MR damper location optimization for the mitigation of structural damage due to high-impact loads

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Abstract

The application of control systems to infrastructure is necessary to prevent structural collapse, to decrease repair costs, and to improve safety. High impact loads, like vessel-bridge collisions, have often received less attention than seismic loads, but can still cause significant infrastructure damage. High impact loads are difficult to work with because they cause higher frequency vibrations than seismic loads and occur over shorter time periods. The use of smart control devices such as magnetorheological (MR) dampers to reduce structural response and to mitigate structural damage is studied in this research. A scaled down bridge pier and MR damper system was designed, built, and set up in the lab for impact testing. Impact drop tests were then conducted to simulate a real highway impact with a bridge. In order to optimize the effectiveness of the MR dampers in mitigating structural displacement and/or accelerations, tests were conducted to determine the optimal location for the dampers. The tests showed that dampers under the impact point helped reduce acceleration response by as much as 82%, while dampers at the end of the bridge pier helped reduce displacement response by as much as 44%. Through these tests, it is apparent that the use of MR dampers is effective in mitigating structural response, and therefore damage, and that the placement of the dampers plays a big role in the reduction of different responses.

Introduction

In the past years, control systems have been studied and applied to civil engineering structures to mitigate the structural damage caused by earthquakes or strong winds. There are three different classes of control systems: passive, active, and semi-active or "smart" control systems.

Passive control systems are commonly used because they are simple and do not require an external power source to operate. However, they lack flexibility since they are unable to adapt to varying magnitudes of load and changing structural characteristics [1]. Active control systems are systems that utilize actuators to help reduce vibration in the structure. Feedback sensors measure the response from the structure, and use control algorithms to help the control forces determine an appropriate response for the actuators [2], which makes active control systems flexible. However, they have not gained general acceptance because these systems are costly, require a massive power source, and are often unstable [3]. During seismic events, a malfunction in the system could cause an unwanted movement or damage in the system. Recently, semi-active control systems have received a lot of attention because they employ the flexibility of active control devices and the stability of passive control devices without the use of large power sources [1]. These smart control systems only require about 20-50 W of power, which can be supplied though a battery [4]. In addition, they do not inject mechanical energy into the systems; instead, they oppose the motion of the structural system, so if these semi-active devices do malfunction, they simply act as passive devices, and will not destabilize the structural system, unlike active control systems [5].

One class of semi-active devices uses controllable fluids such as electrorheological (ER) fluids and magnetorheological (MR) fluids. These two fluids are able to change from a free flowing fluid to a semi-solid in the presence of an electric or magnetic field respectively [5]. MR fluids are composed of 20-40% of pure, soft iron particles that are suspended in a carrier fluid such as mineral oil or synthetic oil [5]. These fluids are not sensitive to contaminants, which make the MR fluid a reliable device [4]. MR fluids have properties that make it more appealing than ER fluids. The maximum yield stress of an MR fluid is around 50-100 kPa, which is greater than the maximum yield strength of an ER fluid, while the amount of fluid needed in an MR device is less than the fluid needed in an ER device [5]. In addition, MR devices are temperature insensitive, meaning they can operate in temperatures from -40 to 150° C [5], and are inexpensive to manufacture and maintain [4].

The problem of high impact loading has received less attention than seismic loads. Control systems used to mitigate damage on bridge structures caused by high-impact loads such as marine vessels or large vehicle collisions are necessary to prevent structural collapse, and death. However, high impact loads cause higher frequency vibrations than seismic loads and occur over shorter time periods, so it is difficult to calculate desired control forces. A radar-based smart control system (RSCS) is proposed to help mitigate structural damage. The proposed RSCS, shown in Figure 1, uses a radar-based force identification system to predict imminent impact loads, MR dampers to dissipate the impact energy, and an effective feedforward control system for system control.

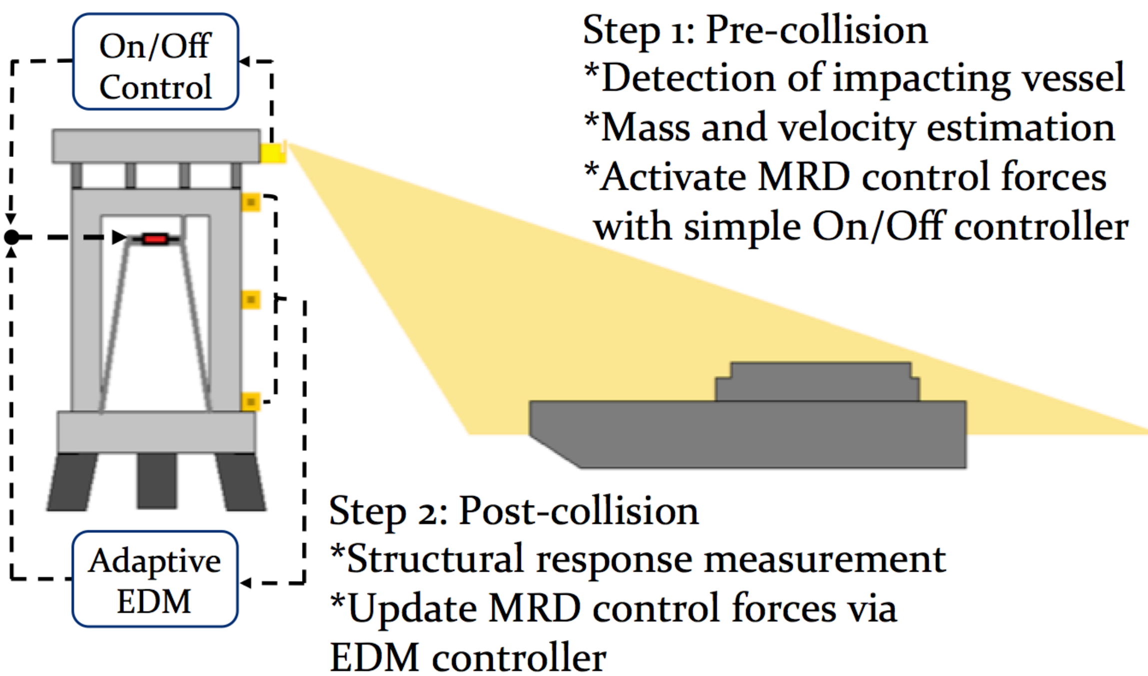

Figure 1. Proposed RSCS

The proposed RSCS will be fixed onto the bridge to identify possible collisions. After it identifies an imminent collision, it uses a radar system to estimate the incoming vehicle's mass and velocity. The RSCS would then use the AASHTO equation (3.14.8-1) $P_s = 8.15V\sqrt{DWT}$, where P_s = equivalent static vessel impact force (kip), DWT = deadweight tonnage of vessel (tonne), and V = vessel impact velocity (ft/s), to determine ship collision force on a pier to provide input for the smart control system (SCS) to plan for pre-impact structural control.

After the initial impact, a feedback controller measures the structural response, and an adaptive controller will adjust the stiffness of magnetorheological (MR) dampers to mitigate damage on the bridge structure. In order to effectively mitigate damage, the location of the MR dampers must be optimized to reduce structural displacement and/or accelerations. This location optimization is the subject of this paper.

Methodology

In order to determine the effectiveness of the MR dampers in mitigating structural response, impact tests were conducted on a cantilever concrete beam designed as a scaled down bridge pier. The scaling was completed geometrically to ensure that relative stiffness to impact load ratio remained constant. The cantilevered beam measures 39 inches long, 10 inches wide, and 7 inches tall. 3 US #3 steel bars were placed both in the top and the bottom of the beam as reinforcement. The impact load was applied at about a third of the length of the beam. Three MR dampers were attached to the beam– one directly under the impact load, one in the middle of the beam, and one at the end of the beam. In order to sense structural response, an LVDT displacement transducer was attached at the end of the cantilever beam, and four accelerometers were attached at various points on the beam.

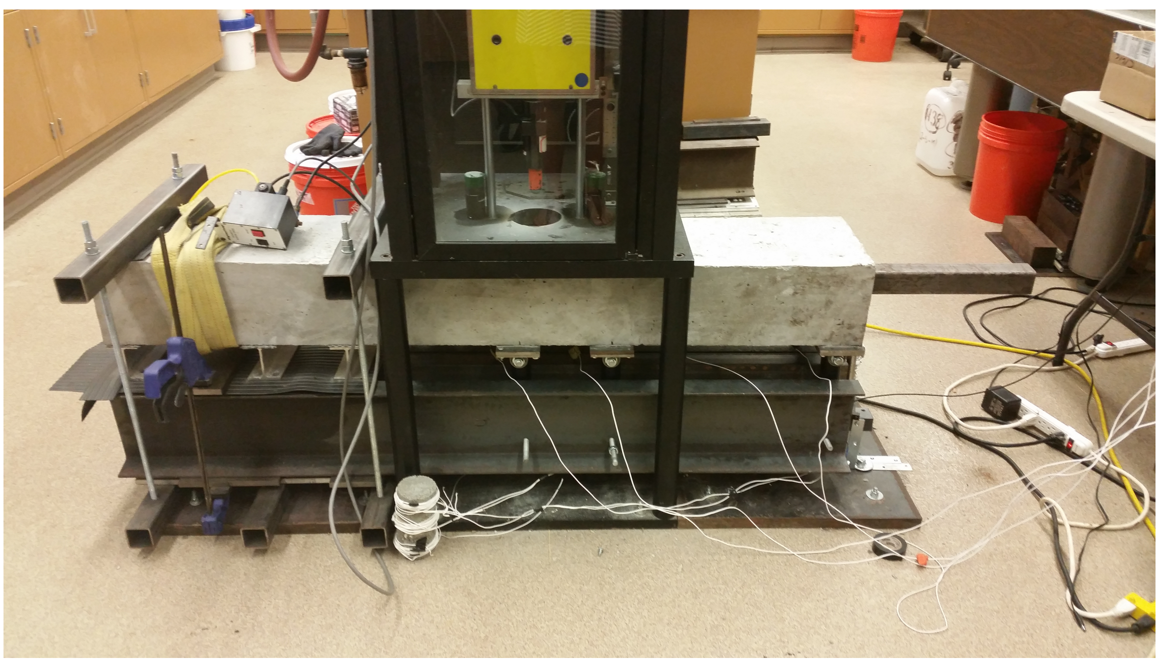

Figure 2. Photo of bridge pier test setup

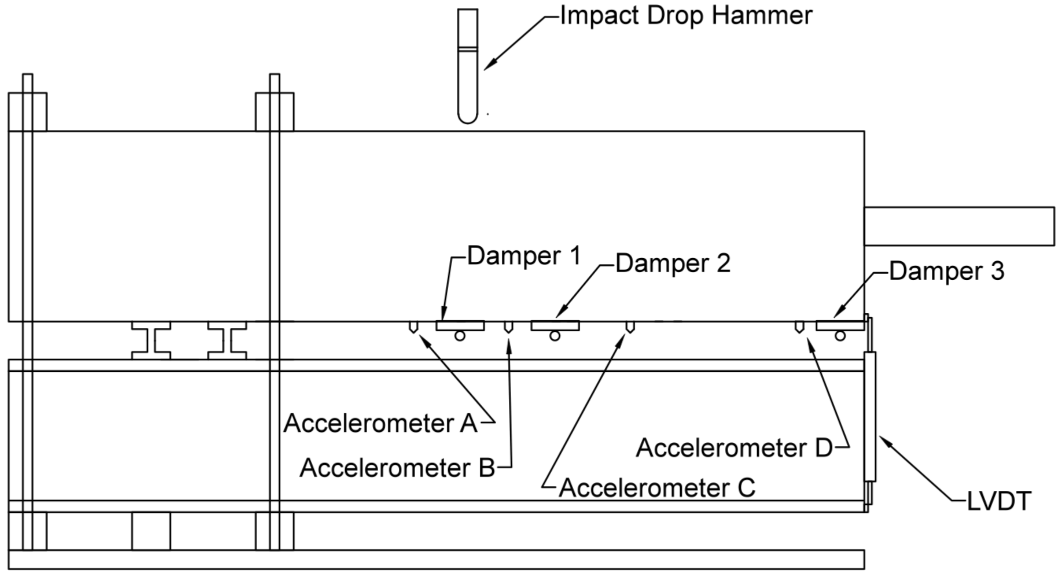

Figure 3. Bridge pier testing setup

The drop tower impact test procedure featured drop heights ranging from 2 inches to 12 inches in 2-inch increments, with different combinations of the damper locations. Within each damping case, passive damping voltages ranging from 0V to 5V in 0.5V increments were used. In order to properly determine the effectiveness of the dampers, tests were also conducted with none of the dampers connected to establish a baseline undamped case. LabVIEW was used to obtain displacement and acceleration responses from the LVDT and accelerometers. The data was then processed through MATLAB, and further analyzed through Excel. The results of these tests helped determine which combination of dampers best mitigated structural response for both displacement and acceleration.

Results

With the dampers and accelerometers in place, the scaled-down bridge pier was subjected to impact testing. Both uncontrolled and controlled cases were recorded on all possible combinations of dampers, and the results were used to determine which dampers were most effective in mitigating structural response. If money is not a factor, using all three dampers will be the most effective, since it shows the greatest response reduction for both displacement and acceleration. Figure 4 shows that the damped case eliminates motion in the structure faster, and has a smaller magnitude than the undamped case. Similarly, figure 5 shows the effectiveness of the damped case in reducing structural response.

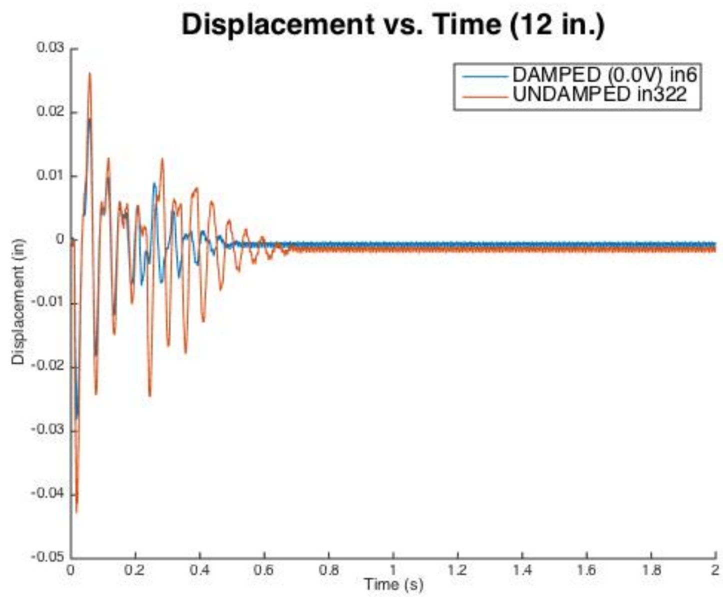

Figure 4. Displacement response controlled with all dampers

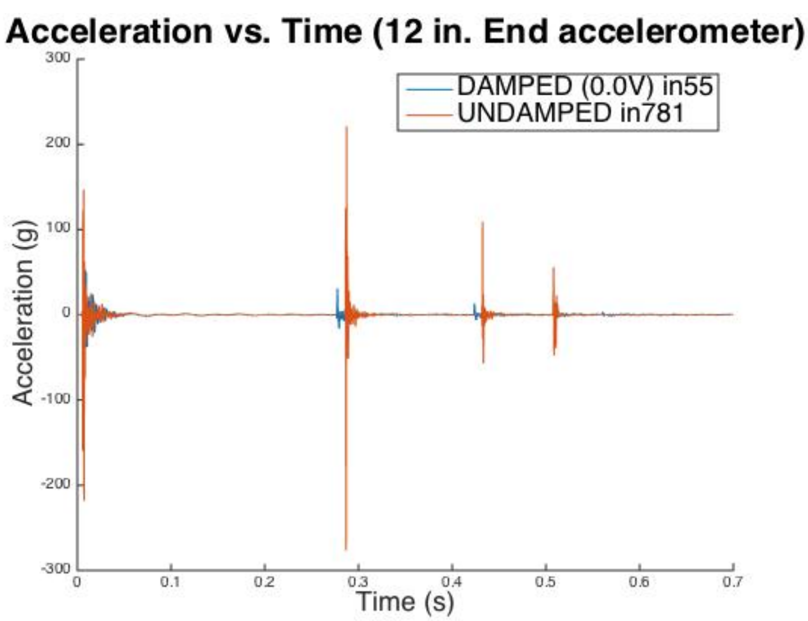

Figure 5. Acceleration response controlled with all dampers

Figure 6 shows maximum and minimum peak displacement responses for each drop height. In figure 6, the damped cases clearly show a reduction in response from the undamped case. The reduction increases as the drop heights increase, which suggests that higher impact loads will be more effectively reduced with the use of dampers.

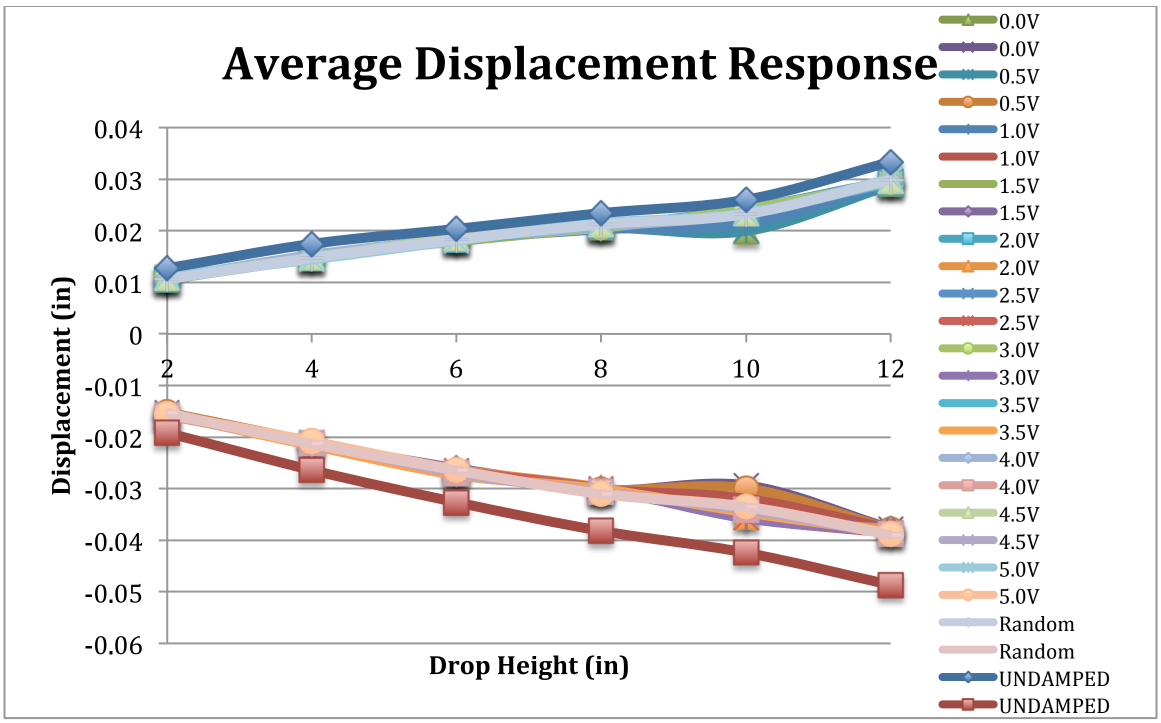

Figure 6. Average displacement response controlled with all dampers

In order to evaluate the effectiveness of the dampers in reducing response from the structure, four evaluation criteria were used. In each of the following, Y_C is the controlled data set, and Y_{UC} is the uncontrolled data set.

$$C1 = \left[\frac{\max{(Y_C)}}{\max{(Y_{UC})}}\right] \tag{1}$$

Evaluation criterion 1 is a ratio of the maximum peak displacement or acceleration measurements of the controlled response to the maximum peak displacement or acceleration measurements of the uncontrolled response.

$$C2 = \left[\frac{\min(Y_C)}{\min(Y_{UC})}\right] \tag{2}$$

Evaluation criterion 2 is a ratio of the minimum peak displacement or acceleration measurements of the controlled response to the minimum peak displacement or acceleration measurements of the uncontrolled response.

$$C3 = \left[\sum \frac{|Y_C|}{|Y_{UC}|}\right] \tag{3}$$

Evaluation criterion 3 is a ratio of the average absolute value of the controlled response to the uncontrolled response. This criterion uses the area under the curves to show structural control.

$$C4 = \left[\frac{\max(Y_C) - \min(Y_C)}{\max(Y_{UC}) - \min(Y_{UC})}\right] \tag{4}$$

Evaluation criterion 4 is a ratio of the peak-to-peak displacement or acceleration measurements of the controlled response to peak-to-peak displacement or acceleration measurements of the uncontrolled response.

After using these evaluation criteria to find ratios for each test case, these ratios were averaged within each drop height, and the best ratio was reported. Since these evaluation criteria show a ratio of response reduction, the value should be less than or equal to 1 to demonstrate effective structural control.

Table 1 shows the best average reduction ratios across the different drop heights when all dampers are connected. We can see a 16.5-28.8% reduction in peak maximum and minimum displacement, a peak-to-peak displacement reduction of 17.9%, and an area under the displacement response curve reduction of 42.9%. We also see a 65.8-76% reduction in acceleration from accelerometer 2, a peak-to-peak acceleration reduction of

70.3%, and an area under the acceleration response curve reduction of 61%. This shows the effectiveness of the dampers in reducing response on bridge structures.

Table 1. Displacement and acceleration response reduction ratios with all dampers

All Dampers	Response Reduction Ratio
Max Displacement (C1)	0.835
Min Displacement (C2)	0.712
Max - Min Displacement (C3)	0.821
Displacement Energy (C4)	0.571
Max Acceleration (C1)	0.342
Min Acceleration (C2)	0.239
Max - Min Acceleration (C3)	0.297
Acceleration Energy (C4)	0.390

However, implementing all three dampers may be out of one's price range, and so the use of only dampers 1 & 2 or dampers 2 & 3 still show significant response reduction.

Dampers 1 & 2 show an excellent acceleration reduction, while the displacement reduction is present, but not as significant as shown in other damper combinations. In figure 7, the damped case shows the effectiveness of applying dampers to the bridge. With the dampers attached, the displacement is very small after .5 seconds of the impact load. In figure 8, there is a clear reduction in acceleration. This shows the effectiveness of implementing both dampers 1 & 2 to mitigate structural response.

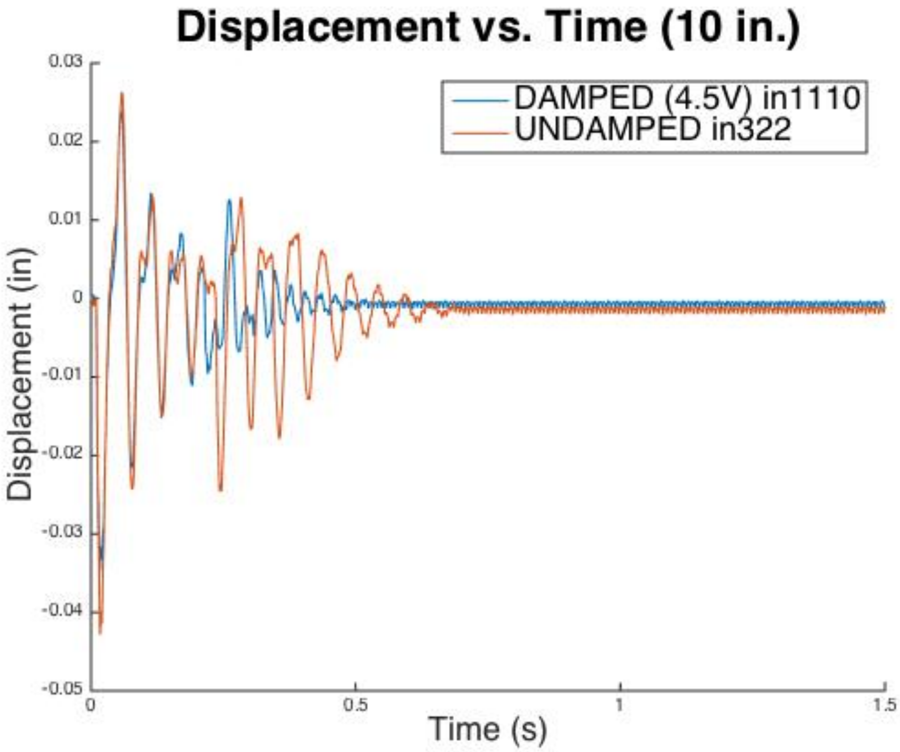

Figure 7. Displacement response controlled with dampers 1 & 2

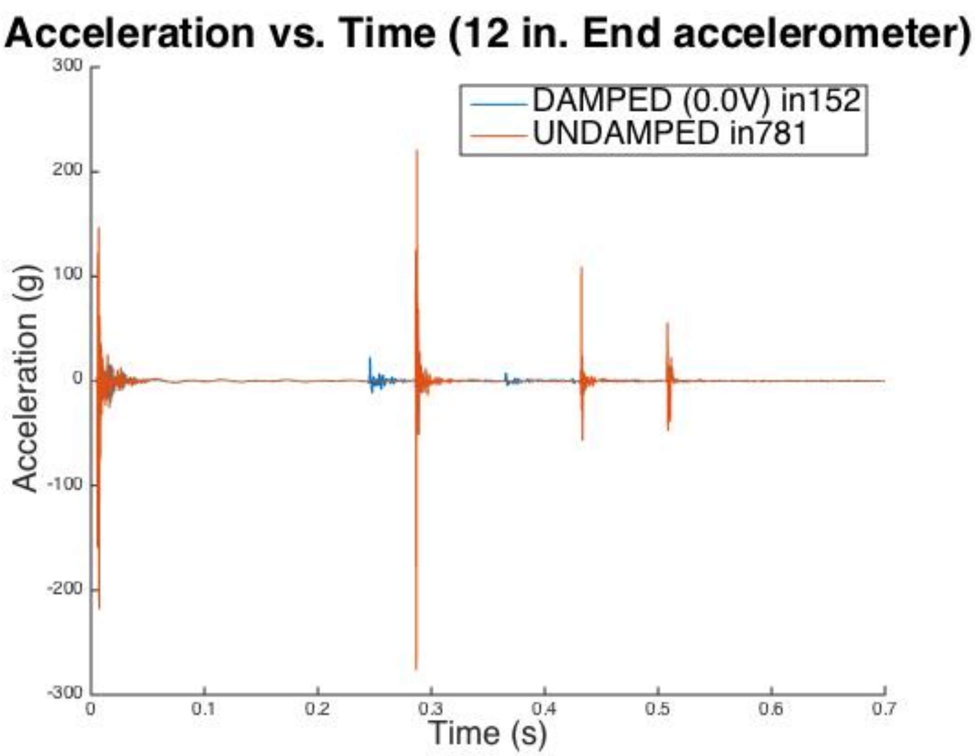

Figure 8. Acceleration response controlled with dampers 1 & 2

Figure 9 shows maximum and minimum peak acceleration responses for each drop height. In figure 9, significant reduction in acceleration is shown. For the undamped case, the acceleration continued to increase as the drop heights increased. However, when dampers 1 & 2 were attached and control voltages were sent to the dampers, a decline in acceleration is seen from the 10 inch drop height to the 12 inch drop height. This demonstrates the strong performance of dampers 1 & 2 in reducing acceleration response.

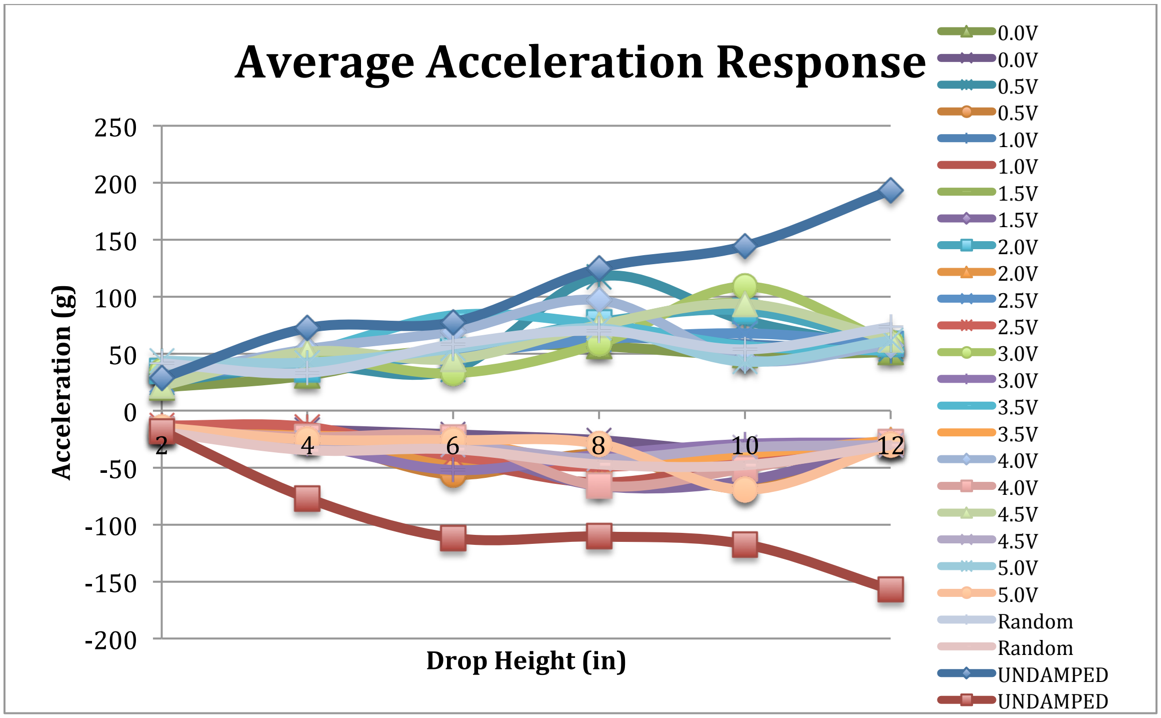

Figure 9. Average acceleration response controlled with dampers 1 & 2

Dampers 2 & 3 show an excellent displacement reduction, and some acceleration reduction. In figure 10, the damped case has a smaller magnitude, and decreases acceleration response much faster than the undamped case. In figure 11, there is some reduction in acceleration. This shows that implementing both dampers 2 & 3 is effective in mitigating displacement response, but not as effective in mitigating acceleration response.

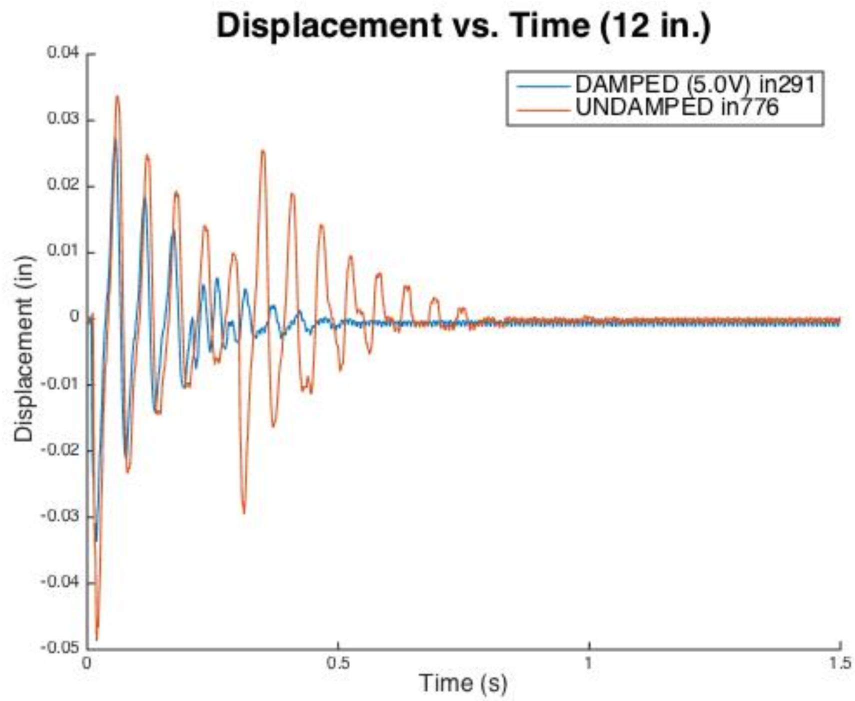

Figure 10. Displacement response controlled with dampers 2 & 3

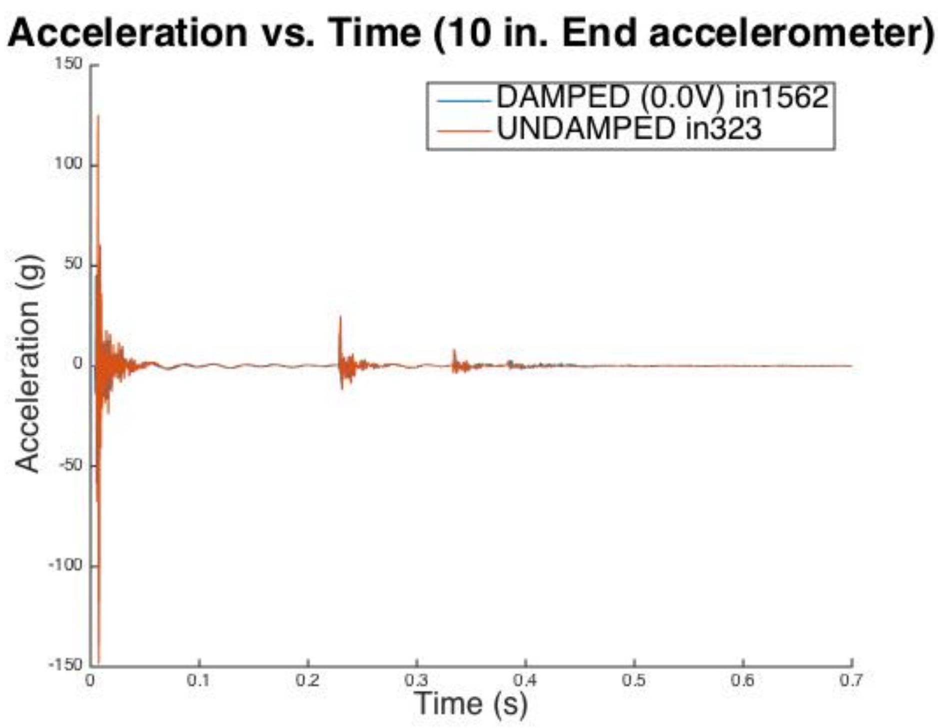

Figure 11. Acceleration response controlled with dampers 2 & 3

Figure 12 shows maximum and minimum peak displacement responses for each drop height. In figure 12, significant reduction in displacement is shown. The average minimum displacement clearly shows the difference in displacement response between the damped and undamped cases. As the drop heights increased, reduction increased, further supporting the idea that higher impact loads are more effectively reduced with the use of dampers.

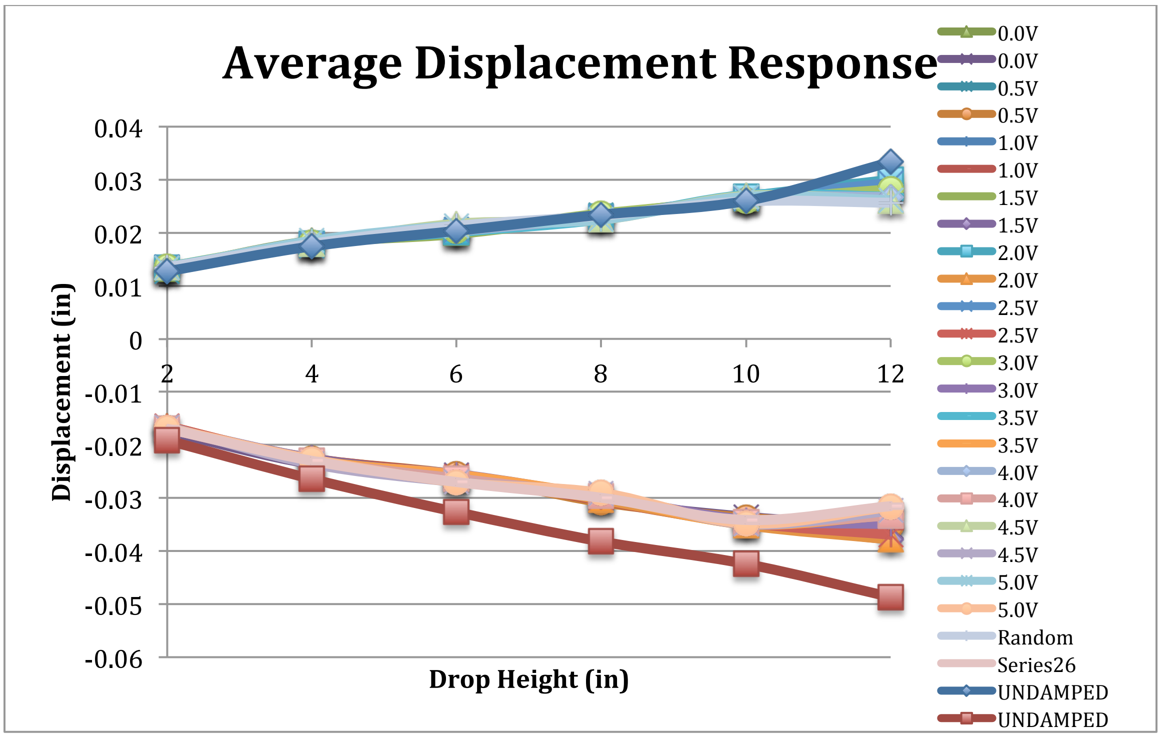

Figure 12. Average displacement response controlled with dampers 2 & 3

Table 2 shows the best average reduction ratios across the different drop heights when dampers 1 & 2 or dampers 2 & 3 are connected. Dampers 1 & 2 show a 70-82% reduction in peak maximum and minimum acceleration response, a peak-to-peak acceleration reduction of 75.3%, and an area under the acceleration response curve reduction of 34.2%, while dampers 2 & 3 show a 51.8-75.7% reduction in acceleration response, a peak-to-peak acceleration reduction of 62.3%, and an area under the acceleration response curve reduction of 50.7%. Dampers 1 & 2 show a 7-19.6%

reduction in peak maximum and minimum displacement, a 14.5% peak-to-peak displacement reduction, and an area under the displacement response curve reduction of 30.5%, while dampers 2 & 3 show a 36% – 44.4% reduction in displacement response, a 23.8% peak-to-peak displacement reduction, and an area under the displacement response curve reduction of 41%. This shows that both combinations are effective at reducing both displacement and acceleration response, but the combination of dampers 1 & 2 is more effective in reducing acceleration response, and the combination of dampers 2 & 3 is more effective in reducing displacement response.

Table 2. Displacement and acceleration response reduction ratios with dampers 1 & 2 and dampers 2 & 3

	Response Reduction Ratio For Dampers 1 & 2	Response Reduction Ratio For Dampers 2 & 3
Max Displacement (C1)	0.930	0.640
Min Displacement (C2)	0.804	0.556
Max – Min Displacement (C3)	0.855	0.762
Displacement Energy (C4)	0.695	0.590
Max Acceleration (C1)	0.300	0.482
Min Acceleration (C2)	0.181	0.243
Max - Min Acceleration (C3)	0.247	0.377
Acceleration Energy (C4)	0.658	0.493

In the event that only one damper can be applied, damper 3 on its own does a good job of reducing structural response, relative to the other dampers. In figure 13, the damped case has a smaller magnitude than the undamped case, although the damped case does not eliminate displacement response faster than the undamped case, like it did when multiple dampers were used. In the figure 14, the damped case shows a significant reduction in acceleration response, showing that with the implementation of just one damper can still greatly help in mitigating structural response.

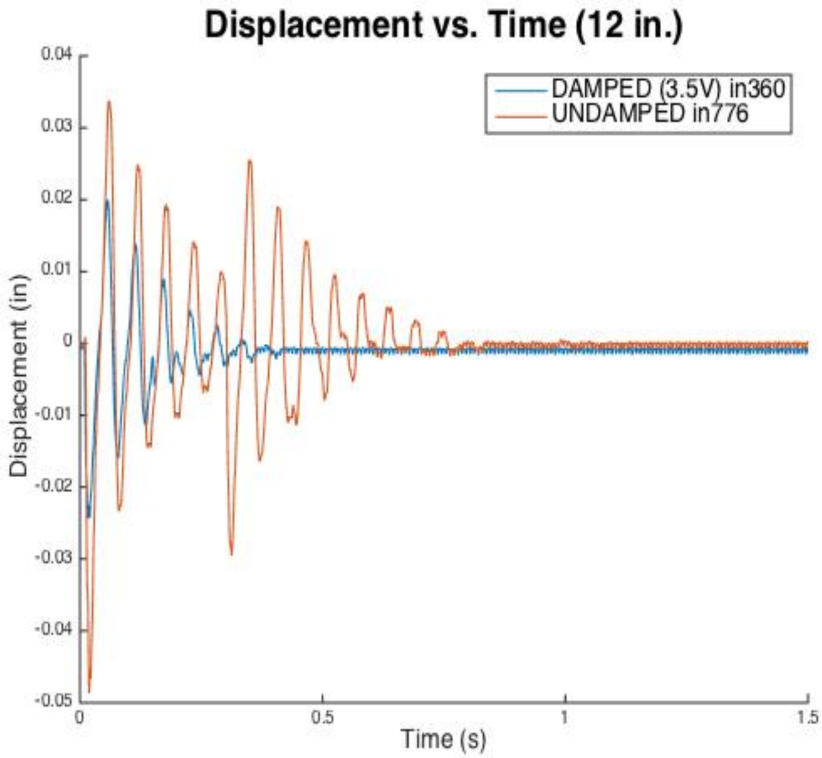

Figure 13. Displacement response controlled with damper 3

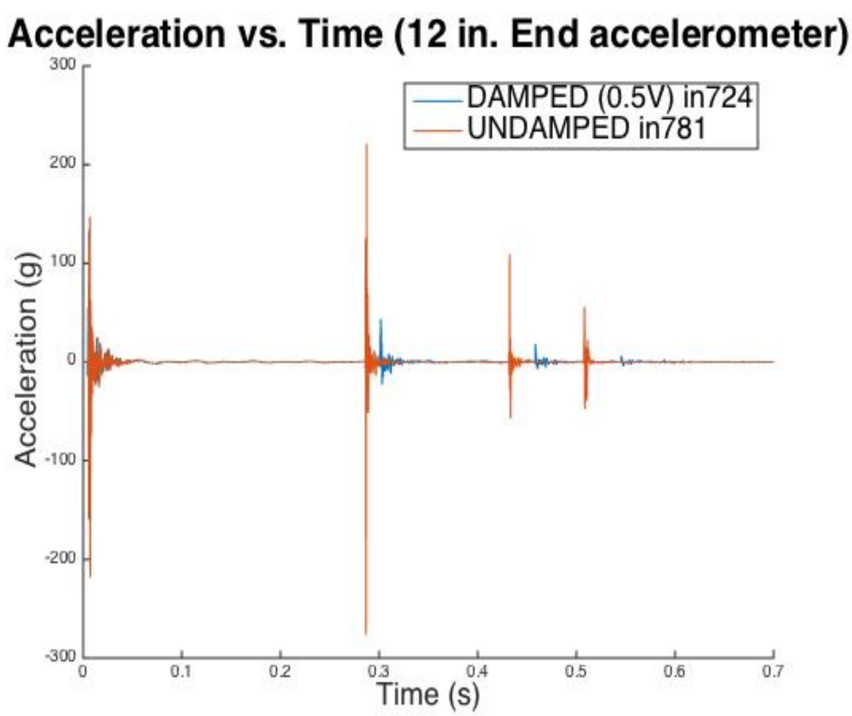

Figure 14.

Acceleration response controlled with damper 3

Table 3 shows the best average reduction ratios across the different drop heights when damper 3 is connected. Damper 3 shows an 8.6-17.2% reduction in peak maximum and minimum displacement response, a 12.5% peak-to-peak displacement reduction, and an area under the displacement response curve reduction of 15.4%. It also shows a 60-74.2% reduction in acceleration response, a peak-to-peak acceleration reduction of 31.2%, and an area under the acceleration response curve reduction of 31.2%. Although the reduction is not as large as the reductions shown with multiple dampers, the reduction is still significant, and helps in mitigating structural response.

Table 3. Displacement and acceleration response reduction ratios with damper 3

Damper 3	Response Reduction Ratio
Max Displacement (C1)	0.914
Min Displacement (C2)	0.828
Max - Min Displacement (C3)	0.875
Displacement Energy (C4)	0.846
Max Acceleration (C1)	0.404
Min Acceleration (C2)	0.258
Max - Min Acceleration (C3)	0.688
Acceleration Energy (C4)	0.688

Conclusion

In order to optimize the effectiveness of the MR dampers in mitigating structural displacement and/or accelerations, scaled down impact tests were conducted on a cantilever concrete beam designed to model a bridge pier. MR dampers were used for structural control, and accelerometers and an LVDT displacement transducer were placed on the beam for response measurement. Structural responses after an impact load with different combinations of dampers attached were recorded, and compared to determine the most effective location for the dampers. After studying each test case, all dampers connected showed the greatest response reduction for both displacement and acceleration. All dampers connected showed a 16.5-28.8% reduction in displacement, and a 65.8-76% reduction in acceleration from the end accelerometer. However, if the use of all three dampers is too costly, the combination of dampers 1 & 2 showed excellent acceleration response reduction, and the combination of dampers 2 & 3 showed excellent displacement response reduction. Dampers 1 & 2 show a 70-82% reduction in acceleration response, and a 7-19.6% reduction in displacement. On the other hand, dampers 2 & 3 show a 51.8-75.7% reduction in acceleration response, and a 36-44.4% reduction in displacement response. In the event that only one damper can be applied, damper 3 on its own does a good job in reducing structural response. Damper 3 shows an 8.6-17.2% reduction in displacement response, and a 60-74.2% reduction in acceleration response. Although the reduction is not as large as the reductions shown with multiple dampers, the reduction is still significant, and helps in mitigating structural response. This indicates that the application of MR dampers on a bridge pier is very effective in reducing structural response, and that the effectiveness of the dampers varies depending on the number of dampers connected.

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