Monitoring Louisiana Bridges for Heavy Truck Loads Hauling Sugarcane

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ABSTRACT

This study assesses the strength, serviceability and economic impact of overweight trucks hauling sugarcane on Louisiana bridges. Researchers identified the highway routes and bridges used in hauling this commodity, and statistically chose samples to use in the analysis. Eighty-four bridges were involved in this study and four different load configurations were examined. The cost of sugarcane truck loads on the remaining safe life of these bridges was computed based on the four different load configurations.

A live load test was performed on a selected typical bridge to determine its stiffness, capacity, and rating. The bridge was instrumented in order to quantify the live load response of the superstructure under normal service loads and sugarcane truck loads. A long-term monitoring system was also installed on this structure. This will be used to monitor health status of the structure over the system's scheduled life. Actual live-load dynamic responses can also be observed over time to verify the appropriateness of the applied impact factor.

INTRODUCTION

The 1998 Transportation Equity Act for the 21st Century (TEA21) allows heavier loads for sugarcane haul on Louisiana interstate highways. These loads are currently being applied to state and parish roads that are traveled by vehicles going from the interstates to the processing plants. TEA 21 further provided Federal funding to enable Louisiana to study the effects of increasing the allowable permitted loads for transporting sugarcane.

Generally, commercial vehicle weights and dimension laws are enforced by highway agencies to ensure that excessive damage (and subsequent loss of pavement life) is not imposed on the highway infrastructure. The axle load and the total load of heavy trucks, which can be considered primarily responsible for decreasing the service life of bridges, are significant parameters of highway traffic. Currently in Louisiana gross vehicle weight (GVW) on interstate routes has typically been restricted to 80,000 lbs., for five axle semi-trailer (LA type 6) vehicles with a maximum tandem axle weight of 34,000 lbs. For many years permitted loads on the type 6 vehicle during harvest season have been allowed for up to 83,400 lbs., GVW and 35,200 lbs., on tandem axles. TEA 21 and the Louisiana legislature now extend the GVW to 100,000 lbs., with tandem axle weights increasing to 48,000 lbs., for interstate travel. Because highways have traditionally been designed for the legal load of 80,000 lbs., permitted trucks of 100,000 lbs., or even heavier than 100,000 lbs., decrease the expected service life of the infrastructure. The results are increased transportation costs due to high maintenance and the need for early rehabilitation.

In March 2005, the Project Review Committee, PRC, of Louisiana Department of Transportation and Development (LA DOTD) and Louisiana Transportation Research Center (LTRC) decided that the loads for sugarcane trucks should be investigated based on a GVW of 120,000 lbs. Since loads of such magnitude would result in reduced service life of the Louisiana bridges, this study evaluated the short-term and long-term behavior of bridges under these overweight vehicles. Several options were reviewed, which might include one or all of the following: 1) the reduction of the load carried by the bridge with alternative vehicle axle configurations, 2) the reduction of the haul loads, 3) the acceptance of more frequent rehabilitation of the bridges, were investigated. The research team also generated bridge costs for GVW 120,000 lbs. Work was performed based on load factors included in the method of design in Load Resistance Factor Design (LRFD).

NEED FOR RESEARCH

Increasing the truck gross weight may reduce the transportation spending remarkably for the sugarcane industry. On the other hand, increasing the truck gross weight may reduce the safety and serviceability of the bridge and increase the rehabilitation cost. To solve this contradiction, it is very important to find the balance point between those two demands. The safety and serviceability of the bridge should be investigated carefully by monitoring and analyzing the bridge under the design truck load and the heavy trucks hauling sugarcane. The economic impact of increasing truck load should be evaluated based on the truck gross weight and truck configurations.

OBJECTIVE

The principal objectives of this study were to:

1. Investigate the strength and safety of a bridge while subject to trucks hauling sugarcane products.
2. Analyze and load-rate the structure for loading vehicles HS-20 and sugarcane truck loadings by performing the live-load field test and corresponding finite element analysis.

SCOPE

The scope of this investigation was focused on: 1) studying the effects of sugarcane truckloads on distribution of forces and moments on slab-girder bridges and 2) determining the structural impact on the life of the structure due to overloads. The analysis concentrated on the effects of the following parameters: 1) Type of loading on the bridge, four types of the sugarcane truck loading were considered, which were shown in figure 1; 2) Geometry of the bridge, which included the girder type, girder spacing, length of the span, number of spans Relative dimensions of the girders and slabs, and support conditions of the bridge.

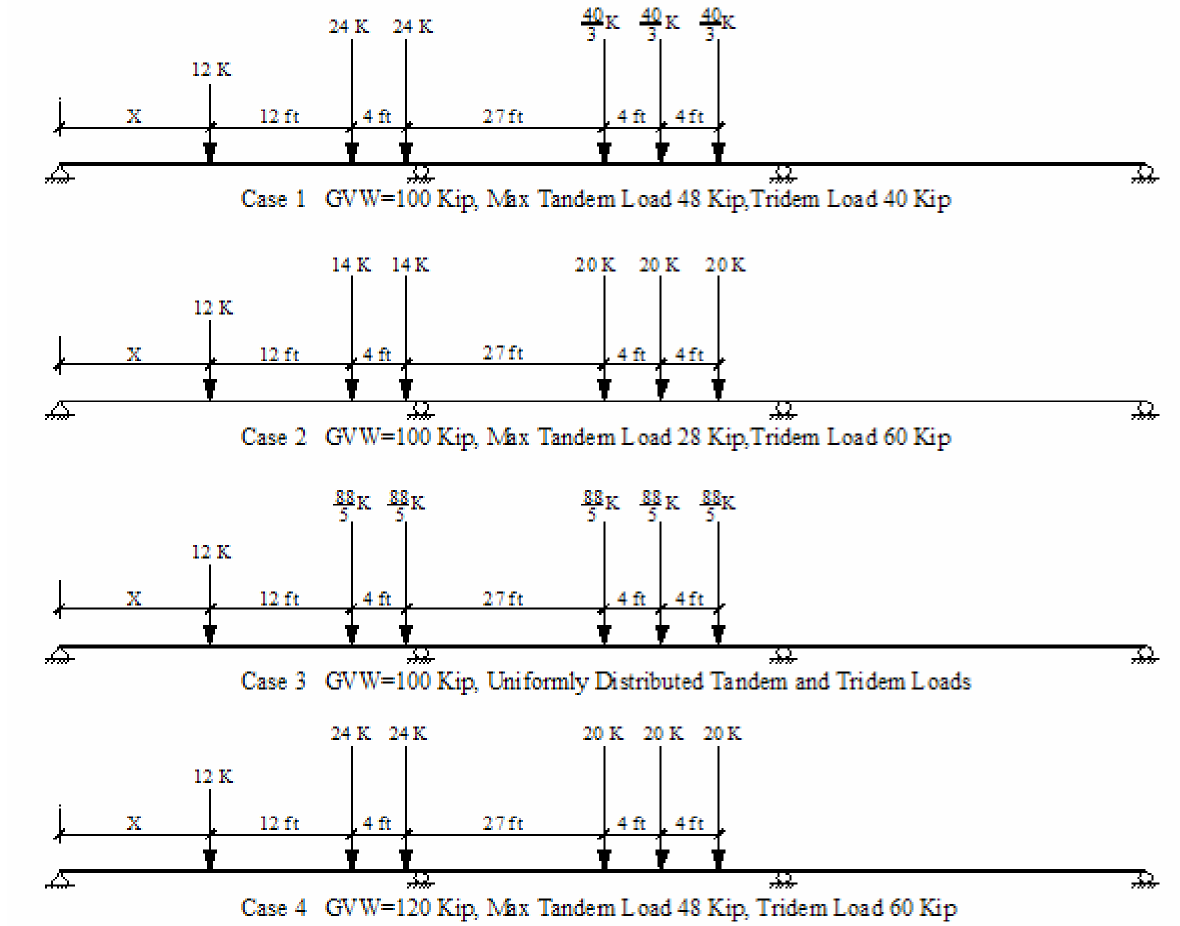

FIGURE 1 Sugarcane truck load configurations, case 1 to 4

METHODOLOGY

There were four steps that were performed. The first step in the study was to identify the bridges on which sugarcane are hauled. The second step was to develop the live load test plan for a representative bridge. The third step was to develop a means for assessing the bridge safety. The fourth, and the last step, was to design and install a long-term monitoring system for the bridge in order to monitor the stresses that the structure will be exhibiting over the system's scheduled life.

Identify the Critical Bridges for Study

The critical bridges for this study were considered to be those that are located on the roads most traveled by the sugarcane trucks. The roads considered are Louisiana State Highways and U.S. Numbered Roads. The Louisiana state bridge inventory was used to locate the state bridges. The review and selection processes were based on two factors: (1) the amount of sugarcane each parish produces; and (2) the parish's geographic location.

The bridges located on these highways are grouped into different categories based on their structural type. Main categories are (1) Simply supported bridges, (2) Continuous bridges.

Concrete Bridge Girder Analysis

LRFD and LFD design recommendations were used in the analysis in order to evaluate the effects of the trucks transporting sugarcane heavy loads on the bridges. The demand on the bridge girders due to the heavy truck loads was calculated based on bridge girder type, span type, and the bridge geometry. The span lengths of simply supported bridges are from 20 ft. to 94 ft., while the span lengths of continuous bridges are from 60 ft. to 90 ft..

The effects of sugarcane truck loads on state bridges were determined by comparing the moment and shear force in the girders and the vertical deflection of the girders. The influence line analyses were performed first to obtain the critical truck locations on bridges. The AASHTO Line Girder Analysis approach and detailed analysis using finite element models, and GTSTRUDL Software were then used to generate the results of maximum moment and shear force in bridge girders. The objectives of this study were achieved by comparing the ratios of those maximum values. Based on the results of the parametric study, one sample bridge was selected for the live load test system installation.

Live Load Test

Based on the analysis results and project review committee's comments, a typical bridge was selected for live load test. This seventeen-span pre-stressed concrete bridge is located on state highway US-90 near New Iberia which is a main corridor used by the sugarcane industry.

The load tests were performed by driving a 30-kip dump truck across the bridge at crawling speed along four different lateral paths. Thirty-eight usable strain transducers were installed on one of the accessible spans. Only one span was instrumented since all of the spans were the same length and in approximately the same condition. Selection of the span to instrument was based primarily on accessibility. Data was recorded continuously at 40Hz during each pass, and the truck position was monitored in order to record the strain as a function of the vehicle position. Typical vehicle speed was approximately 3 to 5 mph to minimize dynamic responses and to facilitate monitoring of the vehicle position.

Model Calibration and Load Rating

While the strain data was obtained from the live load test, the next phase of the investigation was to verify the measured responses using structural analysis techniques. While statistical terms provide a means of evaluating the relative accuracy of various modeling procedures and help determine the improvement of a model during a calibration process, the best conceptual measure of a model's accuracy is a visual examination of the response histories. This part of research was done by developing a two-dimensional model of the structure and making direct comparisons between the analytical results and the measured responses. The differences between the measured and computed data were then used as a means for model modification and improvement until a satisfactory correlation was made. The model calibration process was performed based on load test data with the legal load dump truck. This process was also used to verify linear behavior of the structure and verify that the model could be used to predict the structure’s response to other load configurations.

Once the finite element model was developed and calibrated, the load rating factors were developed based on the results from the calibrated finite element model. The standard HS20 and four configurations of sugarcane truck loads were used for developing the rating factors. Load rating factors were computed using the Load and Resistance Factor Rating (LRFR) methods specified in the 2003 AASHTO Condition Evaluation of Highway Bridges Manual. Rating values were obtained by applying the dead load and the various live-loads to the model and comparing the responses to the available capacity. Shear and moment capacities were computed using current AASHTO LRFD and 17th Edition- 2002 LFD specifications.

Load rating factors were obtained by running each of the load configurations across the model. Standard width trucks were rated assuming two-lane loading. Live-load envelopes were generated for each member and compared with their respective live-load capacities. As per the AASHTO LRFD and LFD specifications, a dynamic allowance factor (impact factor) of 33 and 30 percent was used for all cases, respectively. The loadings based on both the inventory rating level and operating rating level were applied to generate the load rating factors.

A long term monitoring system was also installed on this structure. The instrumentation plans were developed based on the results from the analyses of the critical bridges for this study. The effects of shear forces were monitored by transducers installed at 4-ft from the start and the end of the girders; The effects of positive moments were measured by transducers installed at the middle span of the girders; Effects of the longitudinal and transverse forces in bridge deck were evaluated by transducers installed at the middle span under the deck. Also, the instrumentations on the interior diaphragm are needed to determine the redistribution of the forces between the bridge girders.

This long term monitoring system will be used to monitor deterioration of the structure over the system's scheduled life. Actual live-load dynamic responses can also be observed over time to verify the appropriateness of the applied impact factor.

Model Calibration Based on Live Load Test

Once the finite element model was developed, the field load testing procedures could be reproduced. This process included placing gage locations on the model, generating a "footprint" of the test truck, and defining truck paths that were identical to those in the field. The analysis was run and strains were computed at each gage location for each load case consisting of the truck being moved at three-foot intervals the length of the bridge.

After the first analysis run, the data was compared visually and various statistical measures of accuracy were computed. The stiffness of the beams, end-restraints, and the deck were adjusted to improve the correlation. The stiffness variables were modified. The finite element model was optimized to match the field condition.

The accuracy of the model is determined numerically by the analysis using several statistical relationships and through graphic comparison of the strain histories. The numeric accuracy values are useful in evaluating the effect of any changes to the model, where as the graphical representations provide the researchers with the best perception for why the model is responding different from the indicated measurements. During the model optimization process, various error values were computed by the analysis program that provides a quantitative measure of the model accuracy and improvement. The error is quantified in four different ways: an absolute error, a percent error, a scale error and a correlation coefficient. Each of the errors provide a different perspective of the model's ability to represent the actual structure.

The absolute error is computed from the absolute sum of the strain differences. Algebraic differences between the measured and theoretical strains are computed at each gage location for each truck position used in the analysis. This quantity is typically used to determine the relative accuracy from one model to the next and to evaluate the effect of various structural parameters. It is used by the optimization algorithm as the objective function to minimize. The percent error is calculated to provide a better qualitative measure of accuracy. It is computed as the sum of the strain differences squared divided by the sum of the measured strains squared. The scale error is similar to the percent error except that it is based on the maximum error from each gage divided by the maximum strain value from each gage. This number is useful because it is based only on strain measurements recorded when the loading vehicle is in the vicinity of each gage. The correlation coefficient is a measure of the linearity between the measured and computed data. This value determines how well the shape of the computed response histories matches the measured responses. Table 1 lists the results of those four parameters of the initial model and the calibrated model. The final model remarkablely reduced the error values, which confirmed the calibrated model had more accuracy than the initial model.

TABLE 1 Model accuracy results

Error / Accuracy Term	Initial Model	Final Model
Absolute Error	1864.1με	784.6με
Percent Error	7.50%	1.70%
Scale Error	7.50%	3.70%
Correlation Coefficient	0.9724	0.991

While statistical terms provide a means of evaluating the relative accuracy of various modeling procedures and help determine the improvement of a model during a calibration process, the best conceptual measure of a model's accuracy is a visual examination of the response histories. Some typical data comparison results are shown in figures 2 and 3. In each graph the continuous lines represent the measured strain at the specified gage location as a function of truck position as it traveled across the bridge, and computed strains are shown as markers at discrete truck intervals. As shown in figures 2 and 3, the measured strain data and the strain data generated by the finite element model are well matched, as well as there was very little end-restraint. The resulting final model based on the dump truck loading data was accurate, indicating that the structure was behaving linearly elastic.

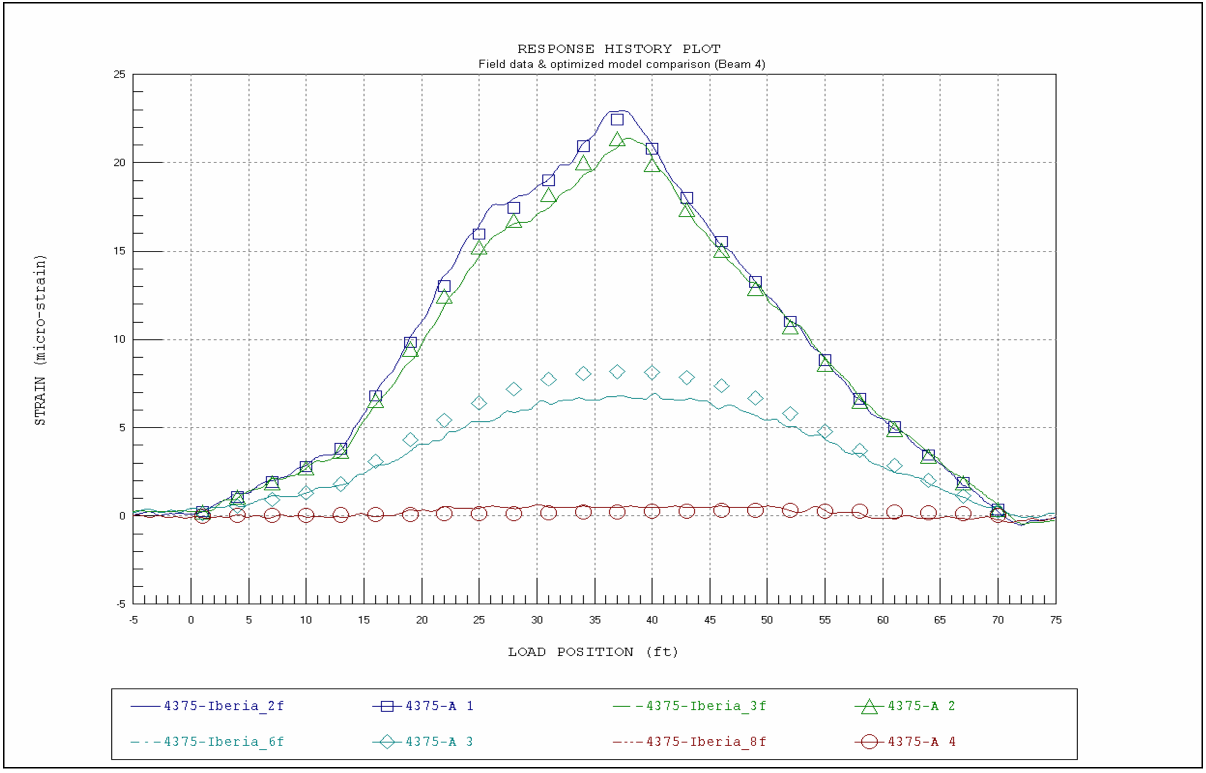

FIGURE 2 Response data comparison for exterior girder at middle span

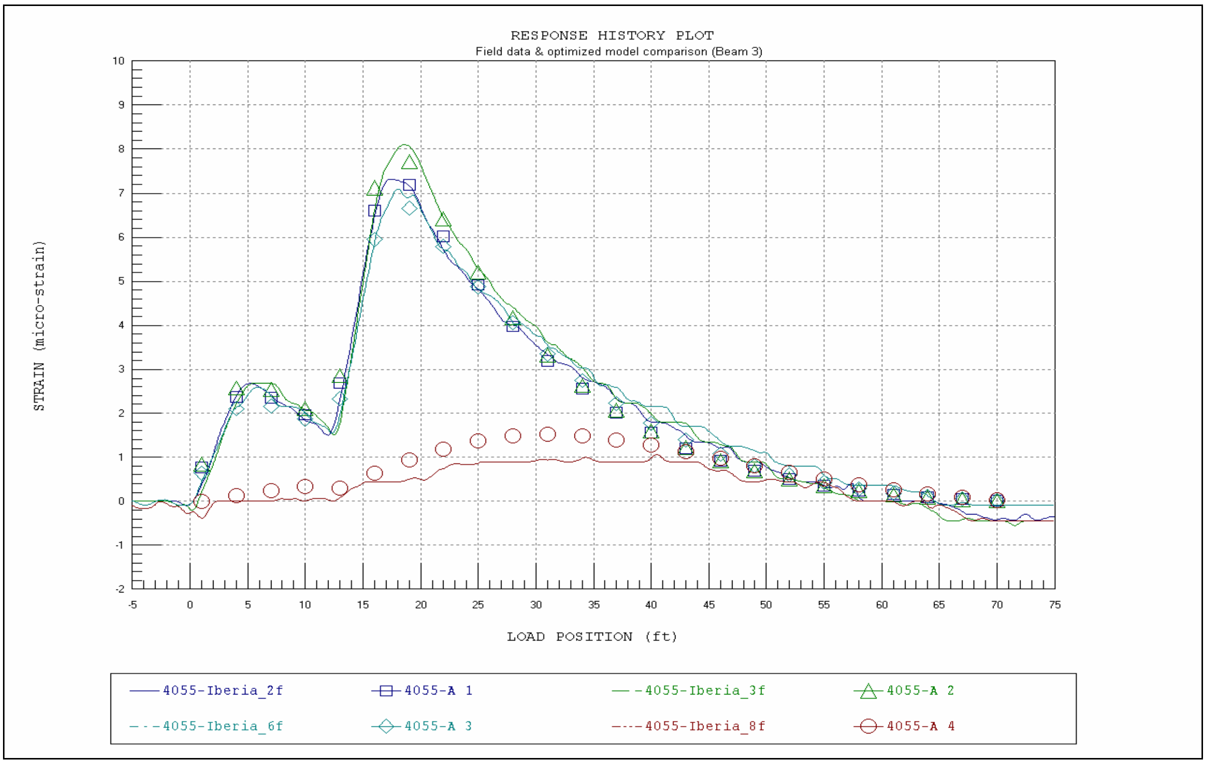

FIGURE 3 Response data comparison for interior girder near abutment

DISCUSSION OF RESULTS

Due to time constraint for the study, the simplified AASHTO Line Girder Analysis approach, detailed analysis using finite element models, and GTSTRUDL Software were used to achieve the objectives of this study. The data of bridge girder analysis presented in this paper are conservative results and as such, it provides sufficient evidence of the long term cost evaluation of the bridges. The bridge strength and serviceability criteria were also evaluated based on live load tests and a corresponding calibrated finite element model.

Short Term Effects on Simple and Continuous Span Bridges

In this study, the effects of sugarcane truck loads on these bridges were investigated by comparing the flexural, shear, and serviceability conditions. The effects of sugarcane trucks loads on bridges designed for HS20 truck loads were evaluated by normalizing the critical conditions for each bridge span to the design load. The details of the methodologies used in this study are based on studies that are documented in (Saber, Roberts, and Zhou, 2006 and 2007). [2 and 3]

Simple span bridges

The ratio of the absolute maximum moment varies between 1.02 and 1.42 for the truck configuration with GVW 120 kip, while the ratio varies between 0.89 and 1.42 for the truck configurations with GVW 100 kip. The ratio of the shear forces varies between 1.02 and 1.40

for the truck configuration with GVW 120 kip, while the ratio varies between 0.92 and 1.21 for the truck configurations with GVW 100 kip. The ratio for deflection caused by sugarcane truck loads as compared to HS20 truck loads varies between 1.01 and 1.62 for the truck configuration with GVW 120 kip, while the ratio varies between 0.89 and 1.62 for the truck configurations with GVW 100 kip. Deflection is a serviceability criterion and high ratios, as reported in this study, will result in uncomfortable riding conditions for vehicles crossing the bridges. Under most situations, the ratios of sugarcane truck load configuration case 3 to HS20 truck load were the lowest.

Where the bridge span is similar to the length of the sugarcane truck, the ratios of the absolute maximum moment and shear are within 10 percent. This confirms the findings in the previous studies that focus on bridge formula. The studies increased the GVW and the truck length to minimize the impact on the stresses in the bridge girders. However, bridge girders with absolute maximum moment ratio or shear larger than 1.1 will be overstressed based on results of previous research [4],

The bridges in this study with absolute maximum moment ratios and shear ratios that are greater than 1.1 can experience more cracking in the bridge girders. Such cracks will require additional inspections along with early and frequent maintenance.

Continuous span bridges

For the sugarcane truck load case 4, the ratio of maximum positive moment varies between 1.07 and 1.24; the ratio of maximum negative moment varies between 1.38 and 1.50; the ratio of the shear forces varies between 1.27 and 1.45. For the sugarcane truck load case 1 through 3, the ratio of maximum positive moment varies between 0.93 and 1.11; the ratio of maximum negative moment varies between 1.17 and 1.30; the ratio of the shear forces varies between 1.06 and 1.25. Also, under most situations, the ratios of sugarcane truck load configuration case 3 to HS20 truck load were the lowest. Where the bridge span is similar to the length of the sugarcane truck, the ratio of the maximum positive moment and shear forces are within the findings of the previous studies. These studies focused on bridge formula and increased the GVW but increased the truck length to minimize the impact on the stresses in the bridge girders and bridge decks. However, bridge girders with a maximum positive moment ratio or shear larger than 1.10 will be overstressed based on results of previous research [4],.

The ratio for negative moment for spans between 60 ft. to 90 ft. is high and will increase the tensile stress in the top surface of bridge decks. These conditions can result in more chances of cracks in bridge decks. The bridges in this study with ratios that are greater than 1.1 can experience more cracking in the bridge girders and bridge decks. Such cracks will require additional inspections along with early and frequent maintenance.

Load Rating Based on Live Load Test and Calibrated Model

The goal of live load test and producing an accurate finite element model was to predict the structure's actual live load behavior when subjected to design and rating loads. The primary benefit of a calibrated model is that responses from the entire superstructure can be investigated rather than just the instrumented locations. This is important because in most cases, the instrumentation is not located at the critical location on the bridge. Since the load rating is based on an analysis, the approach is essentially identical to standard load rating procedures except that a "field verified" model is used instead of a typical beam analysis combined with load distribution factors.

Based on the field calibrated finite element model, selected bridge structure was analyzed and load rated for loading vehicles HS-20 and sugarcane truck loading cases 1 thru 4. Results of load ratings were presented in table 2 and 3. The structure has adequate strength to resist both bending and shear forces for all five loading vehicles. All load ratings were well above 1.0. The lowest inventory and operating rating factors of shear were 2.10/2.72 using LRFR and 1.34/2.24 for LFD. The worst case loading vehicle was the case 4 of the sugarcane truck loading and the critical shear location was at the first change in rebar spacing and size. The lowest inventory and operating rating factors of moment were 2.74/2.20 using LRFR and 3.56/3.67 for LFD, which represent that sugarcane truck loading case 4 also controls the moment rating as well. And those rating factors are acceptable for all 17 spans as long as the construction and the structural condition of each span is the same.

TABLE 2 Load rating results of moment

Truck Load	Live-Load Moment (K-in)	Inventory Rating Factor LRFD/LFD	Operating Rating Factor LRFD/LFD
HS-20 (3 axle 72 kip)	4763	3.10 / 2.48	4.02 / 4.13
Sugarcane Case 1 (6 axle 100kip)	4902	3.03 / 2.42	3.92 / 4.04
Sugarcane Case 2 (6 axle 100kip)	5283	3.06 / 2.26	3.67 / 3.78
Sugarcane Case 3 (6 axle 100kip)	4735	3.16 / 2.53	4.09 / 4.22
Sugarcane Case 4 (6 axle 120kip)	5446	2.74 / 2.20	3.56 / 3.67

TABLE 3 Load rating results of shear

Truck Load	Live-Load Shear (Kips)	Inventory Rating Factor LRFD/LFD	Operating Rating Factor LRFD/LFD
HS-20 (3 axle 72 kip)	34.3	2.52 / 1.67	3.26 / 2.78
Sugarcane Case 1 (6 axle 100kip)	34.5	2.50 / 1.66	3.24 / 2.77
Sugarcane Case 2 (6 axle 100kip)	41.7	2.23 / 1.43	2.90 / 2.39
Sugarcane Case 3 (6 axle 100kip)	38.2	2.44 / 1.56	3.16 / 2.61
Sugarcane Case 4 (6 axle 120kip)	44.0	2.10 / 1.34	2.72 / 2.24

COST BASED ON REMAINING SAFE LIFE OF BRIDGE

Bridge cost is a combination of new design, rehabilitation, and fatigue costs. The focus of this study is only on the fatigue cost resulting from the increase in the load permits for sugarcane trucks.

The long term effects of heavy trucks play an important role in the bridge life evaluation. The selected bridges for this study are designed under standard HS20 truck load. Overloaded trucks traveling across these bridges will increase the cost of maintenance and rehabilitation. An accurate estimate for the cost of the damage is hard to obtain since fatigue damage may lead to repairs, rehabilitations, or replacements. Most of the bridges in Louisiana are designed for a fatigue life of 50 years. Overloaded trucks will definitely shorten the life of the bridges. The bridges in this study are evaluated for fatigue cost based on the results from the strength analyses presented earlier in this paper. Based on a review of the bridges considered in this study, the truck ADT value of 2,500 is used. The concrete bridge costs used in this study are based on projects completed by LA-DOTD during 2004. The average cost to replace a concrete bridge is approximately $90 per square foot. The methodology used to evaluate the cost and results of this study can be referred to the publications by (Saber, Roberts, and Zhou, 2006 and 2007). [2, 3 and 7]

CONCLUSIONS AND RECOMMENDATIONS

The impact of vehicles hauling sugarcane products on the safety and remaining safe life of Louisiana state concrete bridges under current and proposed loads was evaluated. Probability based method was used in this investigation and field experiments on a selected bridge were conducted to compare the theoretical results with the real response of the bridge.

Through the use of a field calibrated finite element model, bridge structure was analyzed and load rated for loading vehicles HS20 and sugarcane loading cases 1 thru 4. Inventory and operating load rating factors were obtained by using LRFD and LFD recommended procedures. The structure had adequate strength to resist both bending and shear forces for all five loading vehicles.

The cost study based on remaining safe life of bridge was performed. The results recommended that the sugarcane loading configuration case 3 be used to haul sugarcane, with GVW 100,000 lb., where the sugarcane load is uniformly distributed. It is not recommended that truck configuration case 4 be used to haul sugarcane with GVW 120,000 lb. due to the high fatigue cost.

A long term monitoring system was also installed on this structure. It is recommended that using this system to evaluate the long-term behavior of bridges to ensure that the bridge is continuing to perform as expected.

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The contents of this study reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Louisiana Department of Transportation or the Louisiana Transportation Research Center. This paper does not constitute a standard, specification, or regulation.

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