Effect of Grade of Concrete and Spacing of ties in the Response of an RCC Bridge Pier Subjected to Ground Blast Loading

ASHALEKSHMI K G [1], Dr SUBHA K[2]

[1] *PG Student, Department of Civil Engineering, NSS College of Engineering, Palakkad, Kerala, India,*
[2] *Professor, Department of Civil Engineering, NSS College of Engineering, Palakkad, Kerala, India.*

Abstract – *The developing technologies are both boon and curse to our society. In the case of fields like space research, medical field etc., technological advancement is a boon; whereas, the misuse of such new technologies in terrorist activities and other related disasters is a curse to the society. Bomb blasts are associated with almost all terrorist activities. This can cause adverse effect on within and nearby the affected structures. Most of the structures are affected seriously due to such extreme loading conditions. Many studies were conducted on the behavior of structures subjected to blast loads and techniques of making a structure blast resistant. It is decided to conduct a study on explosive loading on RCC structures. Ground blast loading on an RCC bridge pier is considered for this study. The mechanisms of various blast waves are explained. The effects of change in stand-off distance of blast, change in charge weight, percentage of steel reinforcement, grade of concrete, spacing of lateral ties etc. are the parameters studied. The thesis is mainly aimed at generalizing the effect of ground blast loading on structures. This is a paper explaining the effect of concrete grade and spacing of ties in the response of ground blast loading on RCC bridge pier.*

Key Words: ANSYS, Bridge pier, Detonations, Explosion, Ground blast, Pressure wave, TNT

1. INTRODUCTION

Technological developments are taking place at a huge pace all over the world. Terrorist activities cause catastrophic effects in our society, more often due to bomb blasts resulting in loss of life and property. Shrapnel from structures is the prime reason for the loss of life and properties. So blast resistant design of structures is essential. Designing the structures for full blast resistance is not a realistic option, however, studies are ongoing to alleviate the effects of an explosion. An explosion is a rapid release of stored energy characterized by a bright flash and an audible blast. Part of the energy is released as thermal radiation (flash); and part is coupled into the air as air-blast and into the soil (ground) as ground shock, both as radially expanding shock waves. To be an explosive, the material will have the following characteristics.

1. Must contain a substance or mixture of substances that remains unchanged under ordinary conditions, but undergoes a fast chemical change upon stimulation.

2. This reaction must yield gases whose volume-under normal pressure, but at the high temperature resulting from an explosion-is much greater than that of the original substance.

3. The change must be exothermic in order to heat the products of the reaction and thus to increase their pressure.

Common types of explosions include construction blasting to break up rock or to demolish buildings and their foundations, and accidental explosions resulting from natural gas leaks or other chemical/explosive materials.

Explosions caused by high explosives like TNT are called detonations whereas those caused by low explosives are called deflagration. An explosion produces blast waves. The loads resulting from a blast are created by the rapid expansion of the energetic material, creating a pressure disturbance or blast wave radiating away from the explosion source. When a small charge explodes in the external space of a building, a pressure wave is formed by the explosion that applies a load on the surrounding building. The blast wave starts propagate from the point of explosion approximately in spherical wave fronts, and upon hitting the surface of a building structure (walls, ceilings, floors, equipment, etc.) or terrain, the wave front is reflected and modified. If the blasting charge explodes in an open area, the action of the pressure of the shock wave on a barrier depends on how the structure is situated with respect to the focus of the explosion, on the path from the explosion to the structure, on the characteristics of the loaded structure, and on the shock wave parameters on contact with the building. During an actual event, the specific course of action of the load depends on the whirl bypass of the surface of the structure, on the atmospheric pressure, on the temperature conditions and other factors which are usually neglected for a simplified analysis [19]. The structure response to explosion load can be estimated, either more accurately by a calculation or approximately based on empiric formulas and criteria.

2. THEORY OF BLAST LOADING

As already mentioned, a blast is a pressure disturbance caused by rapid release of energy. There are many forms of high explosive available and as each explosive has its own detonation characteristics, the properties of each blast wave will be different. Explosions caused by high explosives like TNT are called detonations whereas those caused by low explosives are called deflagration. TNT is being used as the standard benchmark, where all explosions can be expressed in terms of an equivalent charge mass of TNT. The most common method of equalization is based on the ratio of an explosive's specific energy to that of TNT. When a charge explodes, a pressure wave is formed by the explosion that applies a load on the surrounding building. The blast wave starts propagating from the point of explosion approximately in spherical wave-fronts and upon striking any surface or terrain, the wave-front is reflected and modified (Fig- 1) [2].

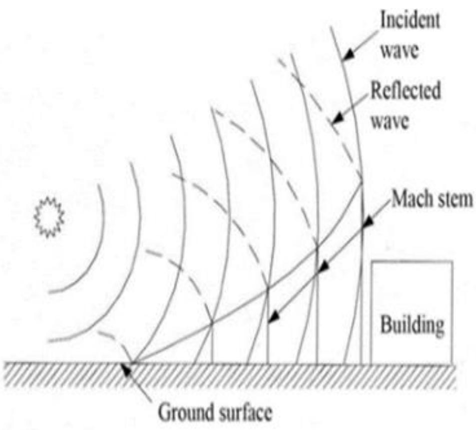

Fig- 1: Propagating blast wave [9]

In the design process it is important to determine the potential danger and the extent of this danger. Most importantly human safety should be provided During an actual event, the action of the load depends on the interaction of the load with the surface of the structure, atmospheric pressure at the time of the scenario, temperature conditions at the time of blast loading and some other factors which are usually neglected for a simplified analysis. The design of such a structure when all these effects are considered will lead to lack of economy. The structural response to explosion load can be estimated, either more accurately by a calculation or approximately based on empiric formulas and criteria.

3. TYPES OF BLASTS

Different classifications of blast loading are there. Based on the degree of confinement against blasting, there are 3 kinds of explosions which are unconfined explosions, confined explosions and explosions caused by explosives attached to the structure. Unconfined explosions include explosion in free air and near the ground. Open air explosion causes a wave that spreads from the source of detonation to the structure without any wave amplification. These explosions are situated at a given distance and height away from the structure and there is a wave increase due to the reflection of the ground before it contacts the structure. The height limitations of these explosions are two to three times of the height of a one-story or two-storey structure. As the shock wave continues to propagate outwards along the ground surface, a wave front commonly called as Mach stem is formed by the interaction of the initial wave and the reflected wave. However, a surface burst explosion occurs when the detonation occurs close to or on the ground surface. The initial shock wave is reflected and amplified by the ground surface to produce a reflected wave. Unlike the air burst, the reflected wave merges with the incident wave at the point of detonation and forms a single wave. This effect can be simulated using two loading; an air-induced blast pressure and a ground shock on to the structure [6].

When an explosion occurs within a building, the pressures associated with the initial shock front will be high and therefore will be amplified by their reflections within the building. This type of explosion is called a confined explosion. In addition to and depending on the degree of confinement, the effects of the high temperatures and accumulation of gaseous products produced by the chemical reaction involved in the explosion will cause additional pressures and increase the load duration within the structure. Appropriate ventilation reduces strength and duration of pressure so the effect of pressure is different in structures with openings and structures without openings.

If detonating explosive is in contact with a structural component, e.g. a column, the arrival of the detonation wave at the surface of the explosive will generate intense stress waves in the material and resulting crushing of the material. In this case, the effect of huge temperature also need to be considered. Except that an explosive in contact with a structure produces similar effects to those of unconfined or confined explosions [4].

4. ANALYTICAL STUDY OF GROUND BLAST LOADING ON RCC BRIDGE PIER

Analytical investigations on an RCC bridge pier subjected to ground blast loading is the thesis work selected. Rather than taking an arbitrary structure, a real RCC viaduct bridge pier of Kochi Metro Rail Project is considered as the structure to be analysed for ground blast loading. Various features of the substructure and super structure of Kochi Metro Rail Project is given below. Loading calculations are also mentioned under this module.

4.1. STRUCTURAL SYSTEM OF VIADUCT PIER

Fig- 2 shows the RCC viaduct pier structure. The viaduct structure for the Kochi Metro is a 'U'-shaped pre-stressed concrete deck, carrying two tracks supported on single pier located on the median of the road. Width of the deck is 9.0 m. The U-Channel superstructure is constructed by pre-cast pre-stressed segmental construction with epoxy bonded joints. The max c/c spans of piers of standard simply supported spans constructed by pre-cast segmental construction technique has been proposed as 28.0m. The other standard spans comprise of 25.0m, 31.0m, 22.0m, 19.0m & 16.0m, which are made by removing or adding usual segments of 3.0m each from the centre of the span. Depth of the superstructure is so chosen that top of flange of U-Channel is to be used as an evacuation walkway in an emergency.

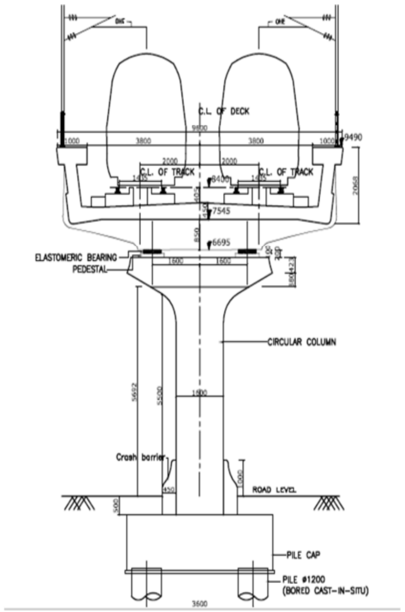

Fig- 2: Cross-Sectional View of the Piers from the Kochi Metro Rail Project [2]

The viaduct superstructure is supported on single cast-in-place RC pier. The shape of the pier follows the flow of forces. For the standard spans, the pier gradually widens at the top to support the bearing under the box webs. At this preliminary design stage, the size of pier is found to be limited to 1.2m circular for most of its height so that it occupies the minimum space at ground level where the alignment often follows the central verge of existing roads. However, 1.6 m diameter is adopted for most of the piers.

To prevent the direct collision of vehicle to pier, a Jersey Shaped crash barrier of 1.0m height above existing road level has been provided all around the pier. A gap of 25mm has been also provided in between the crash barrier and outer face of pier. The longitudinal centre to centre spacing of elastomeric/pot bearing over a pier is about 1.8m. The space between the elastomeric bearings is utilized for placing the lifting jack required for the replacement of elastomeric bearing. An outward slope of 1:200 is provided at pier top for the drainage due to spilling of rainwater, if any. The transverse spacing between bearings is 3.0m. Pile foundation is used at most of the locations. Open foundations were possible at certain isolated locations. The location where the open foundations are possible, the spans of 16m is provided.

4.2. LOADING ON THE PIER

Various loadings on the bridge pier is considered for analysis. They are, dead load, live load and blast load.

4.2.1. Dead Load

Dead load calculation is done by multiplying the volume of each component by its respective density. For this purpose, the density of concrete is adopted as 25 kN/m3 as per the Indian standards. Also, the density of rail section used is taken as 54 kg/m and that of elastomeric bearing is taken as 22 kN/m3 as specified in the detailed report of the Kochi Metro Rail project. Total axial load due to dead load is obtained to be 12500 kN.

4.2.2. Live Load

The live load acting on the piers are generated due to the movement of trains over the girders. For the computation of live loads, the dimensions of the train and axle loads are obtained from the detailed project report of Kochi Metro. The axle load is specified as 13 tonnes per axle. Since the girders are simply supported over the pier caps, the primary moments generated on the girders due to the movement of the train will not be transferred to the piers. Only secondary moments generated due to the eccentricity of the moving loads will be transferred to the pier caps and thus to the piers. So, the axial loads generated due to the various possible cases is computed. The secondary moments are obtained as the product of the axial loads and the eccentricity of the load with respect to the centroid of the pier. Certain cases are identified to be critical cases. The case in which the axial load is maximum is one of these cases. In this case, for having the maximum axial loads, train will be present on both rails and on both sides of the pier. The moments generated due to the trains are equal and opposite in nature, and thus cancels out. The maximum axial load is computed to be 8311.2 kN and the moment generated in this case is found to be zero. The damage to life will be the greatest in this case.

Hence, all together two loading cases were considered along with blast loading. They are, minimum axial load condition of 12500 kN and maximum axial load of 14580 kN.

4.2.3. Blast Load

Ground blast loading is considered in the study. Actually speaking, ground blast loading means blast loading occurring so close to ground surface. In this case, in addition to the blast overpressure, there will be a ground shock effect also which imparts a ground acceleration to the structure, depending upon the stand-off distance and charge weight of the blast. These two loadings are considered in this project. Blast pressure is calculated using Brode's theory and ground acceleration due to blasting is calculated using equation given by IS 6922: 1973.

4.2.3.1. Blast Pressure

According to Brode's theory, the peak overpressure for spherical blast depends on the magnitude of the explosion. Equation- 1 is valid where the peak overpressure is over 10 bar (=1MPa) (near field explosions) and Equation- 2 for pressure values between 0.1 bar and 10 bars (0.01MPa-1MPa) (medium and far-field explosions). The scaled distance is measured in $m/kg^{1/3}$ and the pressure P_{so} in bars.

$$P_{so} = \frac{6.7}{Z^3} + 1 \quad \text{, for Pso > 10 bars} \qquad (1)$$

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

, for 0.1 < Pso < 10 bars ________ (2)

where $Z = R/W^{1/3}$, where R is the stand-off distance in m and W is the charge weight in kg.

4.2.3.2. Ground acceleration due to blast

Equation for ground acceleration as per IS 6922: 1973, is used. As per Clause 5.1, for large charges more than 100 kg, it is desired to design structures for seismic effects of the blasts, Equation- 3 may be used for finding the design acceleration 'in the horizontal direction:

$$\frac{a}{g} = \frac{K_2 Q^{0.83}}{R^2}$$ ________ (3)

where,

a = design acceleration in cm/s^2;

g = acceleration due to gravity in cm/s^2;

K_2 = constant (which may be taken as 4 for soil, weathered and soft rock and 6 for hard rock);

Q = charge weight in kg; and

R = distance of structure from blast point in m.

Also as per Clause 5.1.1, the design acceleration so obtained should be uniformly applied to the structure.

5. FINITE ELEMENT MODELLING OF THE PROBLEM

The FEM model of the bridge pier is shown in Fig- 3 and cross sectional details are shown in Fig- 4. At the bottom of the pier, the rebar extents into the pile caps and, the pile caps and the piers are cast monolithically. Thus, at the bottom, translation as well as the rotations are restricted. Hence, at this point, it acts as a fixed support. Considering the fact that, the top end of the pier is not restricted against any lateral movement, that end is left free. Analysis is conducted by the ANSYS explicit dynamic solver using Autodyn for a duration of 10 milliseconds. Maximum principal stress and Total deformation values are obtained from ANSYS and is exported to Microsoft Excel. Graphs are prepared using Microsoft Excel software.

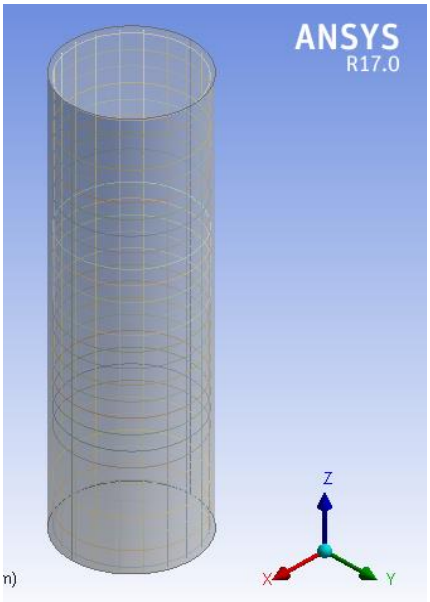

Fig- 3: Model showing pier with 0.8% main reinforcement and 200 mm tie spacing

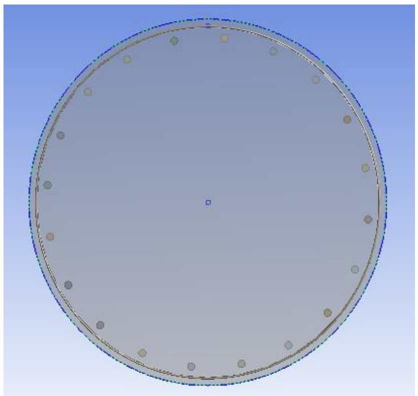

Fig- 4: Cross sectional view of the model showing rebar and ties

Blast pressure calculated using Brode's equation is applied to one half surface of the pier. Standard acceleration due to gravity is also specified. Ground acceleration calculated as per IS 6922: 1973 is applied uniformly to the structure.

Various parameters considered in the study are listed below:

i. Grade of concrete
ii. Percentage of rebar
iii. Spacing of ties
iv. Charge weight
v. Stand-off distance
vi. Various loading conditions

Two grades of concrete are selected to study its effect on the response to ground blast load; i.e., M40 and M50. As per IS 456, main tension reinforcement area should be between a minimum of 0.8% of the gross cross section area and a maximum of 6% of gross cross section area of the compression member. But considering the criteria for spacing of main bars, the maximum percentage is limited to 2.5%. Main bar diameter and tie bar diameter as 32 mm and 8 mm respectively. Grade of steel was fixed at Fe415. Clear cover to main bar was fixed at 40 mm. Tie spacing was varied as 100 and 200 mm. Charge weight, as specified before, was varied between 250 kg to 1500 kg. Stand-off distance was varied between 2 m to 10 m. Analysis was done for minimum axial load of 12500 kN and maximum axial load of 14580 kN. Cross-sectional area of pier is 2.011 m2.

In this particular paper, only the effect of concrete grade and stand-off distance is considered. So results obtained for minimum axial load condition along with blast loading is only considered.

6. RESULTS AND DISCUSSIONS

Analytical results obtained from ANSYS are tabulated and observed facts are given below:

6.1. EFFECT OF GRADE OF CONCRETE

To study the effect of grade of concrete, the analysis results for 0.8% reinforced pier and ties spaced at 100 mm, with axial load 12500 kN is considered.

6.1.1. For near field blasts (2 m)

Table- 1: Max deformation (mm) and max principal stress (MPa) for M40 and M50 grade concrete for near field blast

Stand-off distance (m)	Charge weight (kg)	Max deformation (mm)		Max principal stress (MPa)	
		M40	M50	M40	M50
2	250	535.168	529.450	57.293	69.118
2	500	964.077	959.350	59.101	70.957
2	750	1382.415	1365.900	61.391	72.234
2	1000	2057.138	1896.600	61.898	73.439
2	1250	2800.819	2615.400	62.992	73.966
2	1500	3544.822	3380.000	66.115	75.987

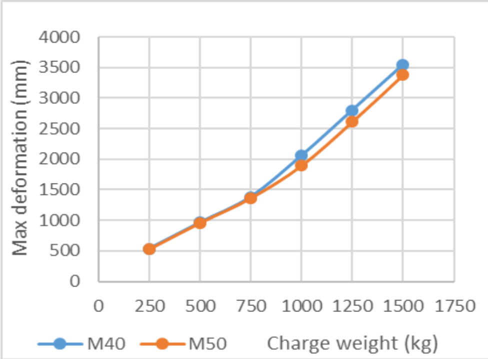

Chart- 1: Effect of grade of concrete on maximum deformation for near field blasts

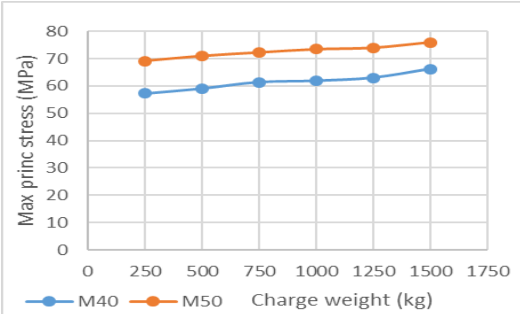

Chart- 2: Effect of grade of concrete on maximum principal stress for near field blasts

For the above graphs, it is observed that M50 grade deforms less compared to M40 grade concrete. However, this difference in deformation is significant in case of large charge weights. Principal stress also is higher for M50 grade when compared to M40 grade. For near surface blasts, the variation in principal stress with charge weight is very small. This may be due to the reduction in strength due to cracking of materials.

6.1.2. For far-field blasts (10 m)

Table- 2: Max deformation (mm) and max principal stress (MPa) for M40 and M50 grade concrete for far field blast

Stand-off distance (m)	Charge weight (kg)	Max deformation (mm)		Max principal stress (MPa)	
		M40	M50	M40	M50
10	250	8.906	8.576	13.588	24.736
10	500	15.433	14.890	32.317	44.567
10	750	21.502	20.807	46.912	59.749
10	1000	27.302	26.457	49.910	61.318
10	1250	32.930	31.934	50.750	62.864
10	1500	36.899	35.908	51.324	63.948

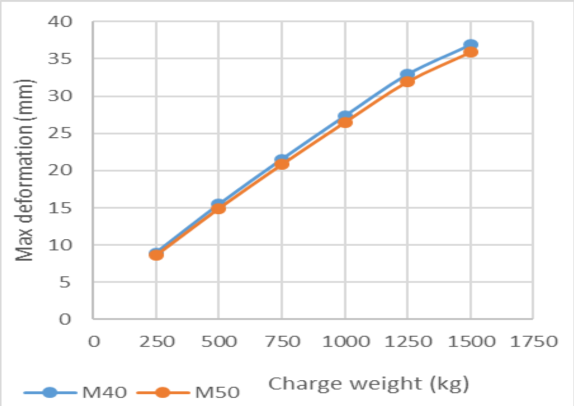

Chart- 3: Effect of grade of concrete on maximum deformation for far field blasts

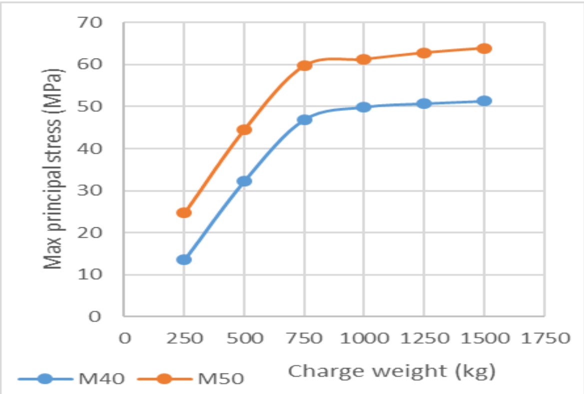

Chart- 4: Effect of grade of concrete on maximum principal stress for far field blasts

For far-field blasts also, deformation reduces with concrete grade. There is a uniform reduction in deformation when compared to those in near-field blasts. Principal stress also increases with concrete grade. Here also, the variation in stress for charge weight beyond 750 kg is at a small rate for further increase in load.

6.2. EFFECT OF SPACING OF TIES

For studying the effect of spacing of ties, 2 % reinforced pier with 12500 kN loading is considered.

6.2.1. For near-field blasts (2 m)

Table- 3: Max deformation (mm) and max principal stress (MPa) for 100 mm and 200 mm tie spacing for near field blast

Stand-off distance(m)	Charge weight (kg)	Max deformation (mm)		Max principal stress (MPa)	
		100 mm	200 mm	100 mm	200 mm
2	250	535.168	529.45	57.293	69.118
2	500	964.077	959.35	59.101	70.957
2	750	1382.42	1365.90	61.391	72.234
2	1000	2057.14	1896.60	61.898	73.439
2	1250	2800.82	2615.40	62.992	73.966
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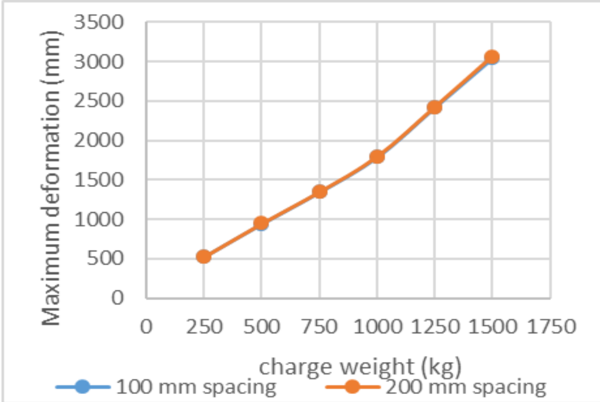

Chart- 5: Effect of spacing of ties on maximum deformation for near field blasts

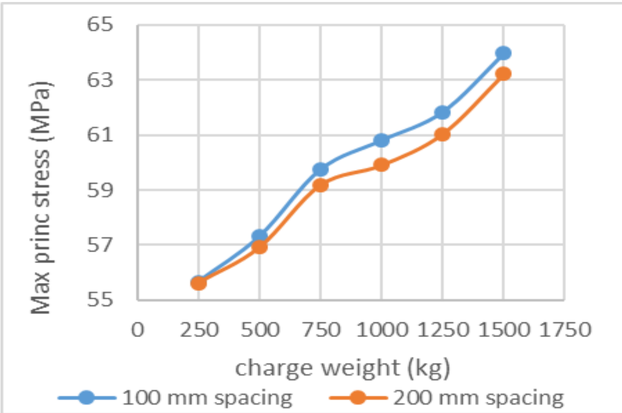

Chart- 6: Effect of spacing of ties on maximum principal stress for near field blasts

It can be seen that, spacing of effect has little effect on the deformation due to blast loading. However, there is significant reduction in the stress values when spacing of ties is reduced. It is the additional confinement provided by the ties, that makes the concrete take more stress before failure.

6.2.2. For far-field blasts (10 m)

Table- 4: Max deformation (mm) and max principal stress (MPa) for 100 mm and 200 mm tie spacing for far field blast

Stand-off dist. (m)	Charge weight (kg)	Max deformation (mm)		Max principal stress (MPa)	
		100 mm	200 mm	100 mm	200 mm
2	250	8.906	8.576	13.588	24.736

2	500	15.433	14.890	32.317	44.567
2	750	21.502	20.807	46.912	59.749
2	1000	27.302	26.457	49.910	61.318
2	1250	32.930	31.934	50.750	62.864
2	1500	36.899	35.908	51.324	63.948

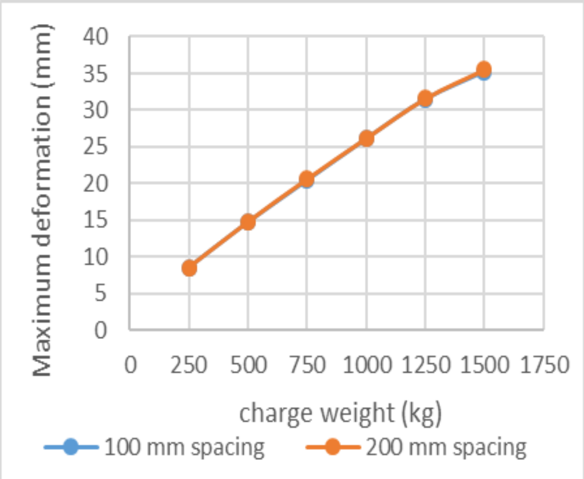

Chart- 7: Effect of spacing of ties on maximum deformation for far field blasts

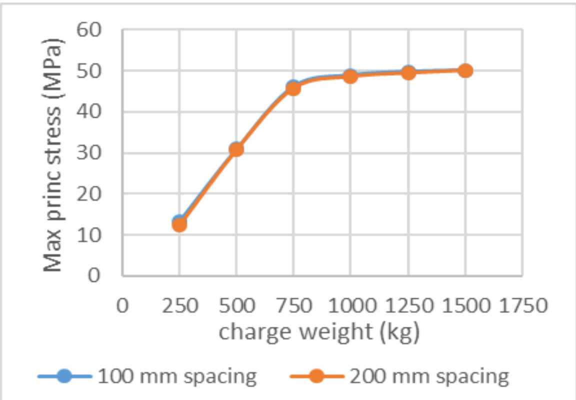

Chart- 8: Effect of spacing of ties on maximum principal stress for far field blasts

For far field blasts also, tie spacing has literally no effect on the deformation due to blast loading. Stress is increased when tie spacing is decreased. But the effect is not that significant as compared to near-field explosions.

7. CONCLUSIONS

This paper describes the effect of grade of concrete and spacing of ties to the structural response to blast loading. The problem was modelled and analyzed in ANSYS software. Various conclusions derived are given below.

- RCC bridge pier of Kochi Metro Rail Project is modelled in the software ANSYS and various material characteristics and load conditions are applied. Analysis was done for finding the effect of various parameters like charge weight, stand-off distance, concrete grade, tie spacing, percentage rebar etc. for various loading conditions.
- Deformation and principal stress increases with charge weight. This effect is more significant in the case of near-field blasts. For larger charge weights, the stress in concrete exceeds the strength even for blasts at large distances upto 10 m.
- Deformation and principal stress decreases with increase in stand-off distance. This may be due to the loss in the impulsive energy as the blast wave reaches the structure.
- Deformations are smaller for M50 grade than those for M40 grade concrete, whereas in the case of principal stress, there is an increase in value for M50 than M40 grade. This reveals the more strength of M50 grade concrete.
- Spacing of ties has little effect on the deformation due to blast loading. But there is significant increase in principal stress when tie spacing is reduced to 100 mm. This is due to the effect of additional confinement provided by the ties at lesser spacing.

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