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A Review on Blast Analysis of Reinforced Concrete Viaduct Pier Structures

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Abstract - *The world population, as we know, is increasing at an exponential rate. To cater the needs of this increase in population, huge development in the infrastructure is happening all over the world. Large numbers of bridges, metros, viaducts, flyover etc. are emerging at various locations of the globe every day. These structures may be made of reinforced concrete, steel, composites etc. Major portion of these structures are still made up of concrete. Even in composite bridges and viaducts, the ducts may rest over piers made up of reinforced concrete. As there is an increase in population, there has also been an increase in accidents. Likewise, there has also been an increase in vandalism and terrorist activities across the globe. Both these events may lead to blasts happening at various locations. One of the key locations where these blasts may occur is near the piers of these viaducts, metros, bridges etc. The failure of these reinforced concrete piers may result in a large number of causalities, especially when the piers of the viaduct structures like bridges, fly overs, metros etc. fail due to the blasts. Various types of loads are generated during the event of a blast. These loads act on the piers and the piers may be damaged partially or it may completely fail.*

Key Words: Blast, Explosion, Blast Waves, Explosive Effects, Blast Loading

1. INTRODUCTION

The increase in population over the years have led to a rapid increase in the number of accidents that are occurring in various parts of the world. Also, the number of activities of terror are climbing up. Due to these reasons, blasts, both accidental and planned, are all over the world. Many structures are affected due to these blasts. A large number of these structures are constructed elevated from the ground level by means of piers. These piers generally do not have any protection except for a small crash barrier. The failure of the piers of the structure can cause to structure to fail and topple over. In the modern metros, roads are running on either side of these piers, as the metros are constructed over the roads. Any accident involving a blast can damage the pier structures resulting in serious injuries and loss of life. Designing the piers to be blast resistant can help in reducing the casualties to a great extent. By understanding the loads generated during a blast and its effects on the structure, we can design the structure to withstand these loads. However, designing these structures to completely resist the blast forces is a tedious process and may not be economical. Designing these structures so that damages may occur to a certain level but the total collapse of the structure does not take place is advisable. As science is evolving, the chemicals used for creating the explosions are also evolving. Some of the new chemical explosives cannot be detected even by using state of the art explosive detection technique. So, it is better that we stay prepared to face such a scenario.

2.EXPLOSIONS

Explosion is a sudden increase in volume and release of large amounts of energy in an extreme manner, usually with the generation of high temperatures along with the release of gases. There are three types of explosions namely unconfined explosions, confined explosions and explosions caused by explosives attached to the structure. Unconfined explosions may occur as an air burst or a surface burst. Unconfined explosions can occur as an air-burst or a surface burst. In an air burst explosion, the detonation of the high explosive occurs above the ground level and intermediate amplification of the wave caused by ground reflections occurs just before the arrival of the initial blast wave at a building. (Fig. 1) As the shock wave propagates outwards along the ground surface, a front commonly called a Mach stem which is formed by the interaction of the initial wave and the reflected wave.

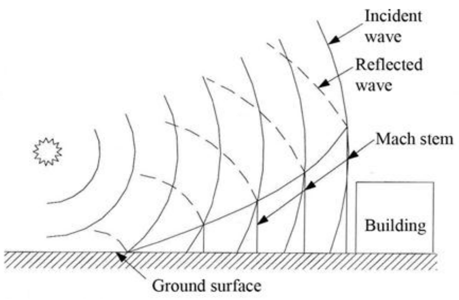

Fig. 1 - Air burst with ground reflections

However, a surface explosion occurs when the detonation occurs very close to or on the ground surface. The initial shock wave is reflected and is amplified by the ground surface producing a reflected wave. (Fig. 2).

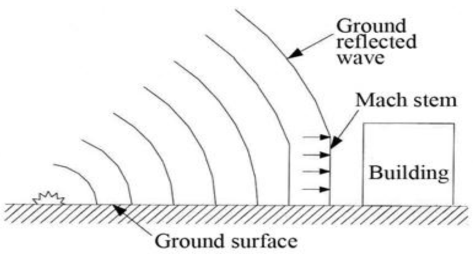

Fig. 2 - Surface burst

Unlike air burst, the reflected wave and the incident wave merges at the point of detonation forming a single wave. In the majority of the cases, terrorist activity occurs in cities, where devices are placed on or very near the ground surface.

When an explosion occurs in a building, the pressure of the initial shock front will be high and will be amplified by reflecting within the building. These types of explosion are called confined explosions. Depending on the degree of confinement, the temperature effects and accumulation of gaseous products produced in the explosion will cause additional pressures and increase the load duration within the structure. Depending on the degree of venting, various confined explosions are possible. (Fig. 3).

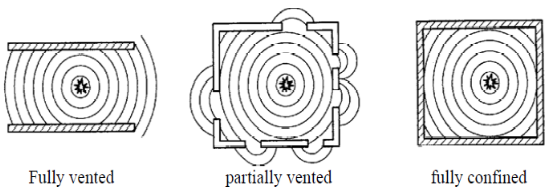

Fig. 3 - Fully vented, partially vented and fully confined explosions

If the explosive is in contact with a structural component, the detonation wave at the surface of the component will generate intense stress waves in the material and as a result the crushing of the material occurs. An explosive in contact with a structure produces similar effects to those of unconfined or confined explosions. There are many forms of high explosive available and as each explosive has its own detonation properties, the properties of each blast wave will be different. TNT is being used as the standard, where all explosions are expressed in terms of an equivalent weight of TNT. The most common method of equalization is based on the ratio of the specific energy of the explosive to that of TNT.

3.EXPLOSION PROCESS FOR HIGH EXPLOSIVES

High explosives are solid in form and are commonly termed as condensed explosive. TNT (trinitrotoluene) is the most common example. An explosion is a result of a very rapid release of large amount of energy within a limited space. This release of energy initiates a pressure wave in the surrounding medium, known as a shock wave. When an explosion takes place, the expansion of the gases produces a pressure wave in the surrounding atmosphere. As this wave moves away from the point of origin of explosion, the inner part moves through the region that was previously compressed and heated by the leading part of the wave. Due to the higher temperature, the velocity of the inner part increases and the inner part gradually overtakes the leading part of the waves. After a short duration of time the pressure waves forms a shock front called the peak over pressure. The overpressure in the shock front decreases steadily and the pressure behind the front decreases in a regular manner. After a small amount of time, at a certain distance from the center of explosion, the pressure behind the shock front becomes smaller than that of the surrounding atmosphere. This is termed as the negative-phase or suction. The blast wave front weakens as it progresses outward, and its velocity decreases and comes nearer to the velocity of the sound in the undisturbed atmosphere. This is show in Fig. 4.

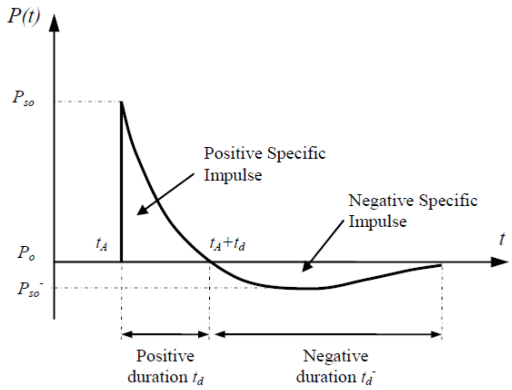

Fig. 4 – Variation of overpressure

Blast loads typically produce very high strain rates in the range of 10^2-10^4 s^{-1}. For reinforced concrete structures subjected to blast effects the strength of concrete and steel reinforcing bars can increase greatly due to strain rate effects.

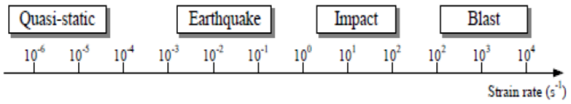

Fig. 5 - Strain rates for different types of loading

4.PREDICTION OF BLAST PRESSURE

Various theories are available for the calculation of the blast parameters like peak overpressure, peak reflected overpressures etc. Some of them are as mentioned below.

Estimation of peak overpressures due to spherical blast is generally based on a parameter termed as the scaled distance, $Z = R/W^{1/3}$. This was introduced by Brode in 1955.

$$P_{so}=\frac{6.7}{Z^3}+1\ bar\ (P_{so} > 10\text{ bar})$$

$$P_{so}=\frac{0.975}{Z}+\frac{1.455}{Z^2}+\frac{5.85}{Z^3}-0.019\ bar$$

$$(0.1\text{ bar} < P_{so} < 10\text{ bar})$$

Newmark and Hansen in 1961 introduced another expression for the calculation of the maximum blast overpressure, P_{so} in bars, for high explosive detonations at the ground surface.

$$P_{so}=6784\frac{W}{R^3}+93\left(\frac{W}{R^3}\right)^{\frac{1}{2}}$$

Another expression of the value of the peak overpressure in kPa was derived by Mills in 1987. The maximum overpressure is expressed as

$$P_{so}=\frac{1772}{Z^3}-\frac{114}{Z^2}+\frac{108}{Z}$$

As the blast wave moves through the atmosphere, the air behind the shock front is moving with a lower velocity. The velocity of the air particles and the wind pressure, depends on the peak overpressure of the blast wave. This velocity of the air and dynamic pressure, q(t) are linked parameters. The maximum value, q_s, say, is given by

$$q_s=\frac{5Pso^2}{2(Pso+7Po)}$$

If the blast wave meets an obstacle perpendicular to the direction of propagation of the wave, the reflection increases the value of overpressure to a maximum reflected pressure P_r as

$$P_r=2Pso\left(\frac{7Po+4Pso}{7Po+Pso}\right).$$

Some of the other theories formulated are Rankine and Huguenot, Sadovskiy equation, Kingery and Bulshman equation, Mays and Smith equation, Kinney and Grahams approach etc.

5.TYPE AND QUANTITY OF EXPLOSIVE

TNT (Trinitrotoluene) is used as a standard for determining the scaled distance, Z. To calculate the explosive wave from a source other than the TNT, it is converted to an equivalent charge mass of TNT. This is done so that the charge mass of explosive is multiplied by a conversion factor depending on the specific energy of the charge and that of TNT. Specific energy of different explosives along with their conversion factors to that of the TNT are given in Table. 2. Explosives are widely used for demolition purposes in military, construction and development works, demolitions, etc. It is also a very common weapon as it is easily available, easy to produce, compact and has a great potential to cause structural damage and injuries. Estimated quantities of explosive in various vehicles are presented in Table. 1.

Vehicle type	Charge mass / kg
Compact car trunk	115
Trunk of a large car	230
Closed van	680
Closed truck	2 270
Truck with a trailer	13 610
Truck with two trailers	27 220

Table 1. Estimated quantities of explosives in various vehicles

Explosive	Specific energy Q_x / kJ/kg	TNT equivalent Q_x/Q_{TNT}
Compound B (60 % RDX, 40 % TNT)	5190	1,148
RDX (Ciklonit)	5360	1,185
HMX	5680	1,256
Nitroglycerin (liquid)	6700	1,481
TNT	4520	1,000
Explosive gelatin (91 % nitroglycerin, 7,9 % nitrocellulose, 0,9 % antracid, 0,2 % water)	4520	1,000
60 % Nitroglycerin dynamite	2710	0,600
Semtex	5660	1,250
C4	6057	1,340

Table. 2 - Conversion factors for explosives

6.LITERATURE REVIEW

Due to the different intentional and accidental explosions taking place over the world, the behavior of structure and its components subjected to blast loading has become an area of considerable research in the recent years. Generally, structures are not designed to resist blast loads. Also, the magnitudes of design loads are significantly lower than those produced by explosions. Conventional structures are often susceptible to damage from explosions. Keeping this in mind, developers, architects and engineers are increasingly seeking solutions for any potential blast situations, to protect the building, its occupants and the structural components.

***Hrvoje Draganić et al in 2012**,* analyzed the action of blast load on structures. They studied the various types of blasts and identified the different loading categories. They studied the structure explosion interaction. They developed a method for calculating the blast load on the structure. Their study was conducted on reinforced concrete buildings. Loading can be defined as the record of pressure and time. The same can be applied for piers.

Ngo et al in 2007, studied RC columns subjected to blast loading. He also conducted a progressive collapse analysis of a multi-storied building. The three-dimensional model of the column was analysed using the LS-Dyna 3D software making use of the nonlinear explicit code and taking into account the material nonlinearity and geometric nonlinearity. It was seen that there is an increase in flexural strength whose value is greater than that of shear strength. This increase in the material strengths under dynamic conditions suggests a shift from a ductile flexural failure to a brittle shear failure mode. In the progressive collapse analysis, based on the local damage assessment due to bomb blast at ground level, progressive collapse analyses were done on a typical building with the help of the software. The structural stability of the building was determined by considering the failure of the perimeter columns, spandrel beams and floor slabs due to the blast. In addition to material and geometric nonlinearities, membrane action, inertia effects, and other influencing factors were taken into consideration.

Zeynep Koccaz et al in 2008, studied the blast resistant building designs and theories, the enhancement of building security against the effects of explosives in both architectural and structural design process and the design techniques that should be carried out. By the appropriate selection of the structural system, well designed and constructed beam-column connections, adequately designed structural elements, moment frames that transfer sufficient load and using high quality materials for construction, it's possible to build a blast resistant building. All the members should be designed to resist the blast load. For the existing structures, retrofitting of the structural elements might be needed. These precautions will increase the cost of construction, but to protect special buildings against terrorist attack risk like embassies, federal buildings or trade centres is necessary.

Yazan Qasrawi et al in 2015, studied the effect of blast and impact loadings on concrete filled FRP tubes by making use of numerical models. The analysis was done using ANSYS Autodyn. They were able to apply the blast loads onto these columns and reach the conclusion that FRP has improved stiffness making it a promising material in blast resistant application. The various elements used in modelling is specified in the paper, which can be used to model the problem of this thesis in finite element software packages.

Ghani Razaqpur et al in 2006, studied the behavior of reinforced concrete panels retrofitted with glass fiber reinforced polymer composite, and subjected to blast load. Eight 1000 x 1000 x 70 mm panels were cast using 40 MPa concrete and reinforced with steel meshes top and bottom. Four of the panels were kept as control specimens while the remaining four were retrofitted with 500 mm wide GFRP laminate strips on both faces fixed using adhesives, one in each direction parallel to the edges of the panel. The panels were subjected to 22.4 kg or 33.4 kg ANFO explosive charge located at a 3-m standoff. Blast wave characteristics, and the stresses and strains developed in the steel, concrete and FRP were measured. The damage after the blast and the failure mode of each panel was observed, and the panels that were not completely damaged by the blast were subsequently tested statically to find their residual strength. It was observed that the values of reflected blast pressure and impulse measured at the same location during different blasts using the same charge size and standoff distance were generally close by, except for in some cases where significant deviation was observed. The results of this study show that that the GFRP retrofit may not be suitable in every situation and its strengthening effects will need more actual blast testing.

Parag Mahajan et al in 2014, made studies to predict the blast loads and its impacts on buildings. Various cases arising in the event of a blast is considered. Various parameters effecting the blast were studied. They were even compared with seismic loads. The structural response was analyzed and various failure mode were also found out.

Avinash C. Singhal et al in 2011, studied the blast pressure on flexible panels. In this thesis, Duhamel integration technique was adopted to simulate the blast loads acting on the flexible panel. Panels of various thickness were modelled and two dynamic load types were examined. Mathematical equations for representing blast loads are described in this paper, which can be used to obtain the pressure values at different points in the event of an explosion.

Luccioni et al in 2005, analyzed the effects of the size of the mesh on pressure and impulse distribution of blast loads with the help of hydro codes. A dynamic analysis using AUTODYN-3D was carried out. The results obtained for different positions of the explosive charge were compared. The effect of mesh size for different boundary conditions is also looked into. The accuracy of numerical results highly dependent on the mesh size. But the mesh size is also limited by the dimensions of the model and the computational power available. One of the major features in the numerical simulation of blast wave propagation is the use of an adequate mesh size.

A 10-cm mesh is accurate enough for the analysis of wave propagation in urban environment. But it is too expensive to model a complete block with this mesh size. Thus, a coarser mesh can be used in order to obtain results for the comparison of the loads. Even coarse meshes, up to 50 cm of side, give a good depiction of the effects of moving the location of the explosive charges. Hence a balance between the mesh size and the available computational power is necessary.

Mohammed Alias Yusof et al in 2014, done a simulation of reinforced concrete blast wall subjected to air blast loading. The simulation was done using Autodyn. The effects of detonations using a comparatively lower charge mass to a relatively medium amount of charge mass is presented in this paper. The paper gives the effects of the various charge masses on a blast wall. This data can help in selecting a charge weight to fit the problem of the thesis.

Aditya Kumar Singh et al in 2014, studied the different types of blast loading and their effects on reinforced concrete structures. The various types of blast loads and different models possible are depicted in this paper.

Russell P. Burrell et al in 2014, studied the response of SFRC columns subjected to blast loading. He concluded SFRC to have better response to blast loading an is much more capable of withstanding blast loads compared to reinforced concrete. This can be adopted to make pier structures more resistant to blast loads.

IS 4991-1968, was studied and the terms and notations used in blast loadings in India were studied. The general characteristics of blast and its effects were looked into. Equations for blast force calculation were studied. Blast loads on structures above ground were studied specifically. The structural response and time period of the structures is given in this IS code. Load combinations for design is also prescribed in the code.

7.CONCLUSION

High explosives are solids and are commonly called condensed explosives. TNT is one of the most common example. There are 3 kinds of explosions, namely, unconfined explosions, confined explosions and explosions in which the explosives are attached to the structure.

Unconfined explosions occur as an air-blast or a surface blast. In an air blast, the detonation occurs above the ground level and the amplification of the wave caused by ground reflections happen before the arrival of the initial blast wave at a structure. As the shock wave continues to move outwards along the ground surface, a Mach stem is formed by the interaction of the initial and the reflected wave.

However, a surface blast occurs when the detonation occurs on the ground surface or close to it. The initial shock wave gets reflected and is amplified by the ground surface to produce a reflected wave. Unlike the air blast, the reflected wave and the incident wave merges at the point of detonation and forms a single wave. Terrorist activity generally occurs in built-up areas of cities, where explosives are placed on or very near the ground surface or the structure.

There are many types of high explosive available. Each explosive has its own detonation characteristics, i.e., the properties of each blast wave will be unique. TNT is used globally as the standard benchmark. Any explosive can be expressed in terms of an equivalent charge mass of TNT. The most common method to find the equivalent mass is based on the ratio of the specific energy of the explosive to that of TNT.

An explosion occurs when a material undergoes a rapid chemical reaction. When an explosion occurs, the gaseous products of the reaction are generated at a high temperatures and pressure. These gases expand suddenly into the surroundings and a blast wave is formed. Since the gases are moving, they result in the movement of surrounding air also. The damage caused by an explosion is a result of the passage of compressed air. Blast waves propagate at very high speeds and gets reflected when they meet objects. As the blast wave expands away from the source of the explosion and its intensity diminishes along with its effect on the objects around.

At the source of any explosion, the blast wave is formed and will exert intense loads which are difficult to calculate. It is easy to separate the different types of loads experienced by the objects in the surrounding when the blast wave has formed and is moving away from the source. Three effects have been. The rapid compressing the atmospheric air is called “air shock wave”. The pressure due to the gases generated from the explosion is called “dynamic pressure” and the rapid compressing of the ground is called “ground shock wave”.

The air shock wave produces a momentary increase in pressure above the atmospheric pressure at some distance from the source. This is known as overpressure. As a result, a pressure difference is generated between the gases and the atmosphere, resulting in a reversal of direction of flow known as a negative pressure phase. This is relative to atmosphere and not an absolute negative pressure. Equilibrium is reached when the air comes back to its original state.

1kg of explosive generates about 1m^3 of gas. As the gas expands, its act on the atmosphere surrounding the source of the explosion and causes it to move due to the increase in pressure. The movement of the displaced air affects nearby objects causing damage. Except for a confined case, the effects of the dynamic pressure reduce rapidly with distance from source.

The ground generated consists of three principal components. A compression wave, a shear wave and a surface or Raleigh wave. These waves propagate at different velocities and have their own unique frequencies.

Explosives are widely used for demolition purposes in military, construction and development works, demolitions, etc. It is the most common terrorist weapon as it is easily available, easy to manufacture, compact and has a great potential to cause structural damage and injuries.

There are various approaches for the calculation of the explosion parameters. In one among them is made by Brode and gives the following values for the peak static overpressure for near (when the Ps is greater than 10 bar) and for medium to far away (when the P_s is between 0,1 and 10 bar):

$$P_s = \left(\frac{6.7}{Z^3}\right) + 1, bar: Ps > 10\ bar$$

$$P_s = \left(\frac{0.975}{Z}\right) + \left(\frac{1.455}{Z^2}\right) + \left(\frac{5.85}{Z^3}\right) - 0.019, bar: \quad 0.1 < Ps < 10\ bar$$

Where Z is the scaled distance

$$Z = \left(\frac{R}{W^{\frac{1}{3}}}\right)$$

R – distance from the center of a spherical charge, m

W – charge mass expressed in kilograms of TNT.

As the waves make their way through the air, the wave front covers the structure and all its surfaces. The whole structure is exposed to the blast pressure. The magnitude and distribution of the loads depends on the following factors:

a) the characteristics of explosives,

b) the detonation location,

c) and intensity and magnification of pressure in the interaction with the ground and the structure itself.

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