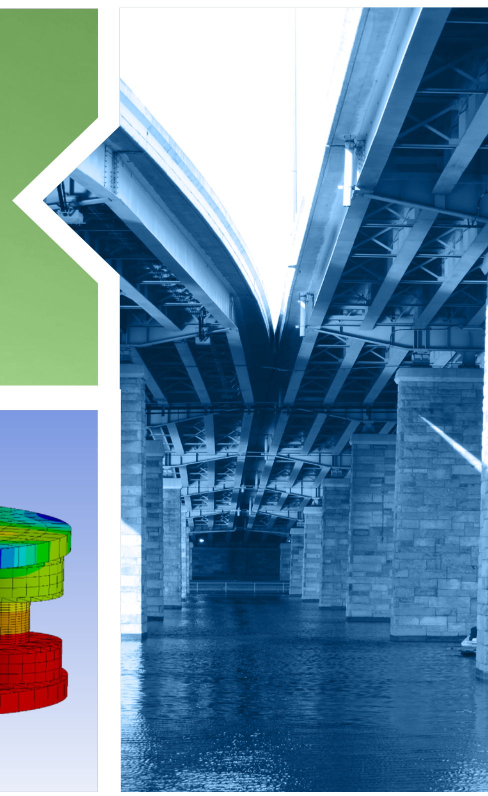
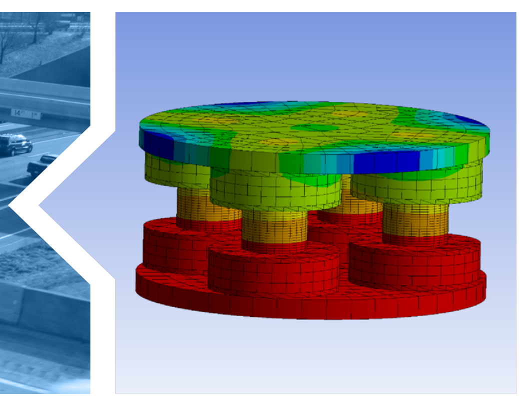
The Exploratory Advanced Research Program

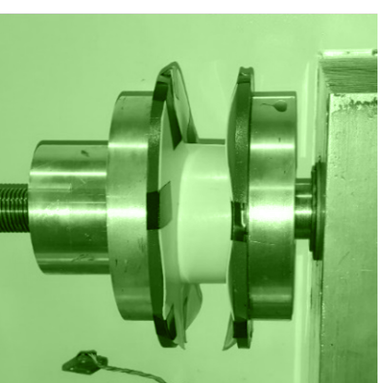
EXPLORATORY ADVANCED RESEARCH

A Self-Sensing Adaptive Material for a New Generation of Multifunctional Highway Bridge Bearing Systems

RESEARCH SUMMARY REPORT







U.S. Department of Transportation
Federal Highway Administration

Notice

Quality Assurance Statement

Photo credits

Please see cover 3 (inside back cover) for copyright credits for all the decorative photos appearing throughout the document.

Technical Report Documentation Page

1. Report No. FHWA-HRT-19-027	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle A Self-Sensing Adaptive Material for a New Generation of Multifunctional Highway Bridge Bearing Systems		5. Report Date February 2020
7. Author(s) Gordaninejad, Faramarz; Itani, Ahmad; Pekcan, Gokhan; Publicover, Nelson; Behrooz, Majid; Yarra, Siddaiah Marsh, Joanna		6. Performing Organization Code
9. Performing Organization Name and Address Mechanical Engineering Department Civil and Environmental Engineering Department Electrical and Bioengineering Department University of Nevada, Reno Reno, NV 89557 TMNcorp 131 Rollins Ave., Unit 4A Rockville, MD 20852		8. Performing Organization Report No. 10. Work Unit No. 11. Contract or Grant No. DTFH61-13-C-00020 DTFH61-15-A-00003
12. Sponsoring Agency Name and Address Office of Corporate Research, Technology, and Innovation Management Federal Highway Administration 6300 Georgetown Pike McLean, VA 22101-2296		13. Type of Report and Period Covered Research Summary Report September 2013 to September 2016 14. Sponsoring Agency Code
15. Supplementary Notes: FHWA's Contracting Officer's Technical Representative: Sheila Duwadi (HRDI-20) Technical Contact/Program Manager: David Kuehn (HRTM-30)		
16. Abstract Researchers at the University of Nevada, Reno explored the feasibility of a self-sensing adaptive bridge bearing system. In this system, rubber bearings and sensors made of a magnetorheological elastomer (MRE) (or controllable rubber) respond to loads and vibrations through automated changes in stiffness. The system has a wireless, self-sensing capability that enables bridge owners to set threshold warnings and receive alerts via text message when a bridge reaches a predetermined level of vibration. Researchers validated the systems by testing and evaluating the performance of its adaptive features under simulated wind and traffic loads. Because the sensors collect data, they can show owners the activities and stresses that a bridge experiences.		

17. Key Words bridges, loads, monitoring, composite materials, research, highways, bridge components, bridge bearings, self-sensing adaptive materials, adaptive magnetorheological elastomer bearings, adaptive bridge bearing, advanced research.	18. Distribution Statement No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161. http://www.ntis.gov

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 16	22. Price N/A

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized.

SI* (Modern Metric) Conversion Factors

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	654.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	millimeters	mL
gal	gallons	3.785	meters	L
ft^3	cubic feet	0.028	meters	m^3
yd^3	cubic yards	0.765	kilometers	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9	Celsius	°C
		or (F-32)/1.8		
		ILLUMINATION		
fc	foot-candies	10.76	lux	lx
ft	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yard	yd^2
ha	hectares	2.47	acres	mi
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	mililiters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candies	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	ft
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

Table of Contents

List of Figures

Introduction

Bridges are subjected to different types of loadings. Environmental factors, such as adverse weather conditions and infrequent natural hazards also can wear down a bridge. By knowing how these loads over time can affect a bridge as a whole and its components, bridge owners can make decisions on what actions need to be taken and when to repair or rehabilitate a bridge.

Researchers have been studying how bridge components can provide intelligent information and even communicate information as needed to assist engineers. Bridge bearings appeared as logical components to explore this idea (figures 1a and 1b). They safely distribute the loads imposed on the bridge onto the bridge piers and foundations. Bridge bearings further accommodate bridge movements in response to bridge expansion or contraction brought about by thermal changes, and displacements and forces induced by wind and earthquakes (figure 1a).

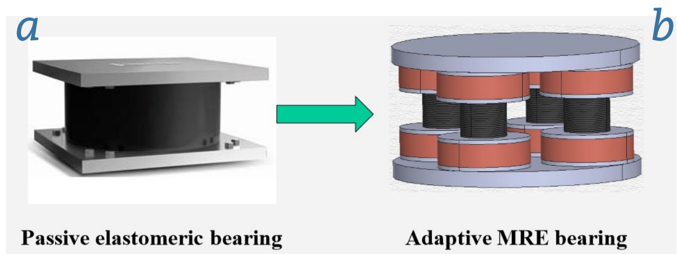
But can bridge bearing designs be taken a step further? Can bridge bearing systems be designed to respond like a muscle when pressure or stresses are placed upon them?

At the University of Nevada, Reno, researchers looked for answers to these very questions. They developed an adaptive material for bridge bearings that allows electricity to flow through, creating a magnetic field that can stiffen a controllable rubber in response to forces being exerted upon it.

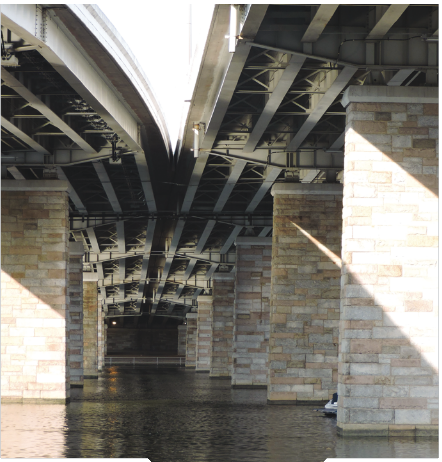
The self-sensing adaptive bearing (SSAB) system designed by University of Nevada, Reno researchers consists of several components (figure 1b). One component enables a bridge bearing system to stiffen as needed in response to forces being exerted on it.

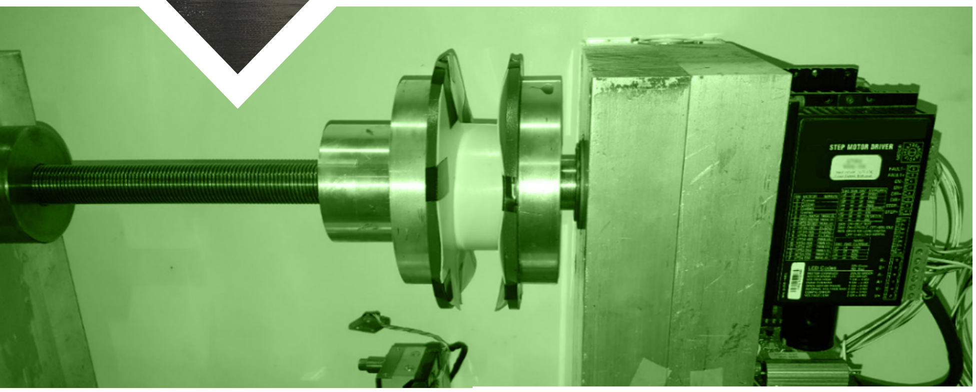
Another component is using the bearing system's materials to track, collect, and send data. The bridge bearing system uses sensors made of the same kind of controllable rubber as in rubber bearings. This rubber is called a magnetorheological elastomer (MRE). The sensors are built into the rubber bearings and are there to automate the changes in stiffness. The sensors also enable transportation engineers to set threshold warnings so that when a bridge reaches a predetermined level of a measured response quantity (e.g. displacement, acceleration), engineers can be alerted via text messages. Because of the sensors' ability to collect data, they will show engineers the activities and stresses that a bridge experiences. The data collected by the sensors could help bridge engineers assess how unexpected loads cause damage or accelerate deterioration. More research will be needed to collect and assess this data and its usefulness.

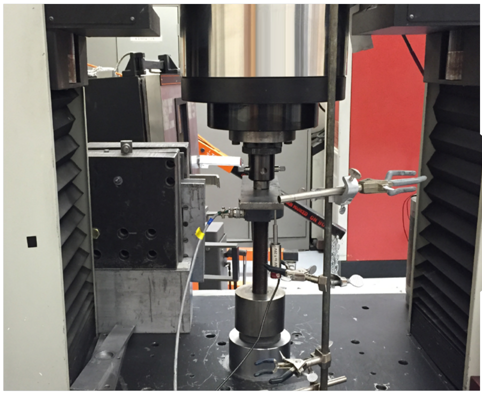
Through this project, the researchers wanted to show that it was feasible to create and demonstrate a fail-safe, self-sensing MRE-based adaptive bearing system that could be used to improve the performance of highway bridges.



Figures 1a and 1b. Researchers at the University of Nevada, Reno explored the possibility of creating a dynamic and responsive bridge bearing by modifying the passive elastomeric bearings (figure 1a) used today. They came up with an adaptive MRE bridge bearing (figure 1b).







PROJECT OVERVIEW

University of Nevada, Reno researchers had two goals in mind for this research project: to design and make an adaptive bridge bearing system with a wireless self-sending capability and to test and validate the performance of this system under simulated wind and traffic loads.

To develop this self-sensing adaptive bearing (SSAB) system, the researchers conducted a multiphase study over 3 years. The researchers sought to develop a rudimentary SSAB system using MREs and sensors. In subsequent phases, the researchers refined the processes to improve the SSAB system they created.

The overarching goal of this research was to create an SSAB system that can be incorporated into future bridges and implemented into existing bridges as repairs warrant. By incorporating this technology into existing and future bridges, transportation engineers hope to extend the life of bridges safely and reliably.

Figure 2. A prototype of the adaptive bridge bearing system. © University of Nevada, Reno

Phase I: Making System Components

The first phase of this project was to see if the researchers could develop a wireless sensor and bridge bearing system that uses the controllable MRE rubber. This kind of rubber consists of polymeric solids embedded with iron particles. MREs have two characteristics that encourage adaptability. One characteristic is piezoresistivity, which changes the material's electrical properties in response to mechanical strain. This allows MREs to quickly measure displacement. The second characteristic is magnetoresistance, which realigns embedded iron particles within the polymer matrix in response to applied magnetic fields and changes the material's physical properties (such as stiffness) in real-time.

In this first phase, the researchers looked at the feasibility of developing an MRE-based wireless sensor for highway bridge bearing systems through analysis and experiments. In an interdisciplinary collaboration among mechanical, civil, and electrical engineers, the team worked in several areas: developing a SSAB system, making MRE sensors, and designing and conducting initial analyses of their SSAB system.

Designing an MRE-Based Adaptive Bearing System

As one research team was working on developing MRE sensors, another team was designing a bridge bearing system with the MRE sensors as one of its components. The researchers designed an initial adaptive bearing system based on the layout of a conventional bridge bearing system (figure 2). They replaced the rubber parts of a conventional bridge bearing system with MRE layers. The MRE layers consisted of polymeric solids embedded with iron particles, which enabled the layers to respond to mechanical strain. Through this characteristic, researchers would be able to measure physical loading. The MRE layers also exhibited magnetoresistance, which realigned embedded iron particles within the polymer matrix in response to magnetic fields and changed the material's physical properties.

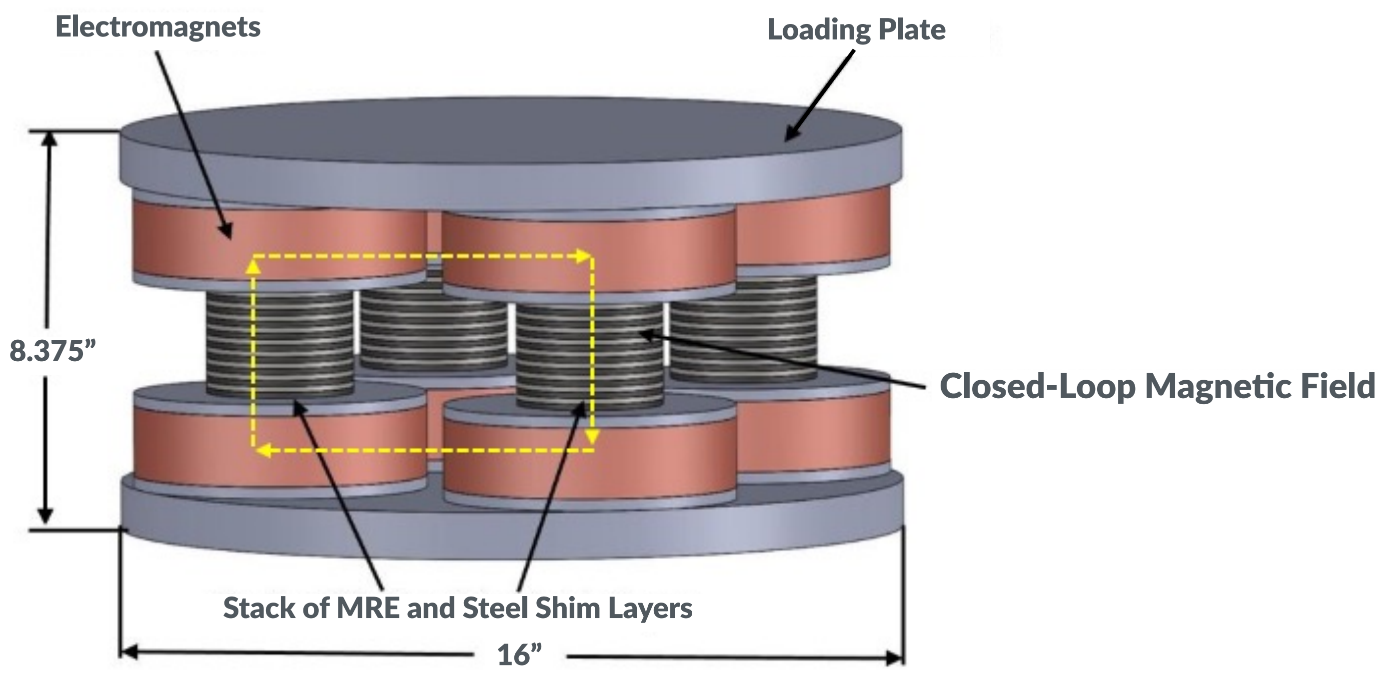


Figure 3. Bearings composed of MRE material sandwiched between electromagnet arrays adjust stiffness and dampening properties in response to strain. © University of Nevada, Reno

Phases II and III: Testing, Testing, Testing

Once the researchers developed a prototype SSAB system, the second phase in the project was to refine the system's components and determine how the system performs in everyday circumstances, such as how the system mitigates wind and traffic-induced vibration and seismic events.

The researchers tested and modified each major component of the bearing system to determine how to improve overall performance. For instance, the researchers sought to configure and optimize the low-power microcontroller to prolong the life of the wireless sensing system if the system is running on a battery. The researchers did this by examining the relationship between power consumption and clock frequency or performance. They also manufactured the electromagnets for the bearings (figure 3).

The researchers studied how silicone-based and natural rubber MREs performed under shear and compression tests to gauge the effectiveness of the materials (figure 4).

The researchers also finalized the design of the adaptive bridge bearing. They constructed one-fourth of the scale of the actual bridge bearing so that they could test it in a laboratory setting. Their design featured eight coils and four stacks of MRE-steel shim layers sandwiched between electromagnets and loading plates. Each stack had 10 alternating layers of MRE and steel shims (figure 5).

With the design in place, the researchers needed to determine the best way to construct the bridge bearing. They conducted tests on the glue that would hold the MRE, steel layers, and coils together. They tested the bonding strength of three adhesives commonly used for bonding silicone and rubber materials. They also decided on what magnet wires and steel quality to use to achieve a high magnetic field for the coils.

The researchers came to several conclusions in the next stage of research, which sought to characterize the mechanical properties of the silicone-based and natural rubber-based MREs to see how they performed under large strains. They confirmed that the magnetorheological (MR) effect, which indicates material stiffness, can change based on the material used.

For silicone-based MRE samples, the MR effect reduces significantly at larger strains because the iron particles that make up the samples became more distant from each other, creating chain-like formations. However, the researchers concluded that silicone-based MREs might still be useful in lower strain applications. Meanwhile, adding carbon nanofibers to the silicone-based anisotropic MRE improved the performance of the MRE because of the desirable magnetic permeability of the carbon nanofibers.

For the natural rubber-based samples, the MR effect was improved primarily due to their isotropic material composition. Furthermore, these samples performed better under axial forces. However, it was observed that the MR effect reduced slightly during high frequency loadings such as those caused by traffic. While reduced MR effect may be perceived as reduced effectiveness of the bearing, it is in fact not concerning since the displacements are small at high frequencies.

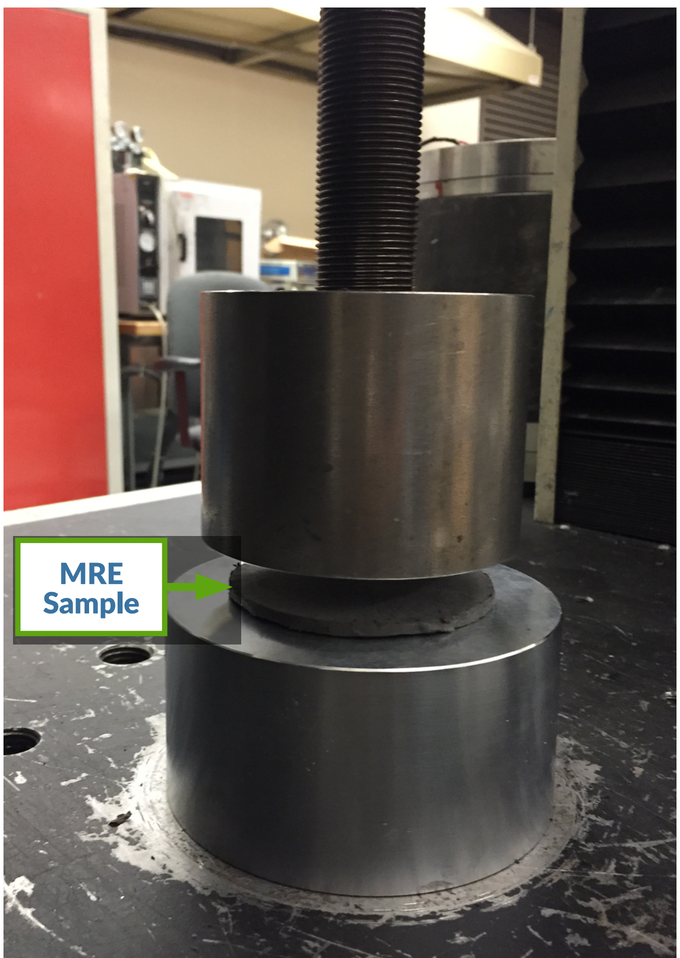


Figure 4. A compression test apparatus includes (A) a load cell that measures compressive force; and (B) a linear variable differential transformer that converts linear motion within a sample to an electrical signal. © University of Nevada, Reno

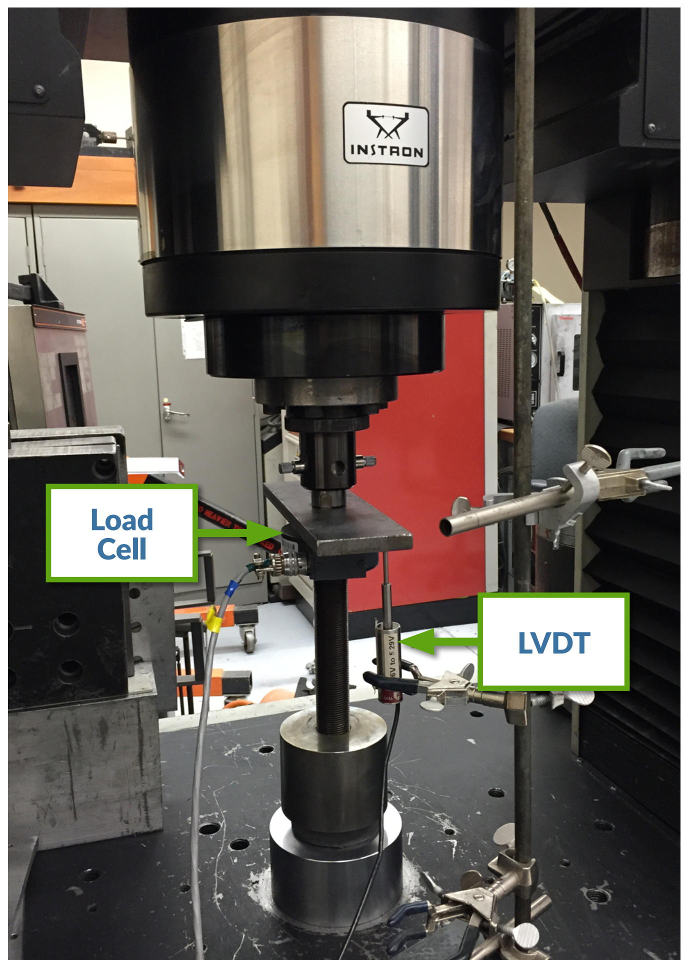


Figure 5. A sample of MRE material between the test apparatus ram and baseplate. An LVDT is a linear variable displacement transducer. It is a displacement sensor that measures deformations in the test specimen. © University of Nevada, Reno

Conclusions

The researchers determined through the three phases of the project that it was feasible and beneficial to use carbon nanofibers and an isotropic mix of iron, nanofiber, and rubber material to create the adaptive bridge bearing. Deploying these materials enables an adaptive bridge bearing to have the strength to withstand sustained loads. These materials also will allow one to collect data and respond in real-time to pressures exerted on the bridge bearing.

The study's finding is that the SSAB system advances intelligent bridge bearing technology. Future research can go in multiple directions. One direction would entail seeing whether the bridge bearings can stiffen and release in response to the forces put upon them, just like a muscle.

Another direction is to put the MRE material under larger strains, especially since initial findings determined that the magnetic field of the MRE material, which gives the bridge bearing the ability to respond to forces, took longer to activate under larger strains. This direction includes looking at how to improve the material design—the MRE material composition and the electromagnet design—so that the bearing system can perform as effectively under strains of 20 percent or higher that may be experienced during a seismic event.

Another direction is to conduct additional shear and compression tests on two materials, silicone MREs and natural rubber MREs, at laboratory scale. These tests can help determine whether mixing carbon nanofibers with silicone MRE can increase the bearing's ability to respond to higher strains. It is noted that strains lower than 20 percent are considered small for bridge bearings. These findings will be beneficial in helping to decide whether silicone MRE is a good candidate for low-strain applications.

To complement the study on the materials that can be used in SSAB system, researchers can study how deformations and forces affect the conventional elastromeric steel-reinforced bearings used on bridges today, and use those findings to improve the design of MRE-based adaptive bearing systems.

Additional future work includes refining the material properties of the bridge bearing system, conducting additional shear and compression tests, and studying simulated situations where researchers can see how the systems respond to controlling vibration-induced forces and deformations. Ultimately, the researchers would like to explore opportunities to bring this adaptive bridge bearing system to full scale, from the laboratory to the field.

Bibliography

Aono, K., Kondapalli, S.H., Lajnef, N., Pekcan, G., Faridazar, F., and Chakrabartty, S. (2017). "Self-powered Sensors to Facilitate Infrastructural Internet-of-Things for Smart Structures." The 13th International Workshop on Advanced Smart Materials and Smart Structures Technology, University of Tokyo, Japan, July 22-23, 2017.

Behrooz, M., Wang, X., and Gordaninejad, F. (2013). "Modeling of a new magnetorheological elastomer-based isolator." *Proc. SPIE 8688, Active and Passive Smart Structures and Integrated Systems 2013* (April 10, 2013): 86880Z-86880Z. http://dx.doi.org/10.1117/12.2009946. (last accessed November 19, 2019).

Behrooz, M., Wang, X., and Gordaninejad, F. (2013). "Seismic control of base isolated structures using novel magnetorheological elastomeric bearings." *Proc. ASME* (2013b): V001T03A027-V001T03A027.

Behrooz, M., Yarra, S., Mar, D., Pinuelas, N., Muzinich, B., Publicover, N.G., Pekcan, G., Itani, A., and Gordaninejad. G. (2016). "A self-sensing magnetorheological elastomer-based adaptive bridge bearing with a wireless data monitoring system." *Proc. SPIE 9803, Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2016* (April 20, 2016): 98030D. doi:10.1117/12.2218691.

Ceylan, H., Gopalakrishnan, K., Taylor, P., et al. (2011). "A Feasibility Study on Embedded Micro-Electromechanical Sensors and Systems (MEMS) for Monitoring Highway Structures." Unpublished paper, last modified June 1, 2011. https://works.bepress.com/halil_ceylan/52/. (last accessed November 19, 2019).

Chen, L., Gong, X.L., and Li, W.H. (2008). "Effect of carbon black on the mechanical performances of magnetorheological elastomers." *Polymer Testing* 27 (May): 340–345, https://doi.org/10.1016/j.polymertesting.2007.12.003. (last accessed February 11, 2020).

Deng, H., Gong, X., and Wang, L. (2006). "Development of an adaptive tuned vibration absorber with magnetorheological elastomer." *Smart Materials and Structures* 15 (2006): N111–N116. http://iopscience.iop.org/0964-1726/15/5/N02. (last accessed November 19, 2019).

Ginder, J.M., Nichols, M.E., Elie, L.D., et al. (1999). "Magnetorheological elastomers: properties and applications." Proceedings of SPIE 3675(1): 131–138. https://doi.org/10.1117/12.352787. (last accessed February 11, 2020).

Norouzi, M., Gilani, M., Alehashem, S.M., and Vatandoost, H. (2017). "Dynamic Characterization and Modeling of Isotropic Magnetorheological Elastomers Under Tensile-Compressive Loadings." *IEEE Transactions on Magnetics* 53(9): 1-12.

Schubert, G., and Harrison, P. (2015). "Large-strain behaviour of Magneto-Rheological Elastomers tested under uniaxial compression and tension, and pure shear deformations." *Polymer Testing* 42: 122–134, https://doi.org/10.1016/j.polymertesting.2015.01.008. (last aaccessed February 11, 2020).

Wang, X., Gordaninejad, F., Calgar, M., et al. (2008). "Electrical properties of magneto-rheological elastomers." In *ASME Conference on Smart Materials, Adaptive Structures and Intelligent Systems, SMASIS2008*, October 28, 2008-October 30, 2008, *Proceedings of the ASME Conference on Smart Materials, Adaptive Structures and Intelligent Systems, SMASIS2008*. American Society of Mechanical Engineers. 869-874.

Yarra, S., Gordaninejad, F., Behrooz, M., and Pekcan, G. (2018). "Performance of natural rubber and silicon-based magnetorheological elastomers under combined axial and shear loading." *Journal of Intelligent Material Systems and Structures* 30: 228-242. https://journals.sagepub.com/doi/10.1177/1045389X18808393. (last accessed February 11, 2020).

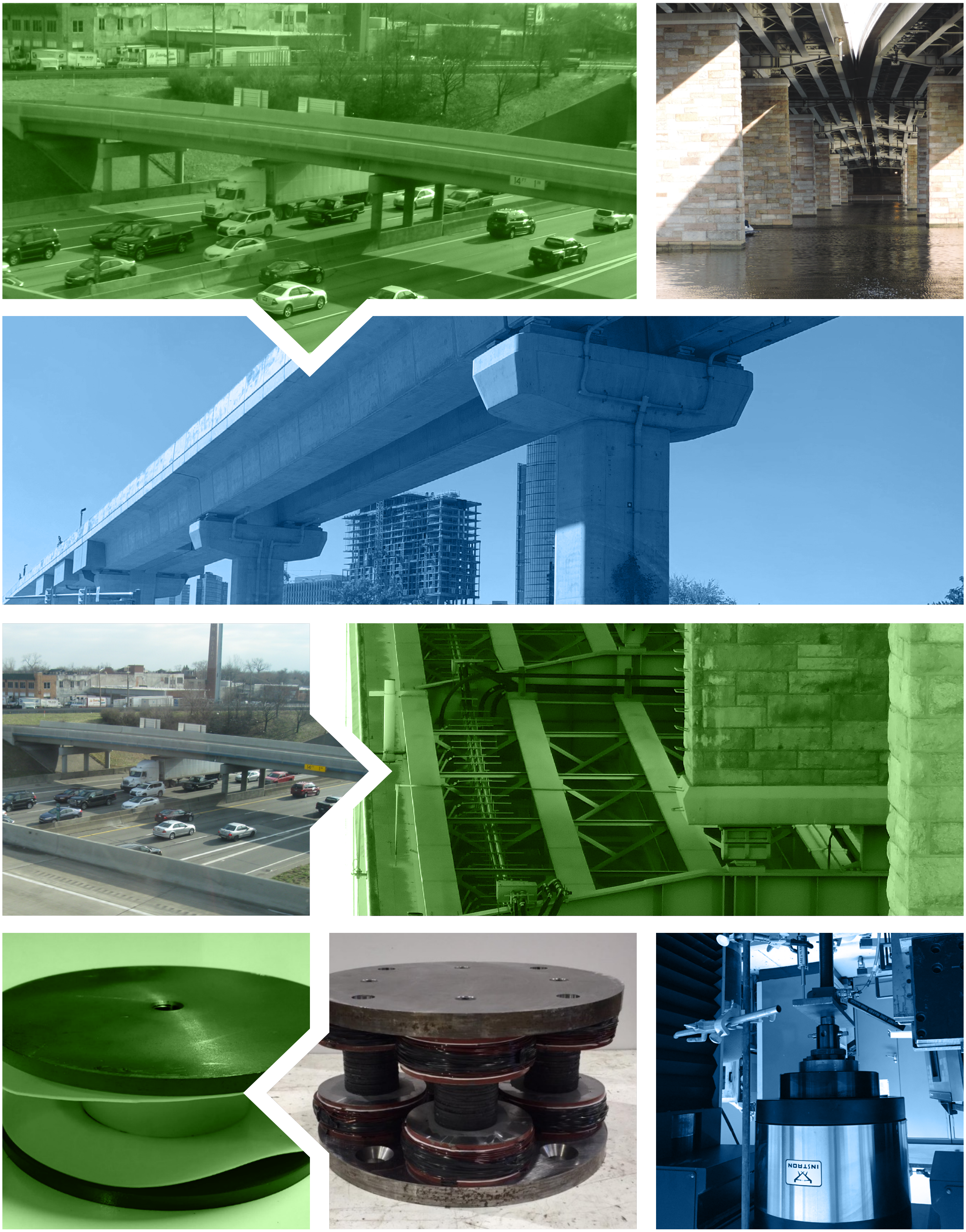
Yarra, S., Gordaninejad, F., Behrooz, M., Pekcan, G., Itani, A., and Publicover, N. (2018). "Performance of a large-scale magnetorheological elastomer-based vibration isolator for highway bridges." *Journal of Intelligent Material Systems and Structures* 29: 3890-3901. https://doi.org/10.1177/1045389X18799493. (last accessed November 19, 2019).

Yarra, S., Pekcan, G., Behrooz, M., and Gordaninejad, F. (2018). "Natural Rubber Magnethorheological Elastomer for Large Scale Isolation Systems." Presented at the 17th International Conference on Electrotheological Fluids and Magnethorheological Suspensions, July 2018.

Yarra, S., Behrooz, M., Pekcan, G., Itani, A., and Gordaninejad, F. (2017). "A large-scale adaptive magnetorheological elastomer-based bridge bearing." *Proceedings of SPIE Smart Structures and Materials, Nondestructive Evaluation and Health Monitoring* (April): 1016425-1016425.

Yarra, S., Pekcan, G., Behrooz, M., and Gordaninejad, F. (2017). "Characterization of Carbon Black-Filled Natural Rubber and Silicone Magnetorheological Elastomers under pure shear loading." *Proceedings of CIMNE 8th ECCOMAS Thematic Conference on Smart Structures and Materials* (June): 860-870.

Notes



Getting Involved with the EAR Program

To take advantage of a broad variety of scientific and engineering discoveries, the EAR Program involves both traditional stakeholders (State department of transportation researchers, University Transportation Center researchers, and Transportation Research Board committee and panel members) and nontraditional stakeholders (investigators from private industry, related disciplines in academia, and research programs in other countries) throughout the research process.

Learn More

For more information, see the EAR Program website at https://highways.dot.gov/research/exploratory-advanced-research. The site features information on research solicitations, updates on ongoing research, links to published materials, summaries of past EAR Program events, and details on upcoming events.

Photo Credits for Decorative Images

Cover:
Top row left: FHWA
Top row right: © Patrick Zickler
Middle row left: FHWA
Middle row right: © University of Nevada, Reno
Bottom row left: © University of Nevada, Reno
Bottom row middle: © Patrick Zickler
Bottom row right: © University of Nevada, Reno

Page 2:
Top row: FHWA
Second row from top, left: © Patrick Zickler
Second row from top, rightt: © Patrick Zickler
Third from top: © University of Nevada, Reno
Bottom row left: © Patrick Zickler
Bottom row right: © University of Nevada, Reno

Page 9:
Top row left: FHWA
Top row right: © Patrick Zickler
Second row from top: FHWA
Third row from top, left: FHWA
Third row from top, right: © Patrick Zickler
Bottom row left: © University of Nevada, Reno
Bottom row middle: © University of Nevada, Reno
Bottom row right: © University of Nevada, Reno

EXPLORATORY ADVANCED **RESEARCH**

U.S. Department
of Transportation
Federal Highway
Administration

EXPLORATORY ADVANCED RESEARCH

FHWA-HRT-19-027
HRTM-30/01-20(WEB)E