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Research Paper

BLAST LOAD GENERATION METHODS ON BRIDGES

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Due to different accidental and intentional events like terrorist attacks related to important structures all over the world, explosive loads have received considerable attention in recent years. The design and construction of bridge to provide life safety in the face is receiving renewed attention from structural engineers. Analysis of highway bridges under blast loads requires accurate generation and application of blast loads and good understanding of the behavior of components of bridge. The purpose of this paper is to introduce some ideas about blast load generation method like pressure wave method, detonation simulation method, hybrid blast load method and multi-Euler domain method. Also verification of blast load results using hybrid blast load method and multi-Euler domain method included in this paper.

Keywords: Detonation simulation method, Hybrid blast load method, Multi-Euler domain method, Pressure wave method

INTRODUCTION

The number and intensity of domestic and international terrorist activities, including the September 11, 2001 attack on World Trade Center towers in New York, have heightened our concerns towards the safety of our infrastructure systems. Terrorists attack targets where human casualties and economic consequences are likely to be substantial. Transportation infrastructures have been considered attractive targets because of their accessibility and potential impacts on human lives and economic activity.

Bridges are an integral part of national highway system. Military assaults, terrorist attacks and accidental explosions may cause serious damage to bridges. As a result, engineers and transportation office workers are more active in the construction of strong bridges to withstand potential blast attacks. Explosion accident analyses, blast-resistant design and anti-terrorist and military weapon design have become more important areas. Damage effect analyses and assessments of bridges under blast loading are very important in these areas. With the rapid development of computer hardware over the last decades, detailed numerical simulations of explosive events in personal computers have become possible.

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Loads imposed on highway bridge components during a blast loading event can exceed those for which bridge components are currently being designed. In some cases, the loads can be in the opposite direction of the conventional design loads. Consequently, highway bridges designed using current design codes may suffer severe damages even from a relatively small sizes explosion.

Importance of Blast Load Generation Methods

The objectives of this paper are to extensively investigate finite element tools for simulation of blast load effects on bridge, investigate performance of bridge under various blast load generation methods like pressure wave method, detonation simulation method, hybrid blast load method and multi-Euler domain method.

Although experimental verification using scaled models is generally carried out in developing design guidelines for structures subject to hazards such as earthquakes, wind, etc., this is not practical in case of blast loads because of following three reasons.

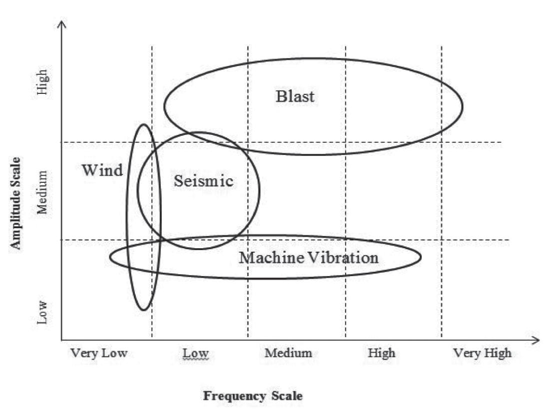
1. It is very difficult to reproduce the same blast wave environment, even in the same test field and using the same amount of explosive charge because of the temperature, humidity and dust condition of the air. Consequently, it is very difficult to carry out systematic experimental study of different parameters affecting behavior of structures subject to blast loads, particularly of relatively complex structures.
2. It is difficult to ensure reliability of sensors and data measurements, e.g., strain gauge, displacement sensors, etc., during explosion tests because of large deformation and fragmentation of the test structure. The sensors are likely to be destroyed during first few milliseconds of these types of experiments. Most of the experimental data / results are inferred from videos or pictures obtained during the experiments.
3. Experimental blast tests are also cost-prohibitive and can only be carried out at select facilities.

BLAST LOAD

Blast Load Characteristics

A structure is likely to be subjected to various types of hazards during its life time. These hazards can be subdivided into two general categories: man-made (blast) and natural (earthquakes, wind, etc.). For a successful approach to any system design, it is essential to understand the nature of the hazard. Dynamic hazards can be described by their relative amplitudes and relative time (frequency) attributes. Figure 1 shows a

Figure 1: Amplitude-frequency Distributions for Different Hazards

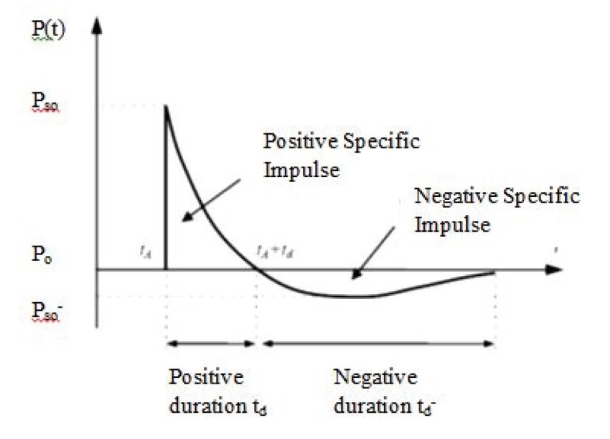


schematic representation of the amplitude-frequency relationships of several dynamic hazards.

It is important to emphasize the principal differences between static, dynamic and short-duration dynamic loads. Typically, static loads do not produce inertia effects in the structural response, are not time dependent, and are assumed to act on the structure for long periods of time (e.g., gravity loads). Dynamic loads, such as induced by earthquake or wind gusts, have strong time dependencies and their typical durations are measured in tenths of seconds. Short-duration dynamic loads, such as those induced by explosions or debris impact, are non-oscillatory pulse loads, and their duration is about 1,000 times shorter than the duration of typical earthquakes. Structural responses under short-duration dynamic effects could be significantly different than those during much slower loading cases. A multi-hazard design of bridges must explicitly address the effects conventional loads as well as severe loading environments imposed by different hazards.

An explosion is a very rapid release of stored energy characterized by an audible blast. Part of the energy is released as thermal radiation, and part is coupled into the air (air-blast) and soil (ground-shock) as radially expanding shock waves. Air-blast is the principal damage mechanism. Air-blast phenomena occur within milliseconds and the local effects of the blast are often over before the structure (building or bridge) can globally react to the effects of the blast. Initial peak pressure intensity (referred to as overpressure) may be several orders of magnitude higher than ambient atmospheric pressure in case of air-blast. Figure 2 represents a simplified model of unconfined blast load on structures.

Figure 2: Simplified Model of Unconfined Blast Load on Structures



For any blast loading, the total dynamic pressure (in psi) and the positive phase duration (in milliseconds) are found in terms of equivalent weight, W, of the explosive in TNT and the distance from the blast centre, R. Generally, blast loads are defined in terms of the scaled distance parameter Z (ft per lb TNT equivalent) as

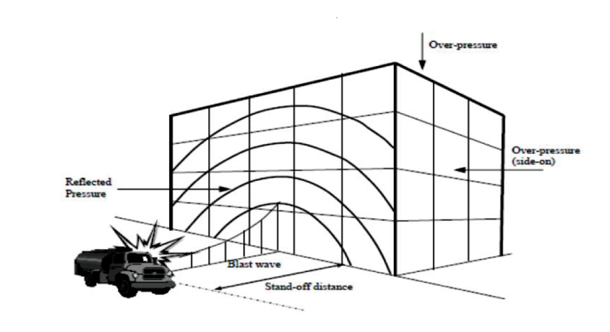
$$Z = R \times W^{-0.33}$$

With the scaled distance in the correct units, published curves can be used to find the total dynamic pressure and the positive phase duration. Similar blast waves are produced at identical scaled distances when two explosive charges of similar geometry and of the same explosive, but of different sizes, are detonated in the same atmosphere.

Stand Off Distance

Stand-off distance refers to the direct, unobstructed distance between a generation point and its target. Figure 3 shows the stand-off distance in blast load analysis.

Figure 3: Blast Loads on a Building



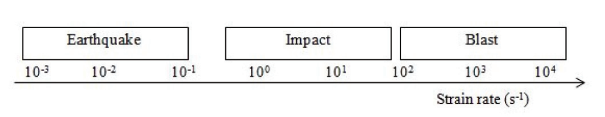
Height of Burst (HOB)

Height of burst refers to aerial attacks. It is the direct distance between the exploding weapon in the air and the target. If the exterior building walls are capable of resisting the blast load, the shock front penetrates through window and door openings, subjecting the floors, ceilings, walls, contents, and people to sudden pressures and fragments from shattered windows, doors, etc. Building components not capable of resisting the blast wave will fracture and be further fragmented and moved by the dynamic pressure that immediately follows the shock front. Building contents and people will be displaced and tumbled in the direction of blast wave propagation. In this manner the blast will propagate through the building.

Material Behaviors at High Strain Rate

Blast loads typically produce very high strain rates in the range of 10^2 - 10^4 s^{-1}. This high loading rate would alter the dynamic mechanical properties of target structures and, accordingly, the expected damage mechanisms for various structural elements. For reinforced concrete structures subjected to blast effects the strength of concrete and steel reinforcing bars can increase significantly due to strain rate effects. Figure 4 shows the approximate ranges of the expected strain rates for different loading conditions. It can be seen that ordinary static strain rate is located in the range: 10^{-6} – 10^{-5} s^{-1}, while blast pressures normally yield loads associated with strain rates in the range: 10^2 - 10^4 s^{-1}.

Figure 4: Strain Rates Associated with Different Types of Loading



External Blast Load on Structures

The blast loading on a structure caused by a high explosive detonation is dependent upon several factors:

1. The magnitude of the explosion.
2. The location of the explosion relative to the structure (confined or unconfined).
3. The geometrical configuration of the structure.
4. The structure orientation with respect to the explosion and ground surface (above, flush with, or below the ground).

ConWep

Accurately modeling blast dynamics is critical in the assessment of vehicles and structures subjected to blast loads. The current industry standard for modeling blast effects in Langrangian Finite Element simulations is ConWep, tabulated pressure data taken directly from blast events. Conwep is limited, however, and may not always be physically representative of the blast/structural interaction that occurs in the field. ConWep can capture shock front interaction and model blast surface.

BLAST LOAD GENERATION METHODS

Blast wave pressure decreases rapidly with the standoff distance. On a SDOF structure a blast load can be applied as a point load. Here, failure mechanisms of structure members are assumed to simplify a structure as a SDOF model. In this paper failure mechanisms of bridge under blast load are investigated.

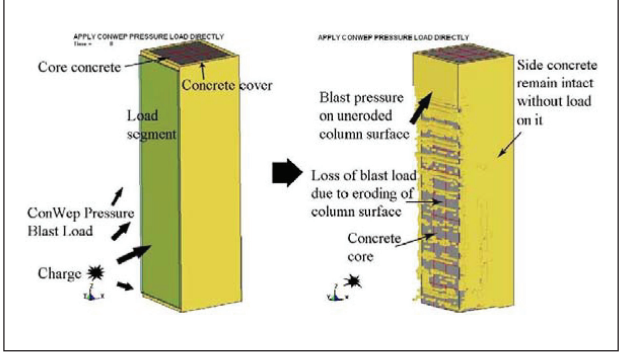
Various methods used for evaluating structural behavior under impact loads are: single or multi degree of freedom, pressure-impulse diagrams, and response surfaces developed from finite element analysis. But these methods have relatively low accuracy in the prediction of either load or structural performance. These methods have their own advantages and disadvantages.

Pressure Load Method

In this method, ConWep (a collection of conventional weapon effect calculations from the equations and curves) has been merged into LS-DYNA to apply a pressure load on structures. Advantages of this method are: it accurately controls load magnitude and does not consume extra calculation time. However, analysis before failure of a structural face only can be done by this method. When elements fail in the FEM simulation, eroding technique is used to avoid element distortion, i.e., "damaged" elements or nodes are removed from the structure.

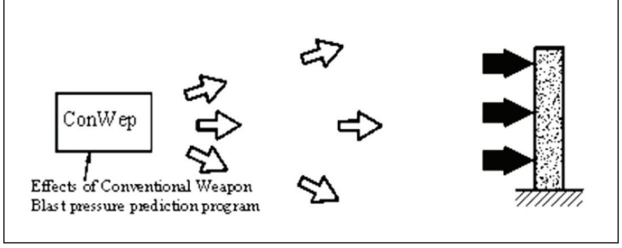
Blast load generated by ConWep acts directly on exposed structural surface. Hence it will be lost once the load contact surface (i.e., exposed structural surface) is eroded. Figure 5 shows ConWep pressure directly acting on the surface of a column. Blast pressure is lost with the erosion of FEM elements in concrete cover. Blast load continues to act on uneroded elements.

Figure 5: Application of ConWep Blast Load Directly on Concrete Structure



Since the load is not transmitted to concrete core after the spalling of the concrete surface, the simulation in Figure 6 underestimates the damage to the structure.

Figure 6: Representation of Blast Load Generation Using Pressure Load Method



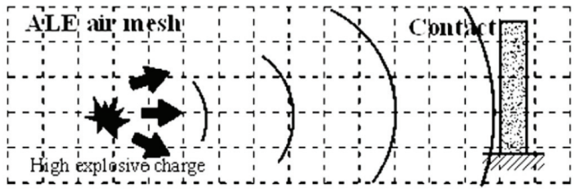
Detonation Simulation Method

Detonation Simulation approach generates blast loads through detonation of high explosives using Arbitrary-Lagrangian-Eulerian (ALE) mesh. The simulation of explosion events requires large deformation of element mesh, and this exceeds the ability of Lagrangian mesh (nodes moving along with material transferring). Eulerian mesh (nodes fix while the material transfers among different elements) is used to solve the large deformation problem. Calculation of the action between the structure with Lagrangian mesh and the Eulerian mesh creates dynamic boundary problem which is difficult to handle (Gong, 2006). Therefore, ALE mesh was chosen to simulate the explosion environment in the bridge blast research. An ALE formulation consists of a Lagrangian time step followed by a "remap" or "advection" step. The advection step performs an incremental rezone (the positions of the nodes are moved only a small fraction of the characteristic lengths of the surrounding elements). The topology of the mesh is fixed in an ALE calculation unlike a manual rezone. An ALE calculation can be interrupted like an ordinary Lagrangian calculation and a manual rezone can be performed if an entirely new mesh is necessary to continue the calculation (Hallquist, 1998).

This method simulates the process of detonation and gives accurate evaluation of incident blast wave pressure through the explosive material. It is perfect for the simulation of interaction action between structure and close blast such as landmine explosion (Wang, 2001). But in simulation of civil structures, standoff distance has to be considered. Explosion generates blast wave in the air and the air blast wave blows the structure. As shown in Figure 7, blast pressure waves are carried to column surface using air as a medium because of standoff distance between charge and structure.

This approach has several advantages over direct application ConWep pressure:

Figure 7: Representation of Blast Load Generation Using Detonation Simulation Method



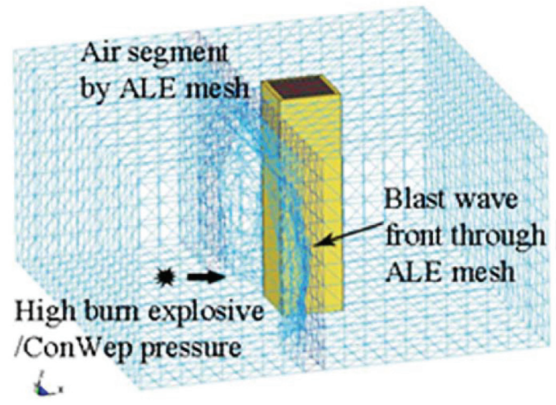
- The blast wave load continues to act on the structure after the eroding of structural surface elements.
- It can predict the reflection and diffraction of the blast wave.
- This method can account for the mutual interaction between structures and blast wave. This interaction cannot be ignored when the structural material yields under blast wave load with the elastic modulus approaching zero.

Hybrid Blast Load Method

It is a new approach that can simulate loads on structural elements similar to ConWep presented in order to overcome limitations of existing approaches. In this approach, ConWep pressure generated for a specific charge weight is transferred to an air layer near structural element. The blast wave front propagates through the surrounding air layer and the air mesh interacts with Lagrangian structure element to apply the load on structural elements (Figure 8).

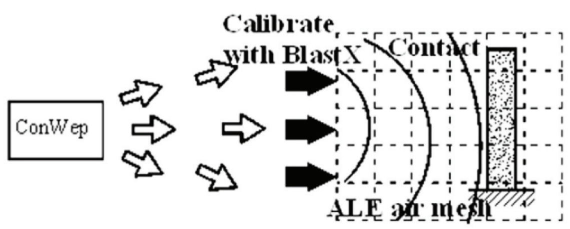
This approach has advantages of both pressure load method and detonation simulation. It produces correct pressure field with the same arriving time of blast wave as ConWep, and can simulate wave reflection and diffraction. When simulation involves

Figure 8: Simulation Under Blast Wave Using Hybrid Blast Load Method



complex geometry or non-air blast waves such as inter-explosion in box girder and air pressure near deck, other experiment data or program such as BlastX are necessary to calibrate the load effect parameters. Figure 9 represents of blast load generation using hybrid blast load method.

Figure 9: Representation of Blast Load Generation Using Hybrid Blast Load Method



In this approach, when pressure load is applied on air layer segment, the pressure of nearest air element should have the same peak as the applied load.

The two key factors in this approach are:

- The arrangement of load segments. Since ConWep reflected air blast pressure with a scale factor is used to simulate the load on structures including internal reflected blast pressure and incident blast pressure, the smaller for each load segment, the more accurate the simulation results. In this paper, one load segment is set for each structure member.
- The air density of the air layer sustaining the segment load. When the load is applied to air layer before the structure, the air layer will be compressed first and form a blast wave front. Then the blast wave front moves on and transfers the blast load. Usually, the wave front air density is 2-6 times of air density of approximately 1.29 kg/m^3. It is found that the smaller the air density (1/10 to 1/100 of the normal air density), the bigger the pressure transferred to structural elements. If the air density of the load air layer is set to smaller than 1.29×10^{-2} kg/m^3, the transferred load drops down. It has been observed from simulation results that the blast pressure is transmitted accurately to structural elements when air density of surrounding air layers is 1/10 of normal air density. In this case, the density of compressed air layer is approximately twice of the normal air density value of 1.29 kg/m^3. This value is close to shock density parameter obtained from ConWep.

Multi – Euler Domain Method

The FEM analysis of explosions is time-consuming as well as requires too many input parameters. Therefore, only small-scale structural components could be simulated by FEM., As the Euler domain should be large enough to cover the entire target in the air range, the analysis for much larger structures had to rely on supercomputers. However, it is difficult to conduct analysis of full-scale structures such as long-span bridges or tall buildings subjected to blast loading as the limitation of element numbers and the poor handling of the geometry of the Euler domain (the Euler domain could be modelled only as cuboids). To solve this problem, a multi-Euler domain method is proposed.

In this method, the initial Euler domain is built as the carrier of the blast remapping input file that was mentioned earlier, and contains a part of the structure. With the propagation of the pressure along the structural longitudinal direction, a new Euler domain is inserted and connected with the previous one. The subsequent Euler domains are introduced gradually, while the previous domains are removed when the boundary pressure decreases. Using this method, the peak pressure can be controlled to a certain air range with fewer Euler elements, thus avoiding any waste of computational resources.

In the multi-Euler domain analysis, to ensure continuous transmittance of the blast wave, a second Euler domain was built and connected with the initial Euler domain as the pressure reached the boundary surface.

COMPARISON ON BLAST LOAD GENERATION METHODS

A comparative study of various blast load generation methods was done in the previous chapter. The analysis results of multi-Euler domain method and hybrid blast load method are discussed below.

Multi-Euler Domain Method

Bridge Model

In this paper, a 24 m single-span RC composite steel slab-on-girder bridge system was adopted. The bridge deck has two layers of steel reinforcements, and the five steel girders are equally spaced at 2 m apart.

Six sub-Euler element domains are defined and built along the longitudinal direction for the complete release of the blast wave on the whole bridge. Each Euler domain has a 2 m length with 10 cm mesh size for considering the time-step of each cycle and the computational resources. The height and width of the domain are adjusted by the bridge dimensions under different blast events. A list of virtual gauges is set for each air domain to capture the pressure time histories. Two blasting scenarios are analyzed with different charge weights and detonation locations, i.e., above- deck and under- deck cases. A 100 kg charge weight of TNT is used to model a medium-scale explosive device for both cases.

Results

Above - Deck Detonation with Medium-Scale TNT

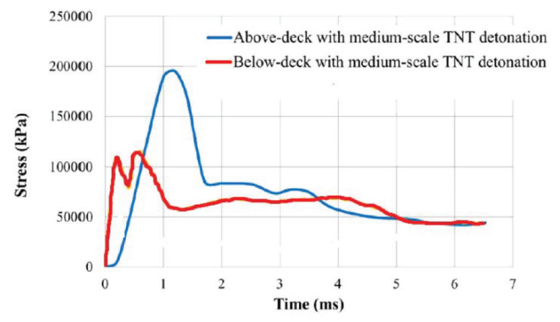
The deck girder system is originally designed for two purposes. One is to carry the loads (superstructure dead load and traffic live loads). Second is to stabilize the substructure from sudden collapse under extreme dynamic loads. First blast waves will damage the upper surface of the deck. Then the downward displacement and pressures will be transferred to the steel girder. The material damage propagates radially outward on the bridge deck. Since some restrains are provided by the supporting steel girders, for first several milliseconds the damage on the concrete is mainly concentrated along the longitudinal direction above the supporting girders. When the pressure reaches the free edges of the midspan, further damage is identified because of the rarefaction wave along the front face. A low-pressure wave is generated at the outer corner, where vortices are shed. As the blast shock wave passes the front surface slight damage appears around the fixed boundary of the bridge, which is caused by the vibration of the bridge instead of being caused by the direct shock of the blast waves.

A maximum stress of 195 MPa appears around 1.2 ms near the surface between the middle girder and the deck and much higher stress of 240 MPa is obtained at around 5.4 ms in the reinforcements.

Under-Deck Detonation with Medium-Scale TNT: Because typical RC slab-on-girder bridges are designed to withstand upward bending moments and negative shear forces with rapid dynamic loads, explosion below the bridge deck and girders may be amplified in those confined regions. Further generate large lateral forces that may cause large deformations or flexural failure, especially if the standoff distance is small. In addition, separation of the girder system and the large bending in the steel girders will make the situation much more severe.

Because the reinforcements are coincident with the concrete, the maximum upward displacement of 216.8 mm represents the deformation of the bridge deck. Compared with the concrete material, the steel girders experience a smaller horizontal deformation of 88 mm without obvious failure, because steel has good ductility and high strength. Figure 10 shows comparison of above deck with medium scale TNT detonation and below deck with medium scale TNT detonation in multi-Euler domain method

Figure 10: Comparison of Results in Multi-Euler Domain Method

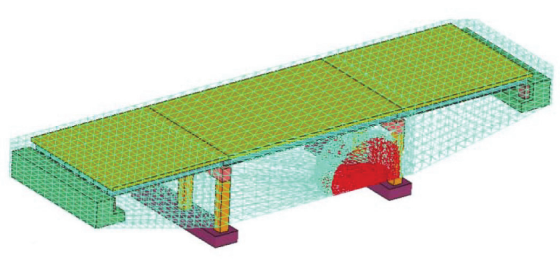


Hybrid Blast Load Method

Bridge Model

The bridge model adopted in this study was a 2 lane, 3 span RC bridge with maximum span 18.9 m. The bridge deck width is 12.2 m and thickness 0.33 m. It is supported over 6 (3 x 2 groups) piers of height 4.9 m and cross section 0.91 x 0.91 m. The bridge structure model is put into an air mesh so that the blast air wave load can be transferred to the structure. An air ALE mesh shown in Figure 11.

Figure 11: Blast Load Simulation on Highway Bridges



Results

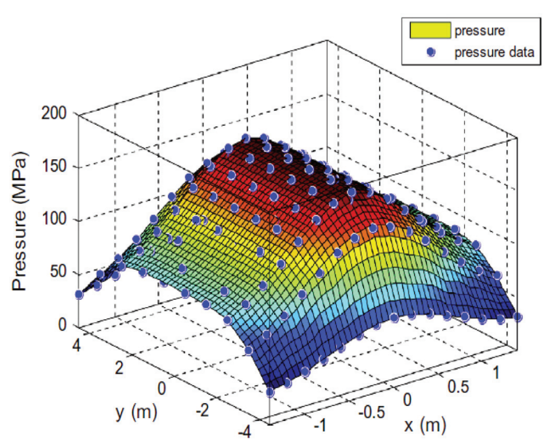
Load due to blast can cause severe damage to bridge components.

Table 1: Bearing Forces Under Blast Load

Load	Maximum Tension (kN)	Maximum Compression (kN)
Low	1480	-1078
Medium	1760	-2125
High	2648	-775
Serviceload	-176	-440

It shows that the bearing compressive force has been increased 2 – 5 times of the service load (Table 1). During blast load event structural components undergo large displacement. Shear displacement of a pier could be several inches at failure. Structural members may also undergo large strains; structure steel may exhibit plastic strains as high as 20%. The core concrete material near the pier bottom is elastic under low and medium levels of blast loads. The highest concrete stress reaches approximately 27.6 MPa while the concrete compressive strength is 55.2 MPa. Figure 12 shows the peak pressure distribution of the deck under the explosive in hybrid blast load method.

Figure 12: The Peak Pressure Distribution Of The Deck Under The Explosive



The core concrete shows highly nonlinear behavior for all levels of loading. After the compressive blast load hits the pier surface, the compressive stress wave propagates in concrete material. When the compressive wave propagates to the back surface of the pier, it reflects back as a tensile stress wave, causing tensile strain on the back surface.

The following observations on the behavior of bridge components subject to blast loads can be made from the preceding simulation case:

- The damage mode for a bridge under blast loads is similar to that for seismic loads. During low and medium levels of blast load, it is in an elastic range and during high levels of load it goes into an inelastic range.
- The damage mode is as a plastic hinge formed in the middle of column. It has bigger energy absorption ability than the local damage mode, such as compressive failure of concrete directly facing the blast wave load.

CONCLUSION

In this paper, a multi-Euler domain method and hybrid blast load method has been developed and applied for blast effects simulation of a RC composite slab-on-girder bridge. By using the hybrid blast load method, the large and complex structural response of bridges under blast loading can be analyzed. Compared with the multi-Euler domain method, which is suitable only for structural components and short span bridges, the new approach shows outstanding efficiency in reducing the number of elements by up to a hundredfold for different types of bridges, as well as shortening the calculation time in each cycle by 40 to 60%, and it is much more convenient to use hybrid blast load with varying mesh size.

Hybrid blast load method has proved to be better than multi-Euler domain methods, as far as the following aspects are considered

- Multi-Euler method involves complicated calculations. The hybrid blast load method is easier as compared to multi-Euler domain method.
- Since multi-Euler domain method involves complex calculations, it is difficult to model the structure.
- For more complex geometry, hybrid blast load method is found to be easier and appropriate as compared to multi-Euler domain method
- Multi-Euler domain method is an approximate method. It approximates the geometry which leads to pressures and impulses higher than that obtained by numerical methods.
- Multi-Euler domain leads to a conservative system. The results obtained by multi-Euler domain method are found to be overestimated as compared to hybrid blast load method. And hence the design using this result will be uneconomical.

SCOPE FOR FUTURE STUDY

The number and intensity of domestic and international terrorist activities have heightened our concerns towards the safety of our infrastructure systems. Terrorists attack targets where human casualties and economic consequences are likely to be substantial. Transportation infrastructures have been considered attractive targets because of their accessibility and potential impacts on human lives and economic activity. A study on blast load generation methods of a highway bridge has been carried out in this report.

Some of the future needs in this area are described in the following.

- Very few data on blast effects to calibrate material models for concrete, steel and elastomer have been found. In order to improve reliability of the finite element simulation, it is necessary to calibrate material models using blast tests on typical bridge components, e.g., concrete; reinforce concrete, stringers, elastomeric bearings, etc.
- In order to fully understand the dynamics of bridge components during blast loads, and develop guidelines, there is a need to investigate different variations of bridge components, e.g., wall type piers, circular piers, continuous bridges, detailing at footings and in piers, etc.
- There is a need to develop detailed knowledge and guidelines on performance based multi-hazard seismic-blast design of bridge components.

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