MOUNTAIN-PLAINS CONSORTIUM

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Safety Factor Increase to Fatigue Limit States through Shear Spiking for Timber Railroad Bridge Rehabilitation – Phase I

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ABSTRACT

The overall project is to demonstrate the effectiveness of shear spiking (technique already developed through a previous project). Many timber railroad bridges are deficient but it is too costly to replace them; hence, inexpensive repair techniques are needed. The proposed project will provide the necessary documentation of the effectiveness of this newly developed mitigation technique under realistic loads using new equipment available from a National Science Foundation grant to Colorado State University. This will ultimately be accomplished through a series of spatio-temporal fatigue tests on stringers for both non-repaired and repaired. The timing and locations of the loading will be determined from influence line analysis of a typical freight train(s). The results will be used as leverage and/or proof-of-concept to approach the American Railway Association for additional funding. This report presents the intermediate results of the project, which is designated herein as Phase I. Phase I focused on development of the actuator control algorithm, which was successfully tested in the Colorado State University Structural Engineering Laboratory in the spatio-temporal test frame using seven actuators simultaneously in force control.

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1. INTRODUCTION

There are numerous timber railroad bridges still in use across the United States, many of them in need of various levels of repair or replacement. Unfortunately, replacement is too costly considering the vast number of bridges in use. Many of these bridges are suffering from decay, which significantly reduces their shear capacity. Bending moment is typically less of a problem because of the multiple supports of the stringers. Over the last several years, CSU has developed and demonstrated a shear spiking technique using 1-inch diameter FRP spikes inserted into the top of beams and secured with high strength epoxy. The system was tested under static load and found to be quite effective, increasing the strength beyond the design capacity. As with most new techniques, in order to apply the technique in-situ, a great deal of proof is needed to convince bridge owners (i.e., railroads) that shear spiking is not only an economically viable, but safe option in lieu of costly stringer replacement. Replacement not only results in significant construction costs but there is down time to consider.

Although fatigue life of structural members through basic cycling is important to determine, the actual load effects induced by train loading on bridges is very relevant to fatigue reliability problems. It is important that the statistics of the load effects, particularly shear, be reproduced at critical (damaged or deteriorated) locations on a girder. This report presents the derivation of the load control algorithm for performing these advanced fatigue tests.

2. PROJECT PURPOSE AND OBJECTIVE

The research objectives for the overall project are to (1) develop a realistic loading sequence along the length of timber bridge stringers using the spatio-temporal load equipment recently procured at CSU, (2) compute the change in safety factor for long-term realistic fatigue loading (e.g., 100,000 cycles) when shear spiking is used as a rehabilitation technique, and (3) compute the change in safety factor based on ultimate capacity using static tests. This report focuses on Task 1.

3. TECHNICAL APPROACH

3.1 Full Project Overview – All Phases

There are numerous timber railroad bridges still in use across the United States, many of them in need of various levels of repair or replacement. Unfortunately, replacement is too costly considering the vast number of bridges in use. Many of these bridges are suffering from decay, which significantly reduces their shear capacity. Bending moment is typically less of a problem because of the multiple supports of the stringers. Over the last several years, CSU has developed and demonstrated a shear spiking technique using 1-inch diameter FRP spikes inserted into the top of beams and secured with high strength epoxy. The system was tested under static load and found to be quite effective, increasing the strength beyond the design capacity. As with most new techniques, in order to apply the technique in-situ, a great deal of proof is needed to convince bridge owners (i.e., railroads) that shear spiking is not only an economically viable, but safe option in lieu of costly stringer replacement. Replacement not only results in significant construction costs, but there is down time to consider. The investigators believe the necessary proof lies in demonstrating the increase in the safety factor under realistic loading conditions for both ultimate capacity and fatigue limit states. Thus, the work tasks include:

1. Selection of stringer orientation for installation into the existing spatio-temporal load frame at CSU. This frame has seven dynamic actuators, which will be oriented and used in load control to simulate the load effects (moment and shear) experienced by the stringer.
2. Influence line analyses using train weight data to determine the load control signals to each actuator. This is the spatial portion of the loading.
3. Development of the numerical algorithm to control the actuators. This will be based on tasks 1 and 2 above and requires the introduction of the trains speed. This is the temporal portion of the loading.
4. Testing damaged-unrepaired and damaged-repaired bridge stringers in a spatio-temporal fatigue test, and testing damaged-unrepaired and damaged-repaired bridge stringers under more significant loads (e.g., ~200 kips) to numerically estimate the safety factor to ultimate load for each based on codified levels. (This is primarily a year 2 activity, but is included for completeness).

The structural engineering laboratory at CSU is in a unique position to be able to perform spatio-temporal loading on bridge test specimens using a suite of seven dynamic actuators in a 30-ft x 20-ft x 18-ft steel test frame. This equipment was recently awarded to CSU in the form of a major research instrumentation (MRI) grant from the National Science Foundation and will be used during the experimental portion of the project.

This report focuses on Task 3 described above.

4. DERIVATION OF ACTUATOR CONTROL

Problem Statement:

It is required to find the forces needed to control a series of actuators so that the errors in terms of displacement, shear, and moment between the simulation and computed case is minimized. This can be extended for each point in time while the actuator is either in displacement or force feedback, and, for any number of actuators.

Solution:

To do this, we use the least-square error equation and derive equations for the forces of actuators. The method is as follows:

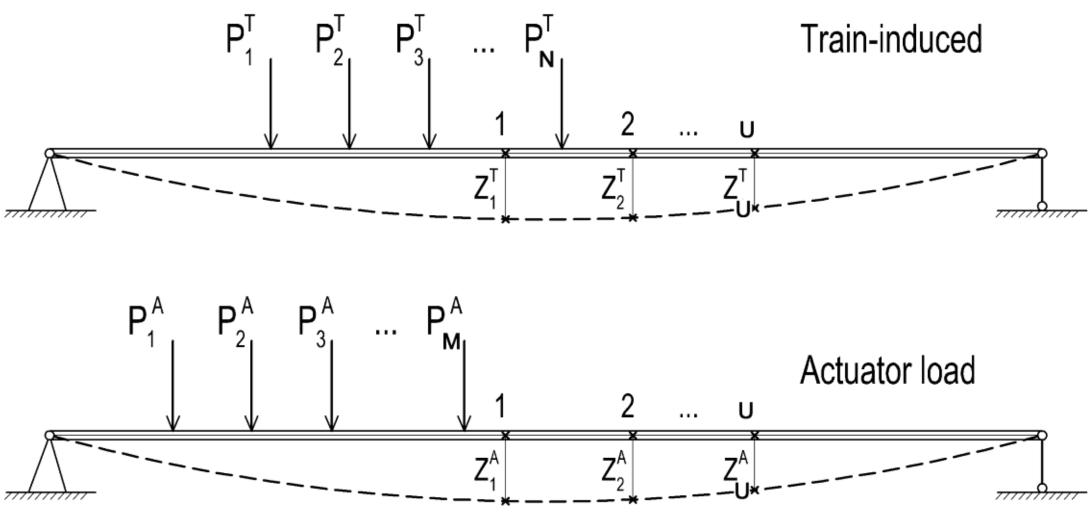


Figure 4.1 Train-induced loads and actuator loads.

Assume the train has *N* axles; thus, we have *N* load points from the train $P_1^T, P_2^T, ..., P_N^T$ applied onto the prototype beam at different locations; and *M* loads from the actuators $P_1^A, P_2^A, ..., P_M^A$ applied on the simulated beam at other locations. Now, we would like to minimize the error of the square of the displacement, moment, or shear at point 1, point 2 ... point *U*.

Let $Z_1^T, Z_2^T, ... Z_U^T$ be the displacement, moment, or shear due to the train loading at point 1, point 2 ... point *U*. Then we have:

$$Z_1^T = \sum_{i=1}^{N} K_{1i}^T P_i^T$$

$$Z_2^T = \sum_{i=1}^{N} K_{2i}^T P_i^T$$

...

$$Z_U^T = \sum_{i=1}^{N} K_{Ui}^T P_i^T$$

Where $K_{1i}^T, K_{2i}^T, ..., K_{Ui}^T$ are the stiffness at point 1, point 2 ... point *U* versus the load from wheel *i*. Therefore we can compute $Z_1^T, Z_2^T, ...Z_U^T$ due to the train from the above equations if we know the loads $P_1^T, P_2^T, ..., P_N^T$.

Let $Z_1^A, Z_2^A, ...Z_U^A$ be the displacement, moment, or shear due to the actuators at point 1, point 2 ... point *U*, then we have:

$$Z_1^A = \sum_{j=1}^{M} K_{1j}^A P_j^A$$

$$Z_2^A = \sum_{j=1}^{M} K_{2j}^A P_j^A$$

...

$$Z_U^A = \sum_{j=1}^{M} K_{Uj}^A P_j^A$$

where $K_{1j}^A, K_{2j}^A, ..., K_{Uj}^A$ are the stiffness at point 1, point 2 ... point *U* from the load from actuator *j*.

The total of the square-errors can be written as:

$$S = \sum_{i=1}^{U} \left(Z_i^A - Z_i^T\right)^2 = \sum_{i=1}^{U} \left(\sum_{j=1}^{M} K_{ij}^A P_j^A - Z_i^T \right)^2$$

Then, to find the minimum of S, we take the partial derivative of S versus P_l^A (l = 1,2,...M), and set it equal zero. We get:

$$\frac{\partial S}{\partial P_l^A} = \frac{\partial}{\partial P_l^A}\left[\sum_{i=1}^{U}\left(\sum_{j=1}^{M} K_{ij}^A P_j^A - Z_i^T\right)^2\right] = \sum_{i=1}^{U}\frac{\partial}{\partial P_l^A}\left(\sum_{j=1}^{M} K_{ij}^A P_j^A - Z_i^T\right)^2$$

$$= \sum_{i=1}^{U} 2\times\left(\sum_{j=1}^{M} K_{ij}^A P_j^A - Z_i^T\right)\times\frac{\partial}{\partial P_l^A}\left(\sum_{j=1}^{M} K_{ij}^A P_j^A - Z_i^T\right)$$

$$= \sum_{i=1}^{U} 2\times\left(\sum_{j=1}^{M} K_{ij}^A P_j^A - Z_i^T\right)\times K_{il}^A$$

and:

$$\frac{\partial S}{\partial P_l^A} = 0 \Leftrightarrow \sum_{i=1}^{U} K_{il}^A\left(\sum_{j=1}^{M} K_{ij}^A P_j^A - Z_i^T\right) = 0$$

$$\Leftrightarrow \sum_{i=1}^{U}\left(\sum_{j=1}^{M} K_{il}^A K_{ij}^A P_j^A - K_{il}^A Z_i^T\right) = 0$$

$$\Leftrightarrow \sum_{i=1}^{U}\sum_{j=1}^{M} K_{il}^A K_{ij}^A P_j^A - \sum_{i=1}^{U} K_{il}^A Z_i^T = 0$$

$$\Leftrightarrow \sum_{j=1}^{M}\sum_{i=1}^{U} K_{il}^A K_{ij}^A P_j^A - \sum_{i=1}^{U} K_{il}^A Z_i^T = 0$$

$$\Leftrightarrow \sum_{j=1}^{M}\left(\sum_{i=1}^{U} K_{il}^A K_{ij}^A\right) P_j^A - \sum_{i=1}^{U} K_{il}^A Z_i^T = 0$$

$$\Leftrightarrow \sum_{j=1}^{M} B_{lj}^A P_j^A = F_l \text{ where } l = 1, 2, \ldots M \text{ and}$$

$$B_{lj}^A = \sum_{i=1}^{U} K_{il}^A K_{ij}^A; \text{ and } F_l = \sum_{i=1}^{U} K_{il}^A Z_i^T$$

We have a set of M equations and M variables, which is easily solved:

$$[\mathbf{B}]\{\mathbf{P}\} = \{\mathbf{F}\} \Rightarrow \{\mathbf{P}\} = [\mathbf{B}]^{-1}\{\mathbf{F}\} \quad (1)$$

We can add the matrix **[B]** and **{F}** of displacement, moment, or shear together if all load effects are of interest, or solve them separately for a better, i.e., more accurate, solution. For train loading, these equations will be extended to be a function of time by simply computing the actuator control at each point in time and feeding these to the actuators. The MTS controller will provide the necessary feedback as the actuator and structure interact dynamically.

5. ILLUSTRATIVE EXAMPLE

In this example, actuators are used to simulate the train load on a bridge that has simply supported beam, the beam has span of 20m, and cross-section is 0.6×1.5m. The concrete modulus is 17000MPa. Assume that a number of actuators are used to simulate the wheel loads when the train moves through the bridge with a speed of 7m/s. There are four wheels and the distance between four wheels is 1.6m, as shown in Figure 5.1.

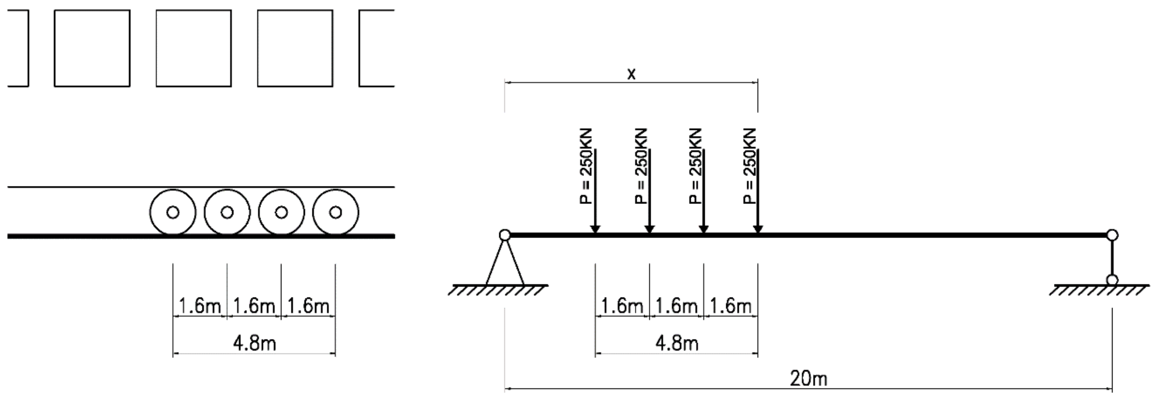


Figure 5.1 Wheel loads

The time for all the wheels to run through the bridge with speed of 7m/s is:

$$\frac{20 + 4.8}{7} = 3.54\ sec$$

In the first try, we use three actuators to simulate the displacement of the beam while the train is running over the bridge. The actuators are installed at 5, 10, and 15m of the bridge span (see Figure 5.2).

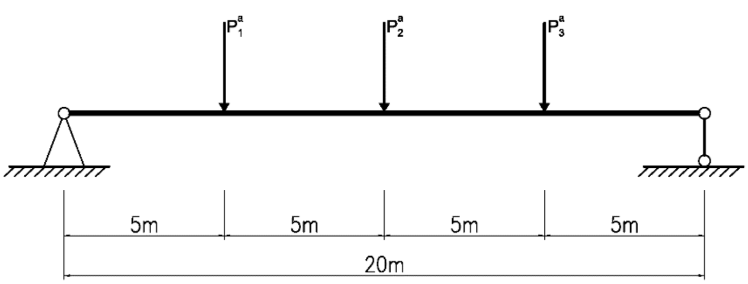
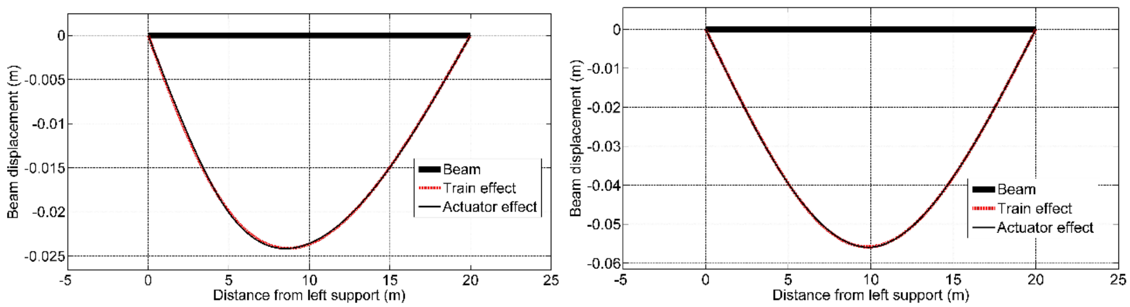


Figure 5.2 Actuators positions

At every time step of 0.05 sec, the forces in all actuators are calculated using equation (1) based on the least square error of beam displacement at 50 points along the span (every 0.4m). Figure 5.3a shows the displacement of the beam due to the train load and actuator simulation at t = 0.75 sec. One can see that at t = 0.75 sec, the train wheels are within the first quarter of the bridge span; therefore, the maximum displacement is somewhere in the first half of the bridge span (not at the mid-span). Even though the beam displacement was not symmetric, the actuators were able to create a beam displacement shape very close to the actual displacement induced by the train load. Especially when the train traveled to mid-span, the beam displacement simulated by the actuators was almost the same as that caused by the train load (Figure 5.3b).

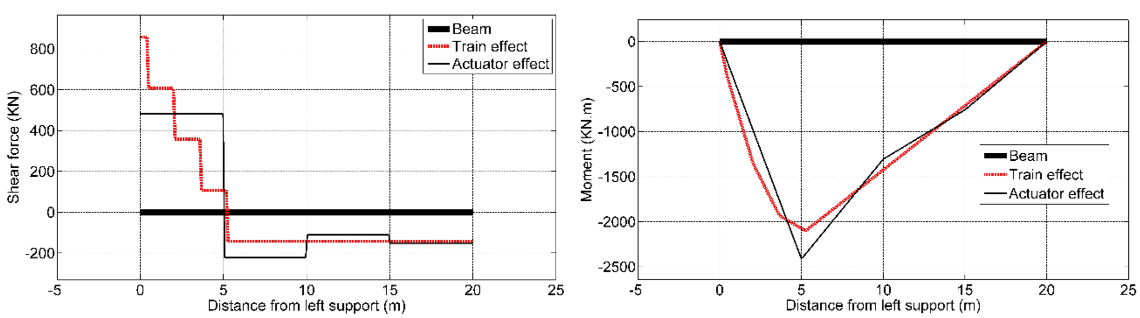


a) t = 0.75 sec

b) t = 1.75sec

Figure 5.3 Train-induced and actuator-simulated displacements at different times

Figure 5.4 shows the comparison of shear and moment between the simulation and train-induced loading. Recall that the simulation target in this first trial is displacement; therefore, the simulated shear and moment are not as close to those induced by the train load at t = 0.75 sec. One can see from Figure 5.4 that the simulated moment has better fit than simulated shear since the beam displacement is dominated by moment.

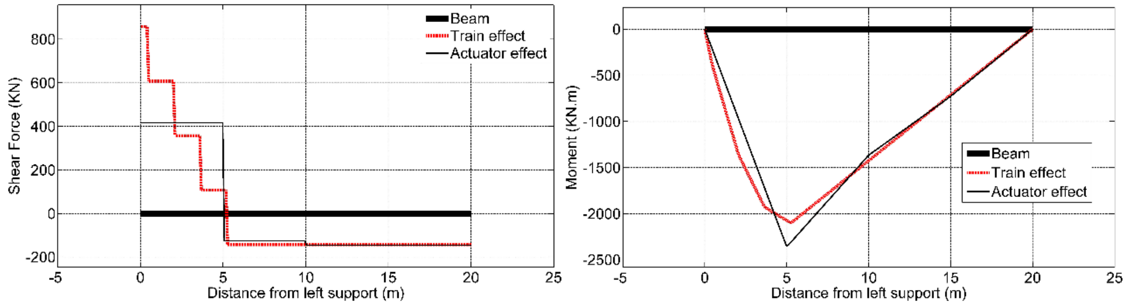


a) Shear

b) Moment

Figure 5.4 Comparison of shear and moment

In the next trial, the same three actuators at the same locations, as shown in Figure 5.2, were used to simulate the train load, but the least square errors are controlled by shear and moment, respectively. Figure 5.5 presents the optimized results of the shear (Figure 5.5a) and moment (Figure 5.5b) at t = 0.75 sec. In both cases, the results were slightly better than in the case of displacement simulation, but one can see that the simulated shear and moment were where not as good as simulated displacement.



a) Optimized Shear at t = 0.75 sec   b) Optimized Moment at t = 0.75 sec

Figure 5.5 Simulated shear and moment

In order to have better simulated shear and moment, in the last trial, more actuators were added to the system to simulate the shear and moment induced by the train load. There were nine actuators used in this simulation. These actuators were placed every 2m, as shown in Figure 5.6.

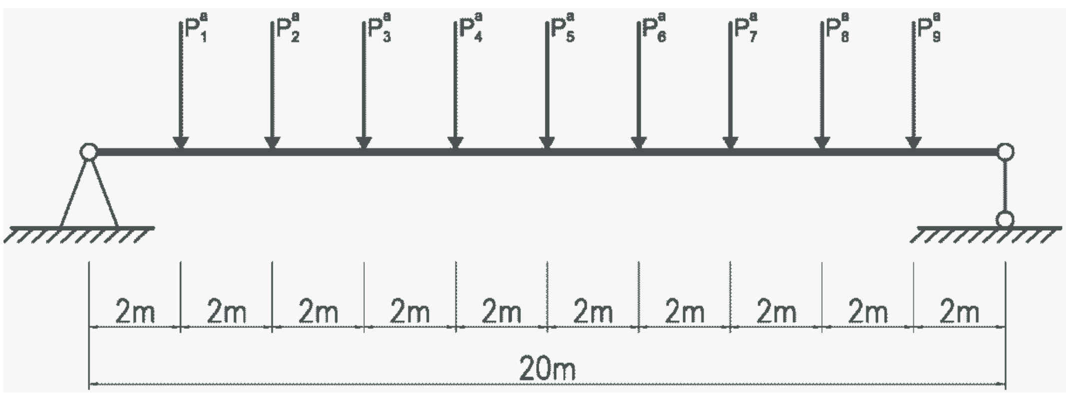
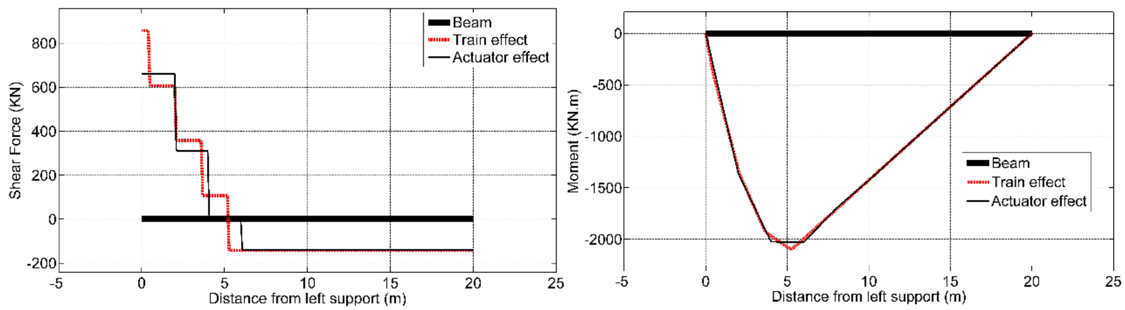


Figure 5.6 Actuators location used in the last trial

Similar steps were conducted to simulate the shear and moment using nine actuators. Figure 5.7 shows the comparison of simulated shear and moment. With more actuators, one can have better simulation of shear and moment. For example, consider Figure 5.7(b); the comparison shows that the simulated moment is almost the same as the train-induced moment. Because the train load induced the concentrated force, which causes jumps in the shear force diagram, it is very difficult to simulate the train-induced shear force using a limited number of actuators. However, the introduced algorithm was able to predict the best fit of shear force simulated by actuators and can inform the decision as to the number of actuators needed for testing in later phases of this project.



a) Optimized shear at t = 0.75 sec

b) Optimized Moment at t = 0.75 sec

Figure 5.7 Simulated shear and moment using nine actuators

As expected, with nine actuators, the results of the algorithm were able to reproduce the train-induced beam displacement perfectly, as shown in Figure 5.8. Figure 5.9 shows the force in the actuators during the simulation. It can be seen in Figure 5.9 that the maximum force in each actuator occurred when the train traveled through the position of that actuator, as one would expect.

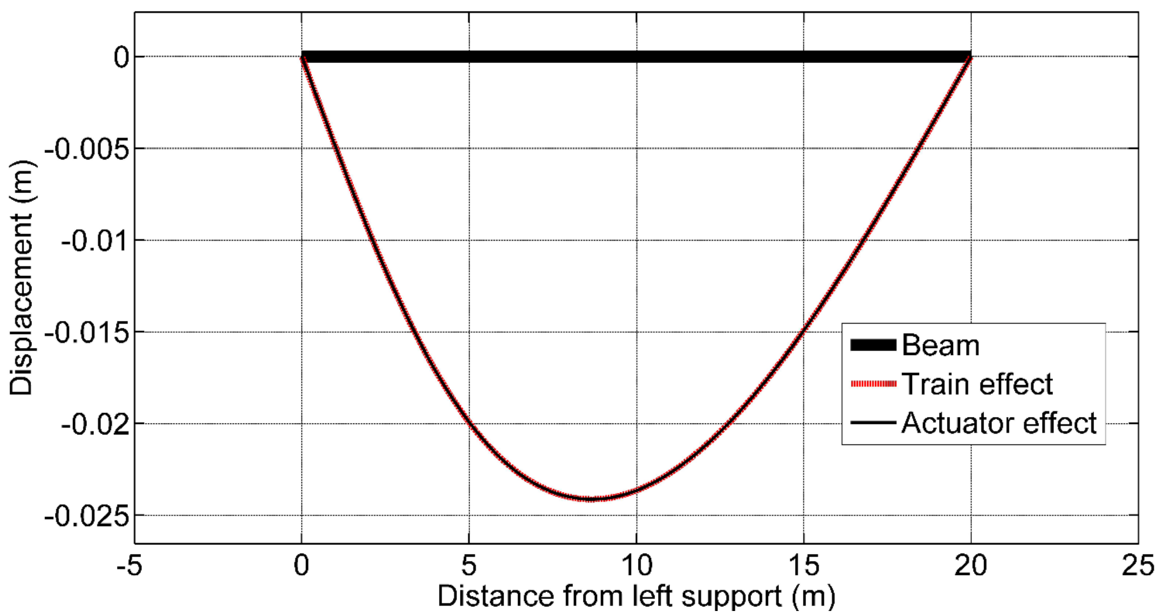


Figure 5.8 Simulated displacement at t= 0.75 sec using nine actuators

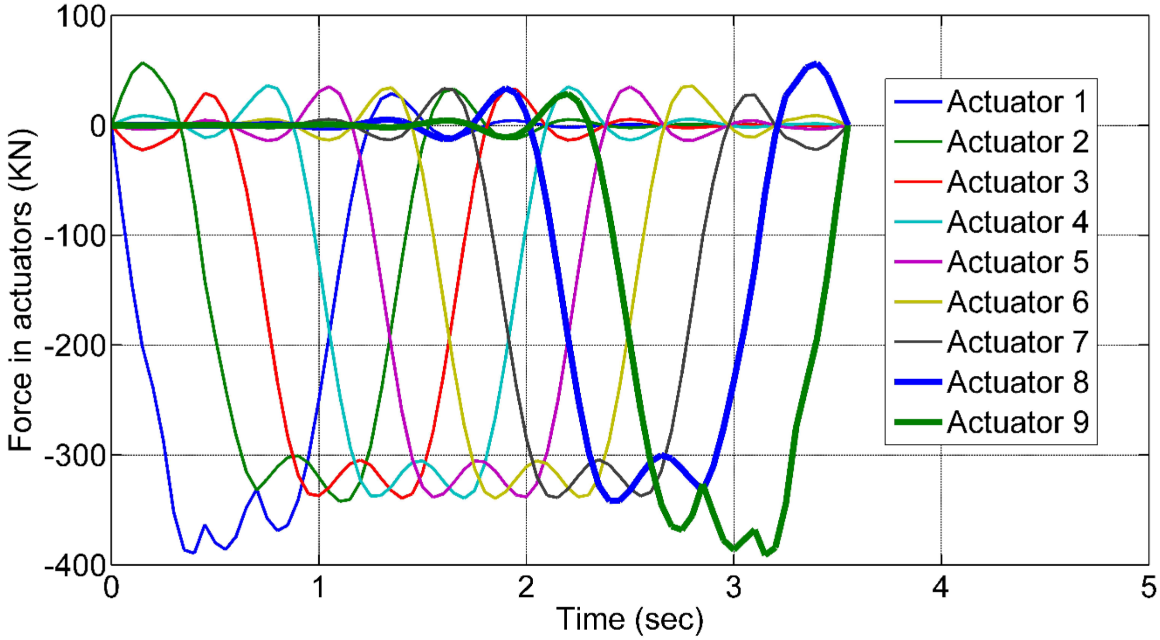


Figure 5.9 Forces in actuators in simulation of train-induced displacement

6. CONCLUSIONS AND RECOMMENDATIONS

In this study, a control algorithm was introduced to control the force in a series of hydraulic actuators so that the train-induced shear, moment, and displacement on a bridge girder can be simulated in the lab. The least square error for the shear, moment, and displacement was used to optimize the actuator-induced shear, moment, and displacement in the beam. From the illustrative examples, it can be concluded that the displacement is the quantity that is easiest to simulate using actuators, while the shear force is the most difficult to control since the loads from the wheels are concentrated forces that induced the jump in the shear force diagram. However, it should be noted that the algorithm introduced in this study assumed that the materials are in the linear range if the displacement is simulated. For simply supported beams or statically determinant systems, since the shear and moment are not dependent on material behavior, these quantities can be simulated regardless of the behavior of the beam material behavior. For non-linear behavior, a real-time updated model should be used to enable the simulation using the same algorithm used in this study.

It is recommended to apply the algorithm developed in this Phase I project in a Phase II project to investigate the change in load effect for repaired versus unrepaired bridge beams. Then, the increase in fatigue reliability for these types of economical repair methods can be quantified demonstrating their viability.