EXPERIMENTAL INVESTIGATION OF INFLUENCE OF LIVE LOAD ON SEISMIC RESPONSE OF A HORIZONTALLY CURVED BRIDGE

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Abstract

Little is understood about the dynamic interaction between heavy vehicles and bridge systems during strong earthquakes. An experimental study was therefore undertaken to investigate this phenomenon. Six, full-scale, pickup trucks were placed on a 3-span, large-scale bridge model, which was supported on the 4 shake tables at the NEES Equipment Site at the University of Nevada Reno. Comparison of behavior when the same model was tested without trucks showed their presence to have a beneficial effect up to a level of shaking defined by the Design Earthquake, and an adverse effect for shaking greater than the Design Earthquake. This bimodal result has been reported by other researchers and confirms the difficulty of isolating and quantifying the critical parameters that govern response.

Introduction

Design procedures for earthquake-resistant bridges in most countries do not require the simultaneous presence of live load and earthquake load to be considered. This decision is based on two major assumptions. First, it is assumed the full design live load will not be on the bridge at the time of the design earthquake, and second, the seismic response of a bridge is dominated by its dead load and live load inertial effects are negligible by comparison. However for bridges in urban areas where congestion is a frequent occurrence, some fraction of the design live load (usually 50%) is now recommended to be included with the dead load when computing gravity load effects (AASHTO, 2010). But this recommendation applies only to gravity load effects and not to inertial effects.

The omission of inertial effects in design is the result of a prevailing attitude that the suspension system of a heavy vehicle acts as a tuned mass damper and reduces the motion in the bridge. It is therefore believed to be conservative to ignore these effects. But in fact little is understood about the dynamic interaction between heavy vehicles and bridge systems during strong shaking and there is no hard evidence that the tuned mass damper model is universally applicable. It is equally possible that the added weight increases the inertial loads in the bridge and the corresponding displacements and forces.

Currently, very little research has been conducted to resolve this issue, and the first step is to understand and model vehicle suspension systems and their interaction

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with the bridge structural systems. Then these numerical models need to be calibrated against experimental work, and finally the validated models should be used to study bridge-vehicle interaction during earthquake ground shaking.

This paper describes an experimental study to calibrate a previously developed numerical model and give some insight into the circumstances leading to beneficial and adverse behavior of live load during an earthquake. This study is part of a larger project involving the development of a set of findings and recommendations concerning the effect of live load on seismic response and how these effects may be included in the seismic analysis and design of bridges in the future.

Literature Review

Most of the research reported in the literature to date on the effect of live load is related to the calculation of impact factors (vehicle dynamic load allowance) for gravity load design. It appears that very little work has been done on the influence of live load on seismic response of bridges. Also, experimental tests on large-scale bridges to study the effects of vehicle-bridge interaction under seismic load do not appear to have been previously carried out.

A study by Sugiyama *et al.* (1990) used a single degree-of-freedom vehicle system that can model rolling in the transverse direction and pitching in the longitudinal direction, but the properties are not given. The bridge was idealized as a nine-mass system with transverse and rotation inertia connected by linear springs and damper elements. A vibration test is reported on an existing steel girder bridge with and without trucks in the longitudinal and transverse directions to verify the results. In the test, two large trucks were parked facing the same direction on a portion of an existing off ramp whose girders were vibrated with an electro-hydraulic exciter. The bridge was tested with the vehicles empty and loaded to various capacities. The results show that the dynamic effect of the vehicle is more dominant in the transverse direction and the vehicle tends to reduce the response of the bridge. The authors also note that as the exciting force level increases, the effects of nonlinearity become more apparent since the dynamic characteristics of the vehicle itself are nonlinear. These results are corroborated by Kameda *et al.* (1992) who used a 5 degree-of-freedom model in their study. These authors state that the vehicle tends to increase the bridge response when the vehicle is in the in-phase mode with the bridge and decrease the bridge response when it is in the out-of-phase mode. Moreover, they also concluded that the ratio of the fundamental frequency of the bridge to the vehicle plays an important role for the response of the bridge.

Another study of the seismic response of a bridge with live load was done by Kawatani *et al.* (2007). These authors analyzed the seismic response of a steel plate girder bridge under vehicle loadings during earthquakes. The vehicles were modeled with 12 degrees-of-freedom that took sway, yaw, bounce, pitch, and roll into account. The observations from the numerical analysis showed that heavy vehicles, acting as a dynamic system, can reduce the seismic response of bridges under a ground motion with low frequency characteristics, but the vehicles have the opposite effect and slightly amplify the seismic response of the bridge under high frequency ground motions.

Kawashima *et al.* (1994) and Otsuka *et al.* (1999) performed a series of studies to determine the effect of live load on a bridge when combined with seismic load. The study modeled a two-span simply supported girder bridge with a mix of ordinary cars, modeled as additional dead load, and large trucks, each modeled with 5 degrees-of-freedom. The bridge was only analyzed in the transverse direction because it was estimated that the deck response would be significantly affected by the rolling of the large trucks. The studies found that the displacement response of the girders increased by 10% when the live load was included; ductility demand at the bottom of the column also increased by 10% with live load on the bridge. This study concluded that these increases were not enough to be significant and that existing safety factors should be adequate to cover these effects. It was also concluded that the increase in response was due to the increase in weight. However, the effect of the large trucks was not just to increase the dead weight, they also behaved as a mass damper.

Scott (2010) developed a simplified modeling approach for dynamic analyses to account for combined live load and seismic load. It is shown that for short-span bridges, the displacement responses are mainly due to the fundamental bridge mode. In addition, for long-span bridges, vehicle speed had small influence on the displacement and acceleration responses of the bridge.

A recent study on the effects of live load a highway bridge under a moderate earthquake in the horizontal and vertical directions is reported by Kim *et al.* (2011). The study concluded that the seismic response of the bridge is amplified when the vehicle is considered as merely additional gravity load or mass and the amplification is dependent on the relationship between the fundamental frequency of the bridge and the response spectrum of the ground motion. However, when the vehicle is considered as dynamic or mass-spring-damper system, which is more realistic, the dynamic effect of the vehicle is greater than its gravity load effect and thus it reduces the seismic response. In addition, the study also showed that the effect of a moving vehicle as compared to a stationary vehicle is negligible, and it is sufficient to model the vehicle as stationary for these studies.

Bridge Model

A three-span, curved bridge model was tested in the Large-Scale Structures Laboratory at University of Nevada, Reno. This 2/5-scale model has a steel plate girder superstructure, single-column reinforced concrete substructures, and seat-type abutments. Overall dimensions are shown in Table 1.

The bridge model has a total length of 145 ft, a total width of 12 ft, and subtended angle of 104° as shown in Figures 1 and 2. Each bent has a single circular column. The column height is 7 ft - 8 in with a diameter of 24 in. The superstructure is a three-span, three-girder steel bridge with concrete deck. The detail of the superstructure and the column can be seen in Figure 3. The superstructure is supported by fixed (rotation-only) pot bearings at the bent locations and slider bearings at the abutments. Moreover, shear keys are provided at the abutments to restrain movement in the radial direction during small amplitude earthquakes, but are designed to fail at higher events to protect the abutment foundations against damage.

The prototype bridge was designed for a site in Seismic Zone 3 (AASHTO 2010) with a 1,000-year spectral acceleration at 1.0 sec (S_1) of 0.4 g. Under this Design Earthquake (DE), the bridge is expected to be damaged but not collapse. The record selected as the input motion for the experimental studies was the Sylmar record from the 1994 Northridge Earthquake near Los Angeles, scaled to have the same spectral acceleration at 1.0 sec. A scale factor of 0.475 was therefore applied to both the NS and EW time histories of ground acceleration from this station.

Table 1. Bridge Geometry Summary.

Parameter	Prototype	Model
Total Length	362’-6”	145’-0”
Span Lengths	105’-0”, 152’-6”, 105’-0”	42’-0”, 61’-0”, 42’-0”
Radius at Centerline	200’-0”	80’-0”
Subtended angle	104° (1.8 rad)	104° (1.8 rad)
Total Width	30’-0”	12’-0”
Girder Spacing	11’-3”	4’-6”
Total Superstructure Depth	6’-6.125”	2’-7.25”
Column Height	19’-2’	7’-8”
Column Diameter	5’-0”	2’-0”

Test Vehicles

The vehicles used in these experiments were six Ford F-250 trucks, each weighing 10,000 lb (10 kip). Dynamic properties of a typical truck were found by shake table testing using the 6 degree-of-freedom shake table in the Structures Laboratory. The ratio of the total vehicle weight to the superstructure weight is around 22%. The rationale of selecting the vehicle is discussed below.

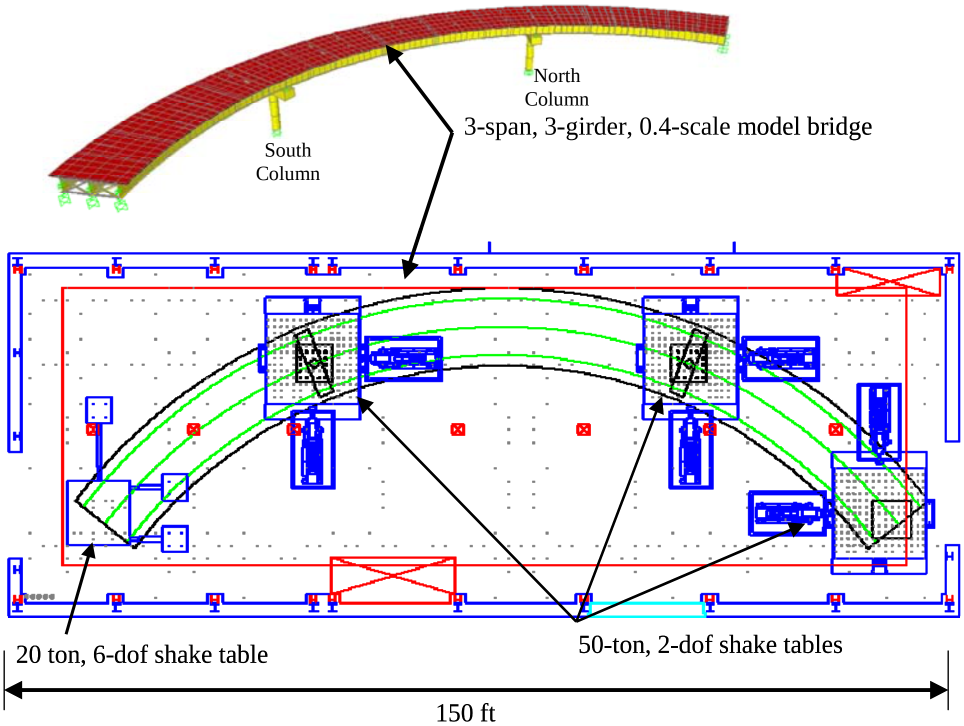
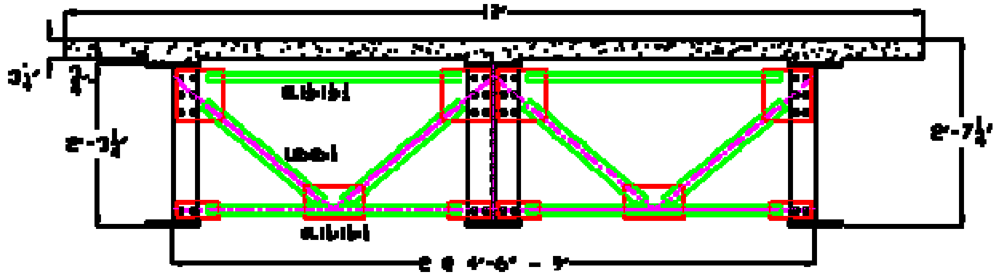


Figure 1. Bridge Model and Layout in Large-Scale Structures Laboratory.

Figure 2. Bridge Model Assembled in Large-Scale Structures Laboratory.



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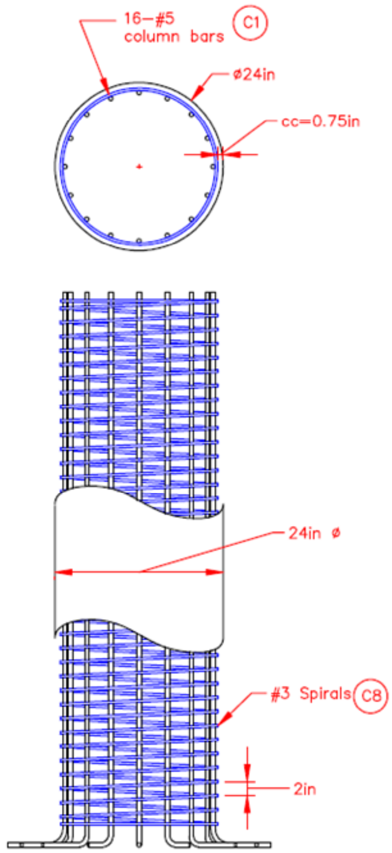

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Figure 3. Typical Superstructure and Column Details.

The starting point for selection of the test vehicle was the H-20 truck from the Caltrans Bridge Design Specifications. This truck is a two-axle vehicle weighing 40 kips (8 kips on the front axle and 32 kips on the rear axle) with a 14 ft wheel base. For a 0.4-scale model, the model truck would have a wheel base of 5.6 ft, be 2.4 ft wide, and weigh 6.4 kip. Since such a vehicle would most likely have to be custom-built, the decision was made to select from commercially available vehicles. The closest possible vehicle to match the modeling requirements was found to be the Ford F-250. Although the similitude requirements are not fully satisfied, the dynamic properties of the chosen vehicle can produce similar effects to those of the target vehicle.

Table 2. Ford F-250 Dimensions and Weight Ratings

Parameter	Value
Overall Length	247 in
Overall Width	68 in
Overall Height	80 in
Wheel Base Length	156 in
Ground Clearance	7.9 in
Curb Weight	6.7 kip
Gross Vehicle Weight Rating	10 kip
Max Allowable Payload	2.3 kip

Experimental Setup

The bridge model was assembled on the four shake tables in the Large-Scale Structures Laboratory and the vehicles positioned on the deck as shown in Figure 4. Instrumentation has been installed on the columns, bridge girders, and trucks to gather response data during testing. The types of instruments range from strain gauges on the column rebar, string pots on the bridge girders and trucks (to measure displacements), and accelerometers on the bridge deck and trucks (to measure accelerations). During the experiment, 383 data acquisition channels were used.

The test protocol followed for this experiment started with 10% of the DE and then the motion was increased in successive increments to 20%, 50%, 75%, 100%, 150%, 200%, 250%, 300%, and 350% of the DE. Before each run, a series of white noise excitations were run to characterize the system's dynamic properties.

Figure 4. Bridge Model with Live Load (Courtesy of M. Wolterbeek, 2011)

Preliminary Results

One of the parameters that may be used to quantify the effect of live load is the column displacement. Figures 5 and 6 show the north and south column displacements with and without live load under 75% and 100% of DE, respectively. It is shown that for these two runs, the maximum displacement is less when live load is present. It is also important to note that during the no-live load case, the shear keys at the abutment failed during the 75% DE run, whereas it took a stronger ground motion (100% DE) to fail these keys when live load was present, i.e. the live load reduced the forces in the shear keys at the same level of excitation. This shows that at these levels of shaking, the existence of live load caused less demand in the column and reduced the radial shear forces at the abutments. The damage in the column was also found to be minor and not as severe as for the no-live load case.

On the other hand, observations from the higher amplitude runs, after the shear keys at the abutments had failed, show a different result. Figures 7 and 8 show the displacements in the north and south columns with and without live load after 250% and 300% of DE, respectively. It is seen at these levels of shaking (and after the keys had failed), the live load exercises the columns to a greater extent and the maximum displacements at the top of the columns became closer to the no-live load case. It is also seen that the residual displacements in the columns for the live load case are about double those without live load. These larger residual displacements indicate greater distress to the columns, and especially the south column, due to the presence of the live load.

Concluding Remarks

A recent experiment was conducted in the Large-Scale Structures Laboratory at University of Nevada, Reno, to study the effects of live load on a 0.4-scale horizontally curved bridge model. From the experimental results for the column displacements and radial shears forces at the abutments, with and without live load, some preliminary conclusions can be drawn. In lower amplitude motions, when the shear keys were still intact, live load gave a beneficial effect. In higher amplitude motions, after the abutments were free to move, live load gave an adverse effect. It is not known at this stage whether this reversal in effect is due to (1) the deteriorating nature of the bridge under increasing levels of shaking and thus a changing vehicle-to-bridge frequency ratio, or (2) the changed configuration of the bridge when the abutments were released in the radial direction after the shear keys failed, or 3) both of the above. Studies are continuing to better understand this phenomenon.

Acknowledgments

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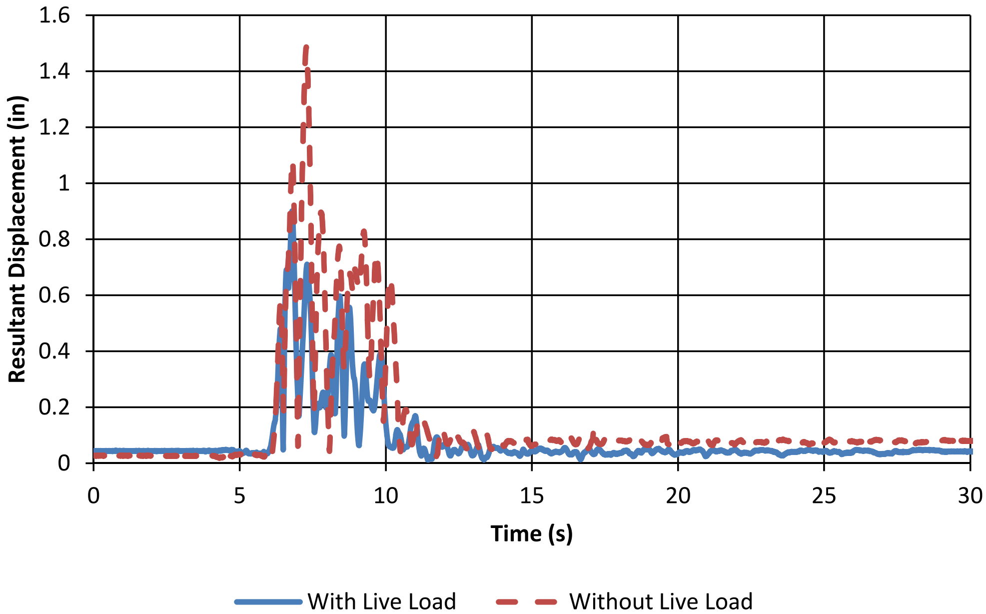

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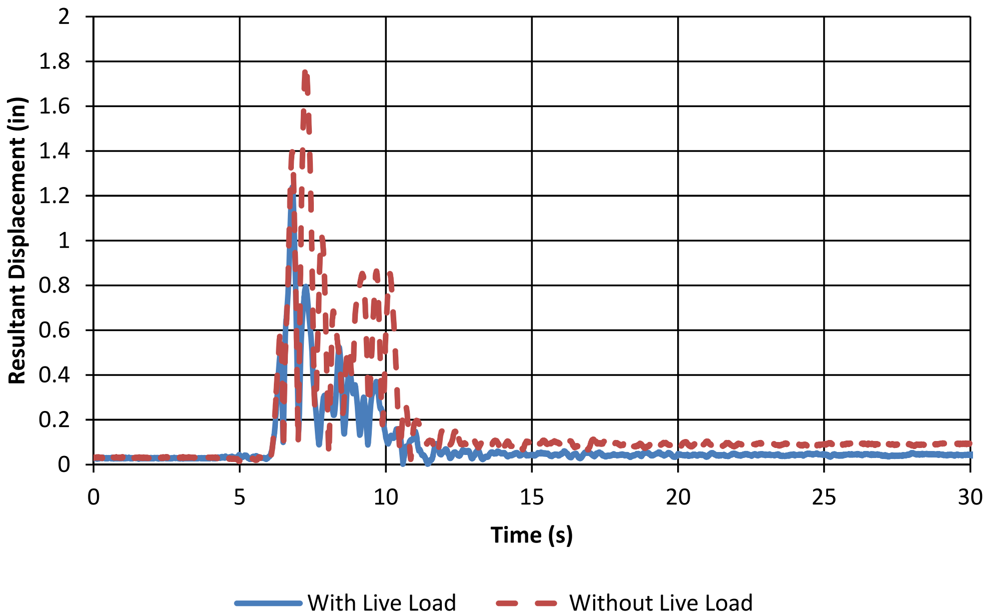

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Figure 5. (a) North and (b) South Column Displacements during 75% DE Run.

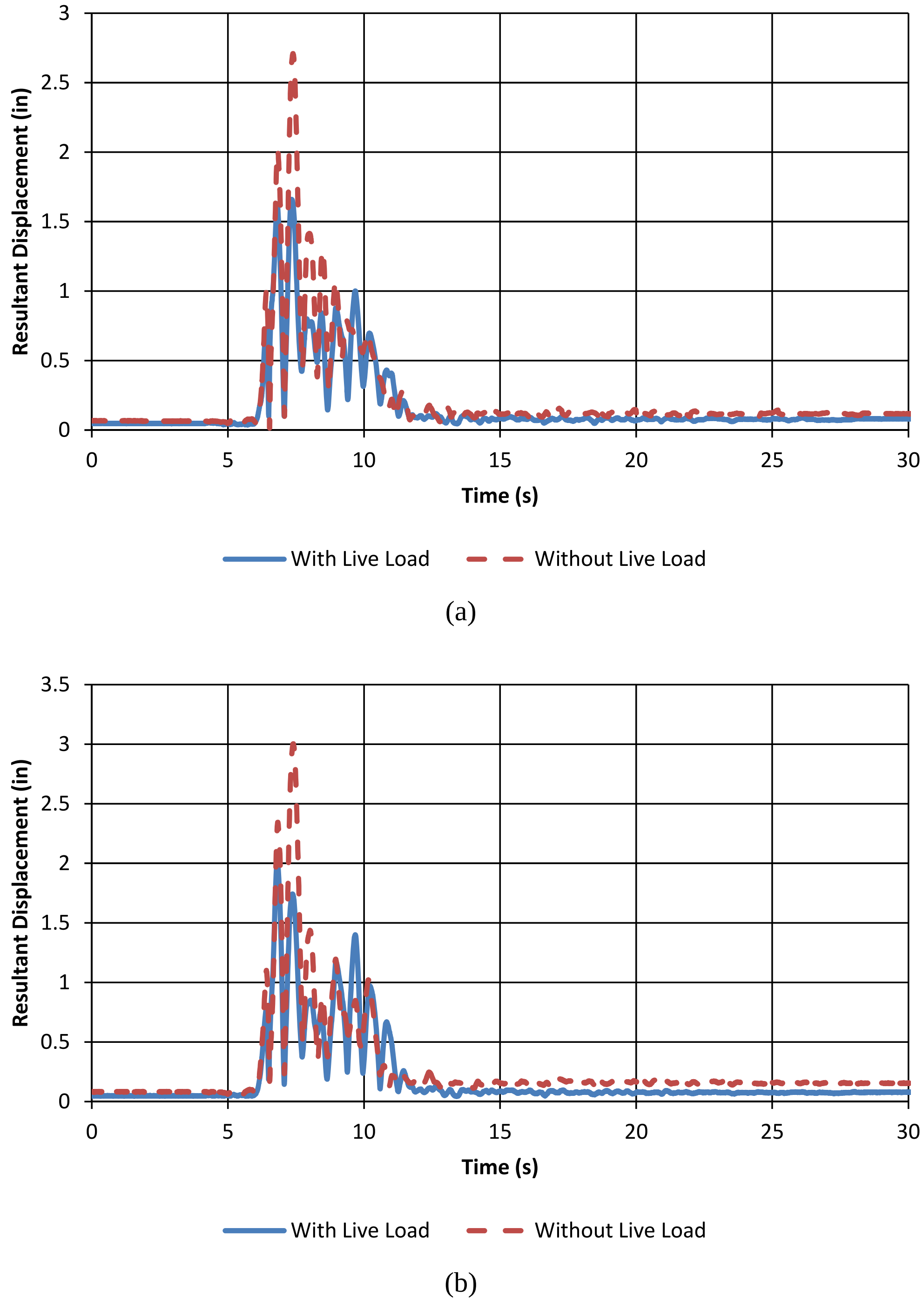
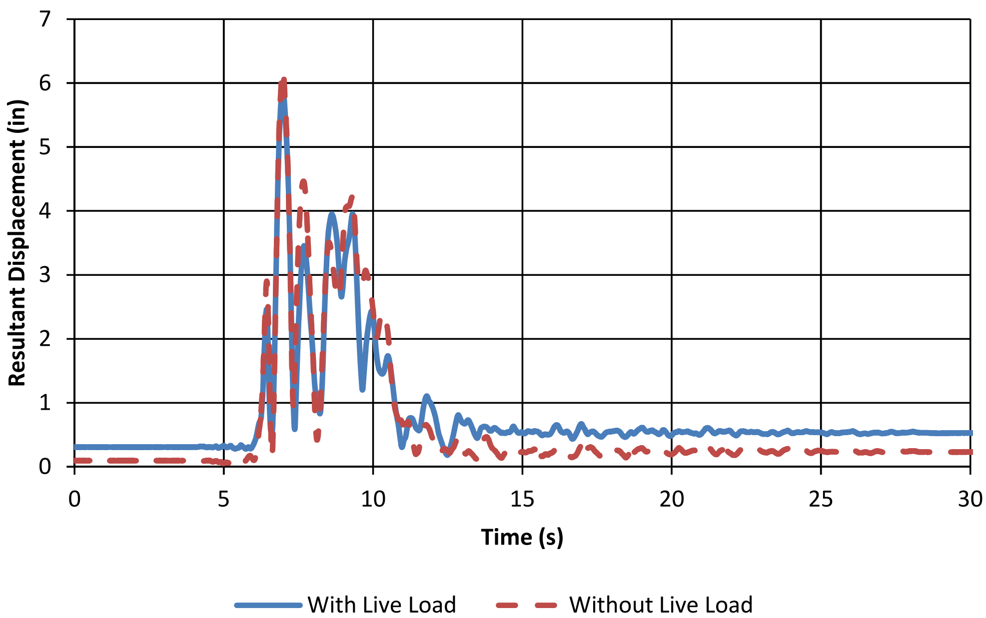


Figure 6. (a) North and (b) South Column Displacements during 100% DE Run.



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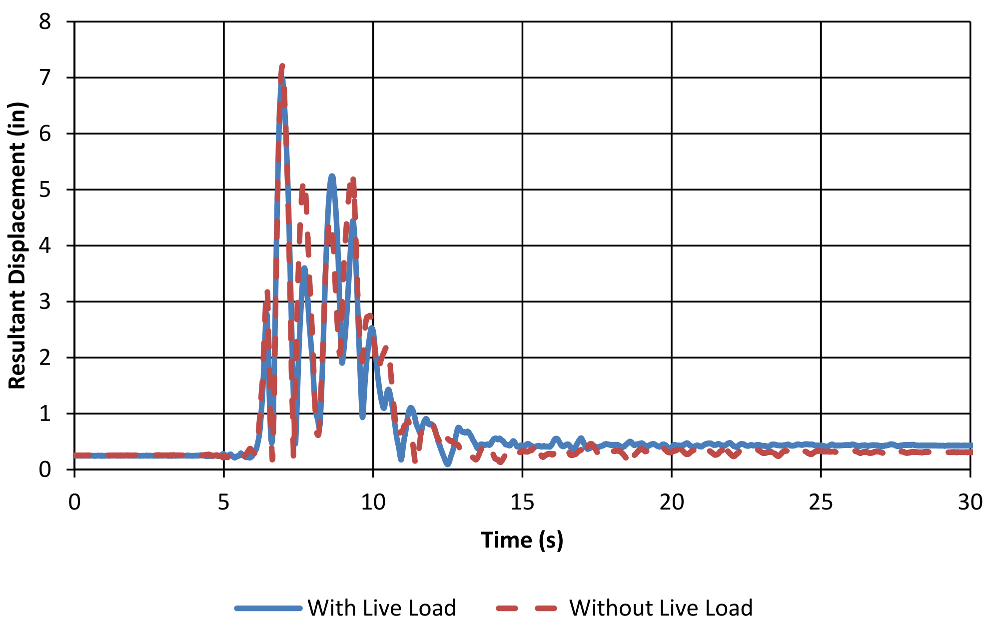

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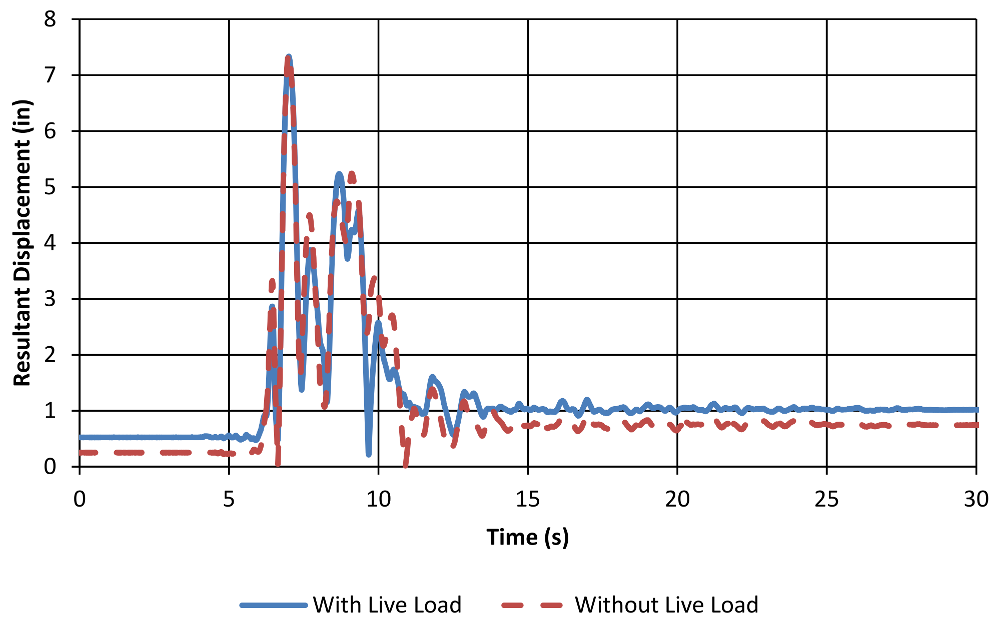
Figure 7. (a) North and (b) South Column Displacements during 250% DE Run.



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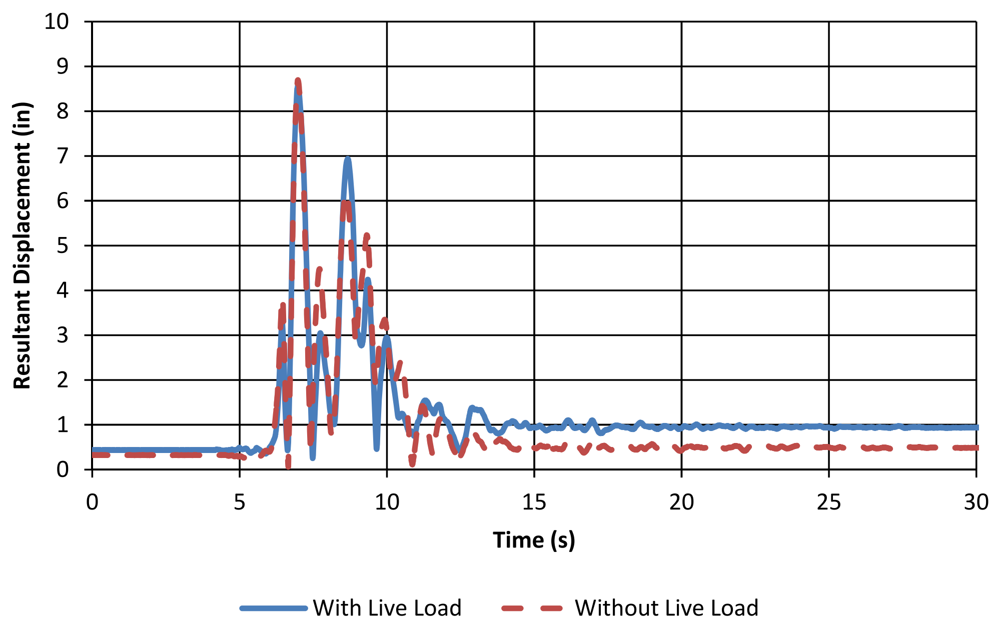

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Figure 8. (a) North and (b) South Column Displacements during 300% DE Run.

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Conversion Table

From	To	Multiply by
in	mm	25.4
ft	mm	304.8
lb	kg	0.45