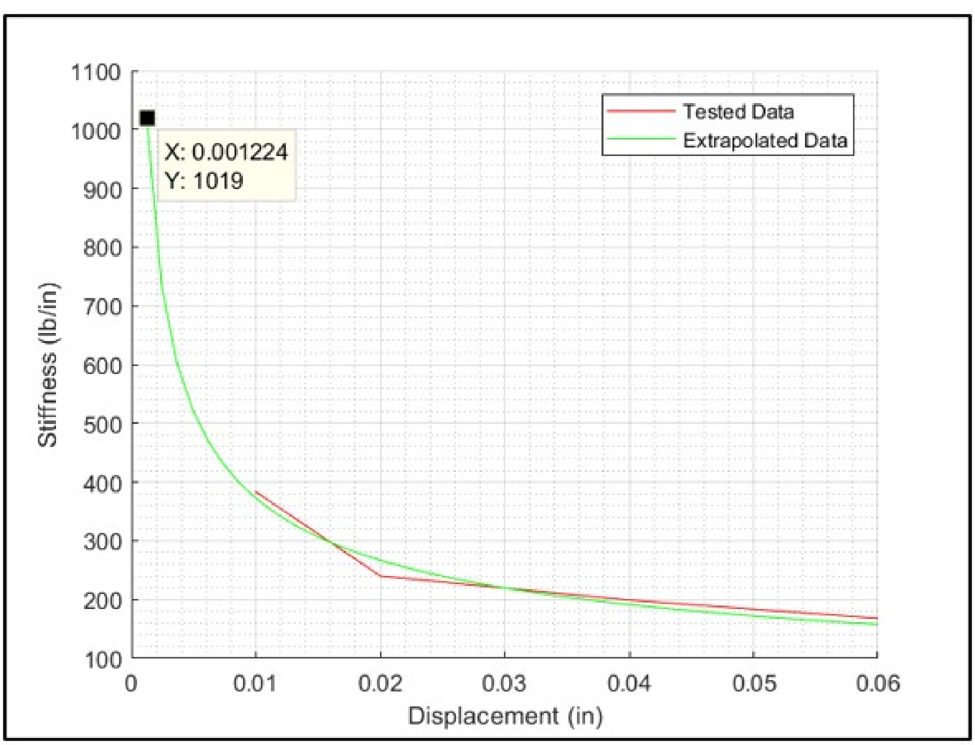
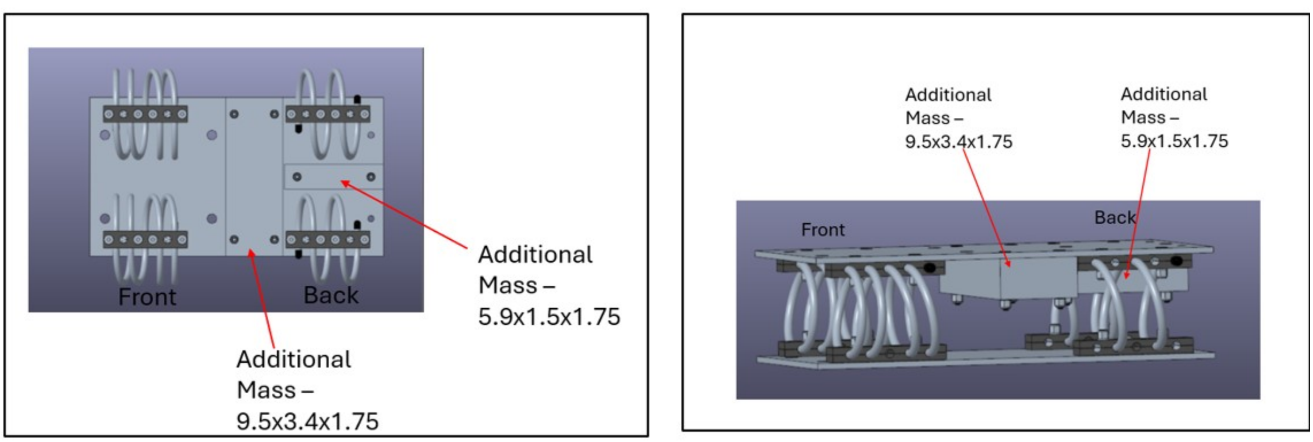


Fig. 10 Stiffness of Wire Rope Isolators Under Operating Conditions

- Based on the updated stiffness parameter under the operating load regime, the dominant frequency was predicted to be 19.80 Hz. Further, the load distribution of the wire rope isolator was noted to be non-uniform.
- Using the dimension and unsymmetric weight distribution of the Bonds atop the wire rope isolators, the rocking modes of the as-built system are predicted to be 31.6 and 33.3 Hz. These predicted frequencies correlate well with the measured frequencies of 20 Hz, 30 Hz and 32 Hz for wire rope isolators.
- Based on the measured vibration response and load distribution on the isolators, it was determined that achieving an isolation frequency of less than 20 Hz would require significantly reducing the stiffness of the wire rope isolators. This would correspond to a lower diameter strand of wire rope which itself is prone to fatigue failure under operating conditions.
- Based on this assessment, the recommendations for the wire rope isolators were modified so that the isolation performance was improved under operating conditions. The specifications for the final design of the wire rope isolators are summarized as follows:

  - Natural frequency of the isolator under operating condition <=20 Hz
  - Wire rope isolators at the front side (with more load from the Bonds) will have 4 loops
  - Wire rope isolators at the back side (with less load from the Bonds) will have two loops
  - Additional mass as shown in Figure 11 should be added to limit the contribution of rocking modes.
  - The maximum acceleration should be 150g with a duration of 2 ms.
  - The maximum dynamic deflection under operating condition should be 2 mm.



Plan View   Isometric View

Fig. 11 Proposed Modifications to the Wire Rope Isolators

Mitigated Vibration Levels

In order to assess high magnitude energy content at frequencies between 700 Hz and 1000 Hz, the original AREMA limit at 200 Hz was proposed to be extended to 2000 Hz. Vibration levels below this modified limit were considered compliant for the assessment.

Using the isolation efficiency of the wire rope isolator setup, predicted mitigated levels from the measured highest vibration levels were obtained. The predicted mitigated results in the vertical direction are shown in Figure 12.

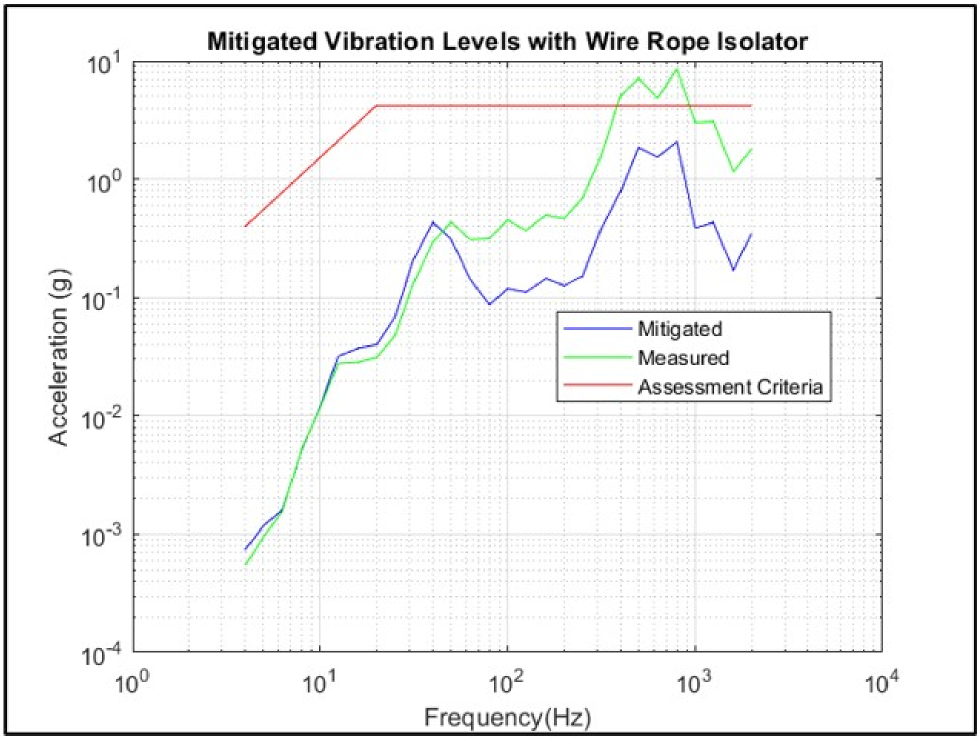


Fig. 12 Predicted Mitigated Vertical Vibration Level using Wire Rope Isolator

Conclusions

In order to determine repeated failures of the Bonds on a major commuter track, extensive vibration measurements were conducted. Consistently high magnitude energy content was measured at frequencies between 700 and 1000 Hz, which are related to wheel rail interaction, particularly due to trains operating at high speed. It was further noted that significant rail corrugation existed at the subject site. The combined effect of trains running at high speed and existing track conditions were concluded to be responsible for generating high vibration levels, which in turn were causing repeated failure of these Bonds.

Based on the existing vibration levels, wire rope isolators were proposed as an effective mitigation measure to isolate these Bonds from track vibrations. Considering the operating conditions, several modifications were proposed to improve the isolation performance of the wire rope isolators. The isolation efficiency of the wire rope was measured to be at least 80% in the frequency range of 700 to 1000 Hz. Overall, the isolation efficiency of the wire rope isolators were significantly better than the current isolation scheme involving 3/8” thick neoprene pad.

The following conclusions have been made:

- Adhering to AREMA Standard for assessing vibration levels on the Bonds may not be sufficient, as significant vibration levels were measured above the currently-specified 200 Hz upper limit of the AREMA criteria. As the PCB board located inside the Bonds could have resonance between 10 Hz and 2000 Hz, it is recommended to extend the measurement range up to 2000 Hz.
- In the design of vibration isolation, care should be taken to address any potential short circuits to reduce vibration transfer to the isolated structure. In addition, the elastic load range of the isolation material should be considerably higher than the applied static and dynamic loads. In this case, the axial force on the bolts exceeded the capacity of the neoprene pad and thus acted as a short circuit pathway for vibration transfer to the Bonds.
- In the case of vibration isolation with wire rope isolators, care should be taken to appropriately characterize the load range under operating condition. The wire rope isolators are non-linear in stiffness, and the properties change with input load level. Stiffness values reported in the vendor product data sheet may not be accurate for the intended load levels. It is recommended that testing be conducted to determine stiffness properties consistent with the load range under expected operating condition.

- In addition to dominant modes of the isolator setup, rocking modes of the as-built set-up should be included in the calculation of isolation efficiency. Depending on the stiffness and load distribution, these additional modes might play a significant role in establishing the efficiency of an isolator configuration.

Reference

1. American Railway Engineering and Maintenance-of-Way Association. Communications & signals manual. AREMA, 2025.