Numerical Prediction of the Dynamic Response of Prestressed Concrete Box Girder Bridges Under Blast Loads

Ahmed Ibrahim
Research Assistant, University of Missouri
Hani Salim
Professor of Civil Engineering, University of Missouri

Abstract

Significant research has been performed on the response and retrofit of buildings under blast loads. Limited research exists on the response prediction and protection of bridges under near-field blast loads. This research focuses on the evaluation and assessment of box girder bridges under blast loads. The objective of this research is to develop a numerical model to predict the damage level in a concrete deck under blast loading and the corresponding dynamic response of the damaged bridge system. The damage level will be function of spalling/cratering the bridge will suffer under the near field detonations. The numerical analysis conducted using the explicit dynamic software LS-DYNA®, which has the abilities to model the blast load propagation towards bridge structures and to its response to these types of impulsive loads. The bridge has a simply supported span of 100 ft (30.48 m) and was designed according to the LRFD manual under HL-93 truck load. Different charge weights were located at a height of 30 inches (0.762 m) between the main vertical webs at the mid-span. The study shows that LS-DYNA predicted the damage severity under blast loads, especially since the testing under these loads might not be feasible. The studied Key parameters were the weight of the charge, and concrete deck properties. The results of this study make the finite element modeling an attractive alternative for blast testing when it is not feasible like the case of bridges. Comparisons of the numerical results are still necessary for code verification before this study can be expanded for additional parametric studies and design recommendations

Introduction

Box girder is the most flexible bridge deck form. It can cover a range of spans from 82 ft (25m) up to the longest non-suspended concrete decks built, of the order of 1000 ft (305m), Richard M. (2007). Single box girder may also support decks up to 160 ft (48.78 m) wide. For the longer span beams which reach about 170 ft (50m), they are practically the only feasible deck sections. The advantages of the box sections are mainly its high structural efficiency, which minimize the prestressed force required to resist a given moment, and its great torsional resistance which is appropriate for a typical traffic loading.

Blast waves are produced whenever an explosion takes place. These waves propagate in the form of spherical waves. Some of the waves transfer across the structures while remaining is reflected back. During this wave propagation, high pressure, high strain rates, and high temperature are generated which travel across the least resistance path of the structure. This entire process of the wave generation and Propagation lasts for a few milliseconds as seen in Fig . 1 which shows a typical pressure time history.

In a study conducted by Marchand, et al. in (2004), the structural response of bridge piers subjected to vehicular and hand placed bombs was evaluated. Various standoff distances and charge weights of vehicular bombs were analyzed while the hand placed bomb was used to investigate the impact of a single bomb versus two counterforce bombs. A simplified beam and spring system was used by Schleyer and Hsu 2000. This analysis was conducted to evaluate the maximum transient displacement of rectangular members subjected to blast loading. In this investigation, only a single beam and spring system was evaluated; however, this system could be combined together to create frames and arches.

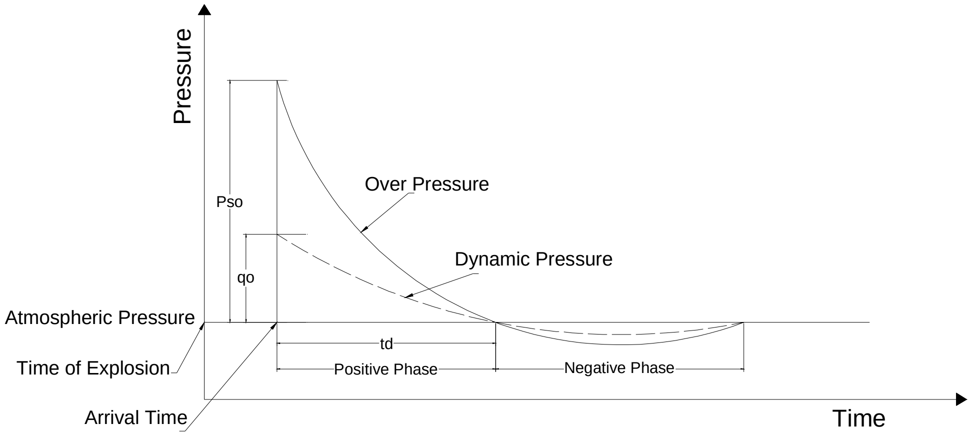

Figure 1: Variation of overpressure and dynamic pressure over time

The springs were used at the end of the beam specimens to represent variable end conditions. An additional spring was used for the formation of the plastic hinge in the center of the specimen. Within the model, coupled mode shapes were used to represent the overall elastic, perfectly plastic behavior of the beam structure under pulse pressure loading. The loading case used for the analysis consisted of a uniformly distributed load.

In addition to the single degree of freedom and the empirical methods, hydrocodes and finite element analyses have also been applied to gain a better understanding of blast and impact loading. Hydrocodes analysis allows for a more investigation into experimental results and allows the researcher to see more details. It also gives the research a more cost effective manner of analysis. In addition to providing a comparison base for experimentation, these hydrocodes can also be used to validate simpler models and ensure accurate results which have been generated. Vulitsky and Karni (2002) developed a numerical simulation using LS-DYNA to predict the effect of the detonation of high explosives on steel structures. This method was aimed at the explosive blast in the air to the structure. The simulation was performed using Jones-Wilkins-Lee (JWL) equation of state to describe the explosive. A linear polynomial equation of state was used to simulate the behavior of air. The mix between air and explosion reaction products is modeled using LS-DYNA multi-materials capabilities. The blast pressure wave travelling through the air interacts with the structure by means of fluid-structure interface algorithms. Numerical results were compared with experiment and the maximum difference in deformations was around 20-40%.

Background information related to loads caused by blasts and analytical modeling options was conducted by Renee Cimo (2007), as well as a literature review of related research findings. A study to determine the most appropriate constitutive models considering the dynamic material properties was subsequently conducted. This resulted in the selection of four constitutive models for the four materials incorporated in the modeling – air, TNT, concrete, and steel. A mesh sensitivity analysis was also performed to determine the optimum element size to be used, considering the conflicting interests of increased accuracy and decreased processing speed and memory availability with smaller elements. For this analysis, AUTODYN results were compared against results generated using the empirically based program called ConWep, as well as hand calculations, which also served as a general validation of the accuracy of the program. The results of the constitutive model studies and mesh sensitivity analyses were incorporated in developing a model of a cross-section of a two-lane bridge, where the performance of the cross-section when subjected to a below deck blast was investigated by Renee Cimo (2007).

David G. et al.(2005), summarized the results of developing performance based blast load design standards tailored specifically for bridges. Based on the best practices obtained from international literature review, the research briefly discuss the integration of substantial security and site outline principles into the design steps against blast loads. The paper gave structural design and retrofit solutions to counter the main effects induced by blast loads.

Nago et al. (2007) estimated the blast loading typically produces very high strain rate ranges of 10^2 to 10^4 s^{-1} ; (the range of impulsive loads) rather than the ordinary static strain rates of 10^{-6} to 10^{-5} s^{-1}. At This strain rates, the dynamic mechanical properties of the structure may be different from the mechanical under static loading. It is reported that the yield stress of the mild steel could be doubled when the strain rate changes from 10^{-3}to10^3 s^{-1}.

The blast capacity and protection of AASHTO girder bridges has been studied by Islam A. (2005). No specific AASHTO design guidelines exits for bridges against blast loading. Structural engineering methods to protect infrastructure systems from bomb attacks are required. The most common types of concrete bridges were investigated and assessed the capacity of critical elements. A 2-span 2-lane bridge with type III AASHTO girders was used for modeling. The girders, pier caps and columns were analyzed under blast loading to determine their capacities. The blast capacities of the AASHTO girders, piers and caps were determined and the required standoff distance of the explosion from the columns that may protect the bridge from failure was also studied.

The performance of cable supported bridge decks subjected to blast loads was conducted by Jin Son (2008), son studied the behavior of steel orthotropic and composite plate girder decks subjected to blast loading and using several materials, a design approach to protect cable supported bridge against blast events was suggested. Using steel orthotropic decks or orthotropic plate girder decks, Son (2008) concluded that Acceleration is the most leading factor affecting local behavior of a deck subjected to blast loading. The axial compressive loading acting on the bridge deck may cause global progressive collapse. The self-anchored suspension bridges proved to be the poorer system among the three cable supported bridge systems with high probability of developing global progressive collapse due to their large axial load in the deck

Numerical Approach

The finite element model was performed using the dynamic nonlinear hydrocode LS-DYNA ver.971, 2009. The box girder bridge was simulated using quarter symmetry model; the mesh was built using the available elements in ANSYS-LS-DYNA. The concrete was modeled using the Lagrangian solid element with one integration point, and the material model WINFRITH_CONCRETE was used for the concrete which can capture the impulsive load effect (the blast load strain rate effect) on structures. The concrete Uniaxial compressive strength f`c was taken 7 ksi (49.2 MPa). The conventional steel was modeled using the discrete beam element formulation with the PLASTIC_KINAMATIC material model. The steel yield stress was taken 60 ksi (415 MPa) with a zero plastic strain hardening modulus according to ASTM A588 Grade60. Finally, the low relaxation prestressed steel strands was considered in the analysis using the ASTM A416 Grade 270. The bridge span was taken to be 100 ft (30.48 m) as a simply supported panel. The simulation was conducted by taking only quarter of the bridge model by assigning the required boundary conditions and the prestressed tendons were assumed straight along the span with eccentricity of 18 in (0.457 m). The finite element model with the concrete dimensions is shown in Fig.2.

Different charge sizes were studied in this paper, the charge size was assumed in terms of the charge weight ‘W’. It was placed above the bridge deck (between the main vertical webs) at a a close range standoff distance (Z) of 30 inches at the mid span of the bridge, as shown in Fig.2. The blast load was applied using the BLAST_LOAD function available in LS-DYNA which calculates internally the incident and the reflected pressure on all the assigned segments. The cases were considered only for the charge weights above the bridge deck. The dynamic relaxation was applied to take the own weight effect in the dynamic analysis and a damping of 2% was applied to the whole analysis although It may not be effective due to the instantaneous effect of the blast load. The bridge behavior after 0.2 seconds was traced by LS-DYNA for the different load cases, which showed widespread element erosion in the model. Which means cracking and spalling of concrete is present as shown in Fig. 5and 6. To track the element erosions as the blast event progressed, a damage-based erosion function was implemented to delete the elements which reached a plastic strain of .005 for concrete and 0.15 for all types of steel. Table 1 shows the different cases that were studied to predict the bridge response under the various charge weights.

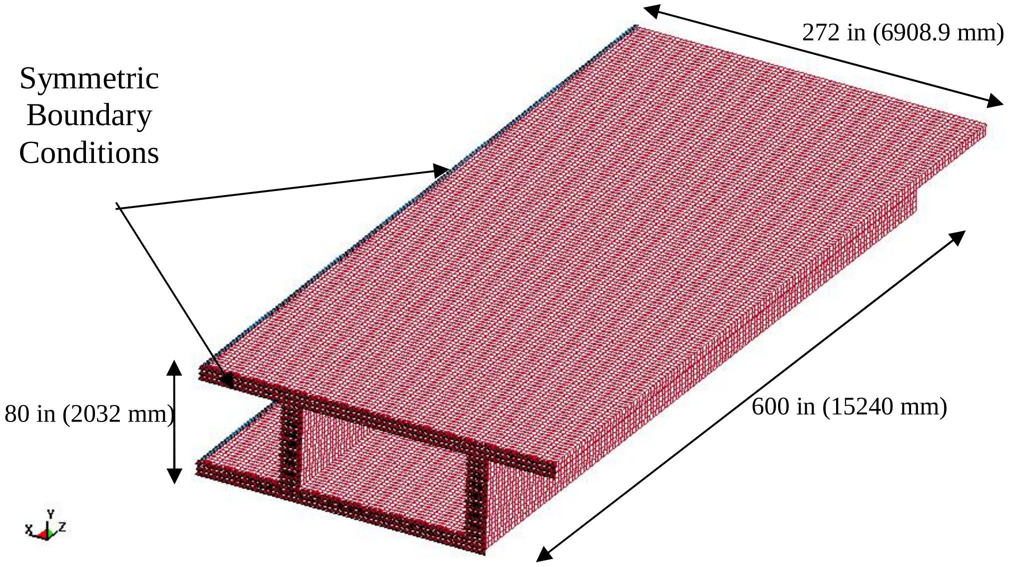

Figure 2: Isometric showing the finite element mesh of the bridge quarter symmetry model

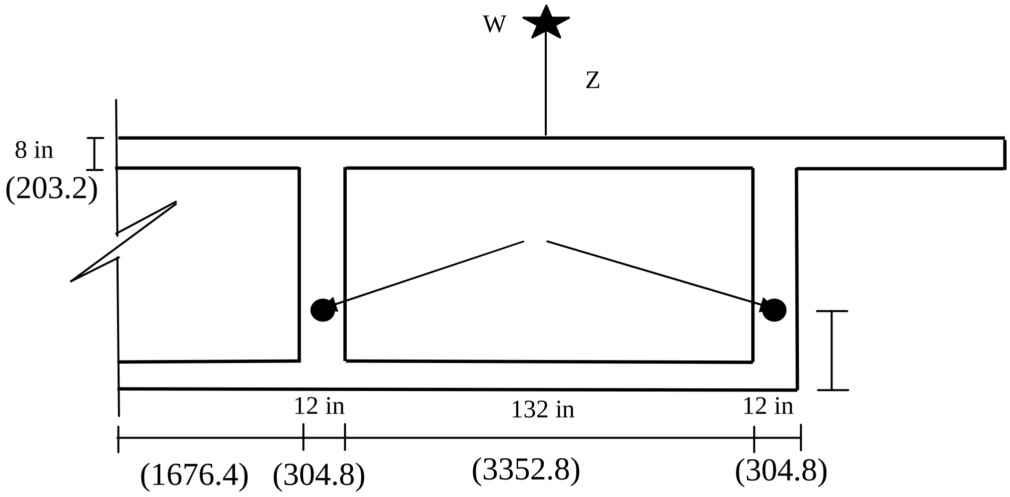

Figure 3: The dimensions of the Bridge model showing the Charge Location, dimensions in brackets are in mm.

Table1: The different charge weights and the estimated bridge damage used in the analysis

Case No.	**Charge Weight**	**Equivalent Damage Diameter in (m)**
A	0.2W	No Damage
B	2W	45 (1.16)
C	4W	163 (4.14)
D	6W	186 (4.73)
E	8W	202 (5.12)
F	10W	225 (5.80)

Results and Disscusion

The structural and material responses of the simply supported box girder bridge under different charge weights located between the main vertical webs were studied in this paper. The results are in terms of the concrete effective stresses, plastic strain, and the damage size of the nearest point to the detonation center.

The bridge response varied from the case of no damage to a global failure. The damage herein is measured by the equivalent diameter of the hole resulted from the detonation process. It is observed from all the above studied cases that the concrete was damaged at the first .0009 seconds and some of the steel reinforcement was failed, but the majority did not due to the positive phase time was very short so the steel does not have time to respond and that was the very fast strain rate which does not allow the steel to respond. It is noticed also that in all the cases the prestressed strands which are located at a distance of 18 in (0.457) from the bottom flange side did not fail because most of the explosion energy was absorbed by concrete in the first few milliseconds which accounted by the theory of propagation of waves in solids.

Figs. 4 and 5 show the effective stresses and plastic strain time histories for all the charge weights. As expected, when the charge weight increases the effective stresses increase. That effective stresses and plastic strain were figured at the nearest element from the explosion center. It is seen form the results that the effective stresses varies from 3000 psi (20.7 MPa) for case A to 46,000 psi (317.2 MPa) for case F where the bridge experienced crushing of concrete and fracture. It can be concluded that the dynamic increase factor for concrete is very important to be considered in analysis of structures under blast loads which included in the WINFRITH_CONCRETE model available in LS-DYNA. The results of effective stresses show that under case F, the dynamic increase factor for the concrete element was equal 6.7.

The results of Plastic strain shows after a certain limit of the charge weight the effective plastic strain was suddenly increased above the allowable ones and that appears in Figure 5 for cases E and F, which indicate a global failure of the bridge stiffness and that is confirmed from the damage size as shown in Fig.7. The allowable plastic strain for concrete is .003 in/in and it is shown from Fig. 5 that the concrete suffered too much strain before failure as seen for case F which gives a strain of 0.062 in/in.

The damage size (equivalent diameter) is considered a very important parameter in this study. The equivalent diameter of the damage was recorded for all the charge weights. An approximate estimation was done for measuring the damage size. As shown in Table 1, the crater hole increases as the blast load increases, the equivalent hole diameter varied from no damage for case of A to a completely damaged bridge for case F. Fig. 6 represents case B shows the deck under the detonation completely failed and small spalling was experienced by the main web. On the other hand, Fig. 7 shows the damage for case F which indicates a huge crater of diameter 340 in (8.64 m) formed in the deck and almost the whole web failed under this loading case.

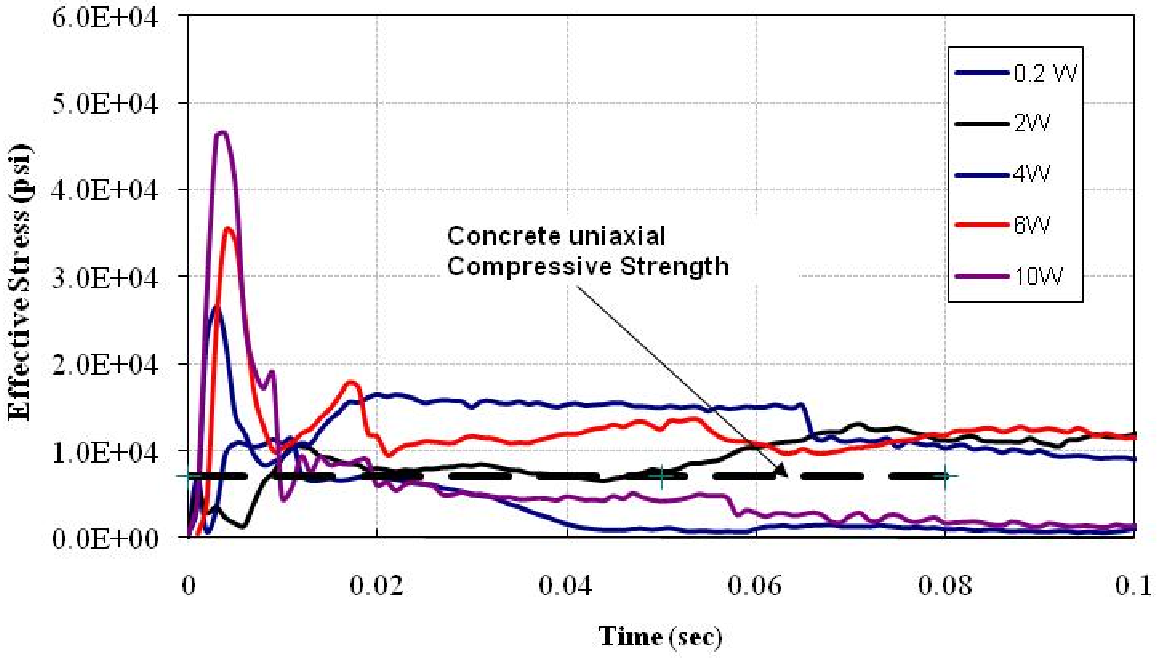

Figure 4: The Effective Stress Time History with different Charge Weights

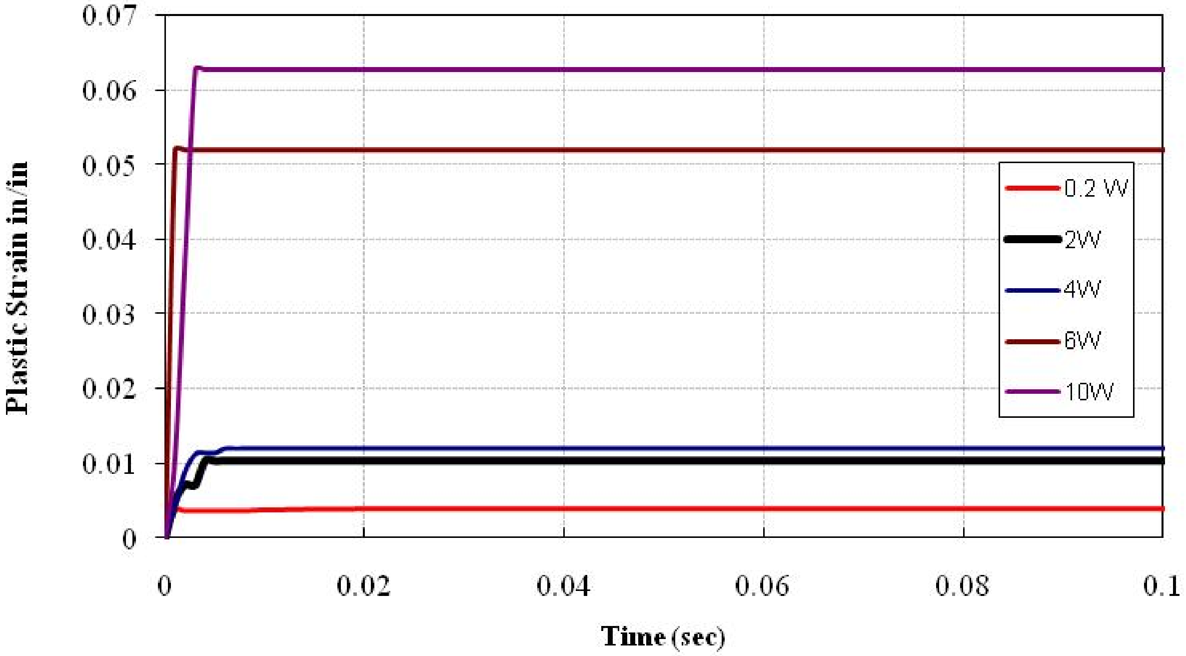

Figure 5: The Plastic Strain Time History with different Charge Weights

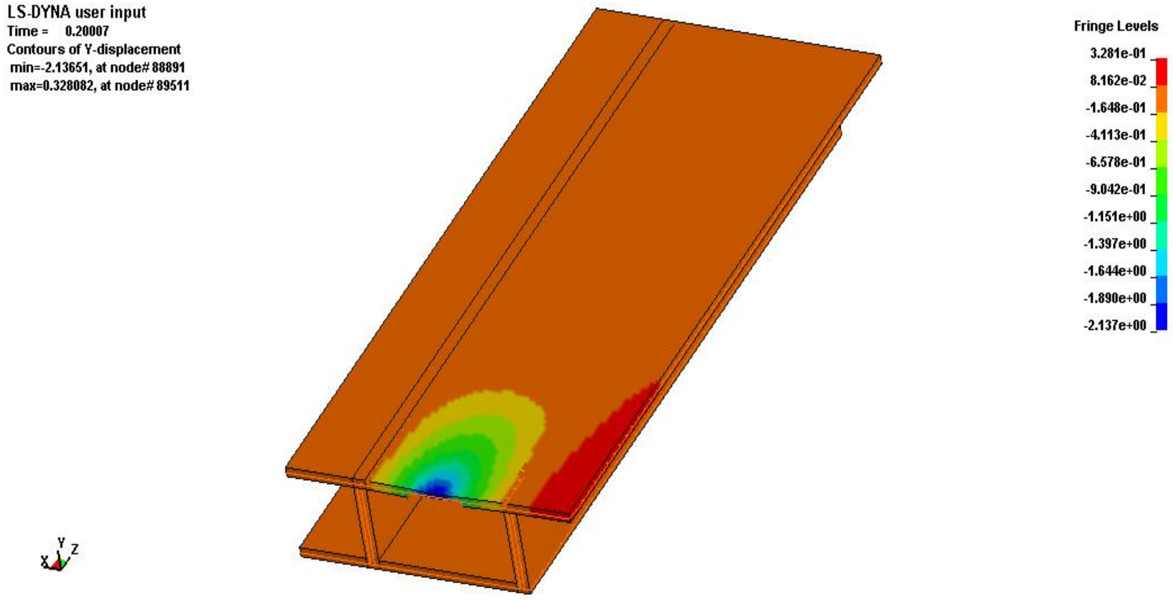

Figure 6: The Displacement Contours of the Bridge in Case A

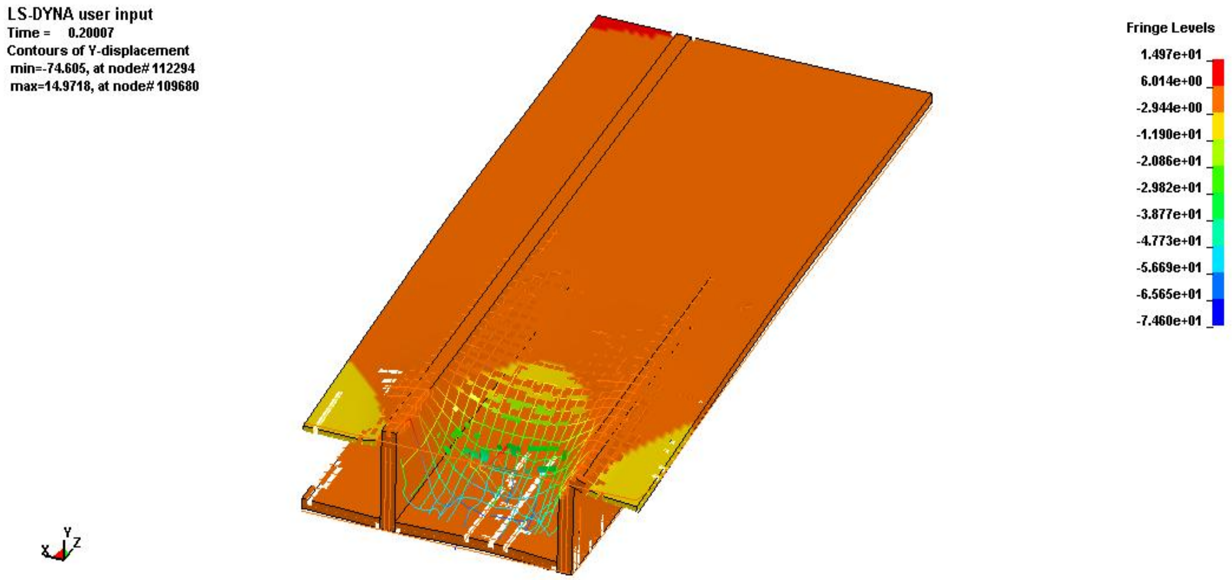

Figure 7: The Displacement and Damage (Crater Size) of the Bridge in Case F

Conclusion

Numerical analysis of a simply supported prestressed concrete box girder bridge was conducted under different charge weight placed over the bridge deck. The analysis was performed using the explicit nonlinear dynamic software LS-DYNA. All the charge cases were placed at a standoff distance of 30 inches (0.762 m) between the interior webs. The model using BLAST_LOAD command was capable to capture the dynamic response under blast loads and to predict the damage level from the case of no damage passing by the spalling and cratering of concrete. The results of this study make the finite element modeling an attractive alternative for blast testing when it is not feasible like the case of bridges. Comparisons of the numerical results are still necessary for code verification before this study can be expanded for additional parametric studies and design recommendations

References

David G., Kirk A., and Eric B. (2005). Analysis and Design of Critical Bridges Subjected to Blast Loads, *Journal of Structural Engineering*, ASCE August, 131(8):1243-1255

Islam.A (2005). Performance of AASHTO Girder Bridges under Blast Loading, PhD dissertation, *Florida State University*, Florida, USA

Jin Son (2008), Performance of Cable Supported Bridge Decks Subjected to Blast Loads, PhD dissertation, *University of California, Berkeley*, USA

LS-DYNA® Keyword User's Manual Version 971, Livermore Software Technology Corporation 2009, Livermore, California .

Marchanad K.E.B Willaimson and D.G Winget. (2004). Analysis of Blast Loads on Bridge Substructures.,*Transactions of the Wessex Institute.*

Nago, T., Mendis, P., Gupta, A. and Ramsay, J.(2007). Blast loading and blast effects on the structures-An overview. *Electronic Journal of Structure Engineering*. Special issue Feb., 76-91.

Renee Cimo (2007). Analytical Modeling to Predict Bridge Performance under Blast Loading, Master Thesis, *Univeristy of Delware*., USA.

Richard M.,and Jay A.(2007) Design of Highway Bridges and LRFD Approach. John Wiley & Sons, Inc.

Schleyer, G.K and S.S Hsu. (2000). A Modeling Scheme for Predicting the Response of Elastic-Plastic Structures to Pulse Presure Loading, *International Journal of Impact Engineering,* 3: 759-777.

Vultisky, M., and Karniz, Z. (2002), Ship structures subject to high explosive detonation. *In: 7th International LS-DYNA Users Confernce*.Michigen, USA: Livemore Software Technology Coprporation(LSTC) and Engineering Technology Associates(ETA)