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Behaviour of a Blast Loaded Laced Reinforced Concrete Structure

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ABSTRACT

According to existing provisions, large separation distance has to be maintained between two conventional explosive storage structures to prevent sympathetic detonation. In this paper, reduction of the separation distance with the use of earth covered laced reinforced concrete (LRC) storage structure is demonstrated, which will result in saving of land cost. Details of blast resistant design of 75T (NEC) storage structure based on unit risk principle are presented. Performance of the storage structure is evaluated in an actual blast trial. Strain and deflection profiles are obtained from the trial. Based on these, the storage structure is found to be re-usable after the blast trial.

Keywords: Laced reinforced concrete, storage structure, separation distance, blast resistant design

1. INTRODUCTION

The unit risk principle states that an accidental explosion occurring in one unit should not trigger a similar explosion in adjacent units, thus preventing a sympathetic explosion. To ensure this condition, specified minimum separation distance has to be maintained between explosive storage structures. For conventional storage structures made of reinforced cement concrete (RCC), this distance is large, thus requiring a huge area of land. In present day scenario, land cost in very high and in turn, storage structures becomes expensive. Earth covered magazines help in reducing this distance and to prevent sympathetic explosion. But, serviceability of the explosives stored in these magazines is not ensured.

Laced reinforced concrete (LRC) structures have been advocated, where high-intensity non-uniform blast loads are encountered, i.e., close-in detonation[1-5]. LRC consists of reinforcement on both faces of a structural element and are continuously tied by lacing. Structural components made of LRC can achieve support rotation as high as 4°, compared to that made of RCC which can achieve a maximum of only about 2° support rotation. Moreover, structural integrity is also enhanced by using lacings. Inter structure distance can be reduced further by using LRC structures.

Design details of elements of LRC storage structure and the behaviour of such structure subjected to air blast loading are presented in this paper. Reduction of separation distance with the use of LRC storage structure is demonstrated.

2. BLAST RESISTANT DESIGN

An explosion is a phenomenon resulting from sudden release of a tremendous amount of energy. This energy release sets up a blast wave, which travels at high speed in radial directions from the centre of explosion. The blast wave induces sudden increase in pressure to a value above the ambient atmospheric pressure known as side-on overpressure, which immediately begins to decrease exponentially with time. After a short time, the pressure behind the front may drop below the ambient pressure. During such a negative phase, a partial vacuum is created and air is sucked in. This is also accompanied by high suction winds that carry the debris for long distances away from the explosion source. Typical time history of blast pressure is shown in Fig. 1. As the blast wave travels rapidly

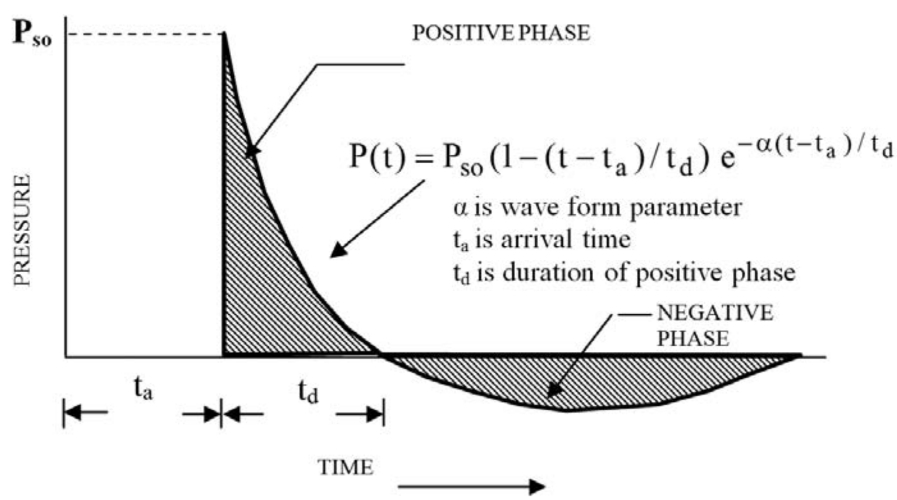

Figure 1. Time history of blast pressure.

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away from the source, its peak pressure and velocity decrease. Consequently, as it strikes a structure, a reflected shock wave is formed. This has the effect of increasing the blast pressure. The value of the reflected pressure depends on the incident angle and the incident side-on overpressure.

Blast loading differs from other dynamic loads mainly due to its transient and impulsive nature[6,7,8]. Moreover, blast loading on various parts of the structure can have different intensities and pulse durations. Peak pressures realised are much higher than the static collapse load of the structure and their duration are very small compared to the natural period of the structure. It is uneconomical to design such structures to behave elastically. Therefore, energy-dissipating capability has to be utilised in the design of such structures.

The approach to the design of a structure, capable of surviving the effects of high intensity, but short duration loads, has to be different from the one adopted for the conventional design. The structure has to be designed as a flexible system, permitting their joints to deform considerably. The stresses in the elements must be allowed to go beyond the elastic limit, so that the available strength in the post-yield region is fully utilised. This approach, called the elasto-plastic design approach, also utilises the enhanced yield strength due to high strain-rates possible in the case of blast and impact loads. The low probability of occurrence and repetition of shock loads allow the designer to utilize the energy-absorbing characteristics of a carefully designed structure. This means that the structure should be engineered to be as ductile as possible[9,10].

If the structure is located far from burst point, it is subjected to fairly uniform blast loads. RCC with additional detailing is suffice to resist such loads. Structures that are located near by an explosion threat are exposed to non-uniform high intensity blast loads. These structures must be designed for close-in pressure values and are susceptible to local failure of structural elements. For such structures, RCC is not sufficient and a material that can permit large deflections and maintaining the structural integrity is actually required. LRC has enhanced ductility and is suitable for close-in design range.

3. LACED REINFORCED CONCRETE

Conventional RCC is known to have limited ductility and confinement capabilities. These properties are especially required for structures present in the blast loading environment. The structural properties of RCC can be improved by modifying the concrete matrix and/or by suitably detailing the reinforcements. LRC as shown in Fig. 2 consists of continuously bent shear lacings along with longitudinal reinforcements on both faces of a structural element. LRC enhances the ductility and provides better concrete confinement. Moreover, LRC is cost effective compared to RCC for structures that are to be designed for impulsive loading of a given magnitude.

Resistance-deflection curve shown in Fig. 3 demonstrates the flexural action of a typical RCC element. Initially, the resistance increases with the deflection until yielding of the reinforcement takes place. After the reinforcement exhibits plastic deformation, any further deflection, can

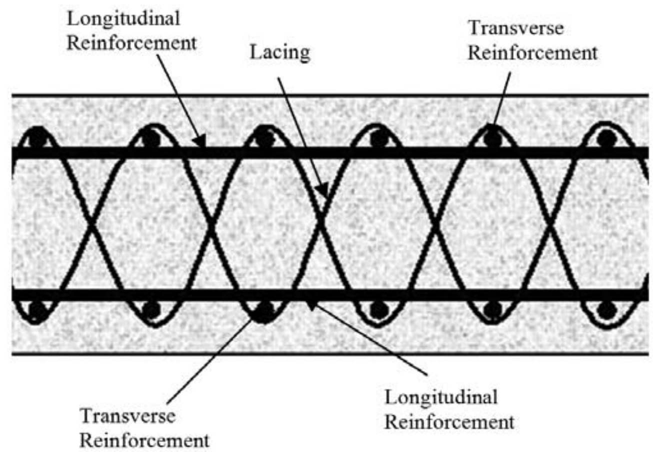

Figure 2. Typical laced reinforced concrete (LRC) structural element.

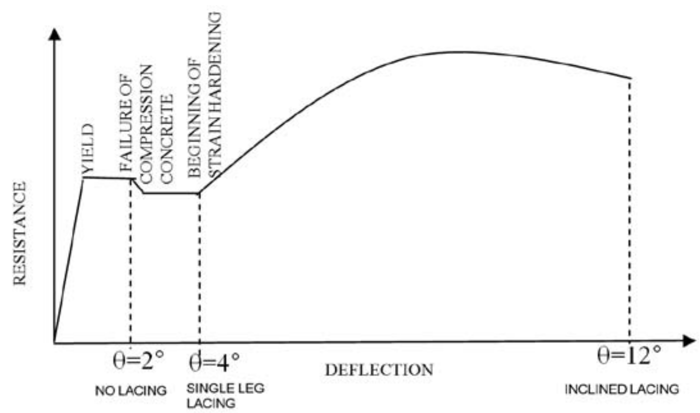

Figure 3. Resistance-deflection curve for flexural reinforced concrete elements.

therefore, occur without any additional resistance. At a deflection corresponding to 2° support rotation, the concrete in compression crushes. For elements without shear reinforcement, i.e., without confinement of concrete, this crushing of the concrete results in failure of the element. For elements with single leg stirrups or lacing, the reinforcement enters into its strain hardening region as the element further deflects. Element with single leg stirrup loses its structural integrity and fails at 4° support rotation. On the other hand, lacing by its truss action will restrain the reinforcement through its entire strain hardening region until tension failure of the reinforcement occurs. While the TM manual[4] suggests a plastic support rotation capacity of 12°, the tests conducted at CSIR-SERC[1] showed that it varied only between 6° to 8°. The results of the above investigations suggested a plastic hinge rotation of 4° at support and 8° at centre for continuous construction. The continuous lacings are inclined between 45° and 60° to horizontal. Thus, Fig. 3 demonstrates significance of shear resistance in enhancing the ductility of a flexural element. A sudden shear failure is obvious in the event of inadequate capacity. However, studies have shown that under cyclic loading the failure rotation is reduced and hence a conservative estimate of 4° support rotation has been suggested for design purposes[1,2].

4. DESIGN OF 75T (NEC) STORAGE STRUCTURE

Donor and acceptor storage structures are nearby each other and explosion takes place in the former due to which latter one is subjected to air blast loading. According to existing provisions[5], for conventional explosive storage structure, adjacent structure is to be constructed with a separation distance of 2.4 $W^{1/3}$ (m) where W is the charge weight in kg. In this study, separation distance between two storage structures has been reduced to 0.7 $W^{1/3}$. For a charge weight of 75 T (NEC), in real terms the separation distance is reduced from about 101 m to 30 m. Internal dimensions of the 75T (NEC) storage structure are 9.5 m x 15 m x 3.6 m. Haunches are provided at junction of walls and wall with roof and floor slab. General arrangement of donor and acceptor storage structures is shown in Fig. 4.

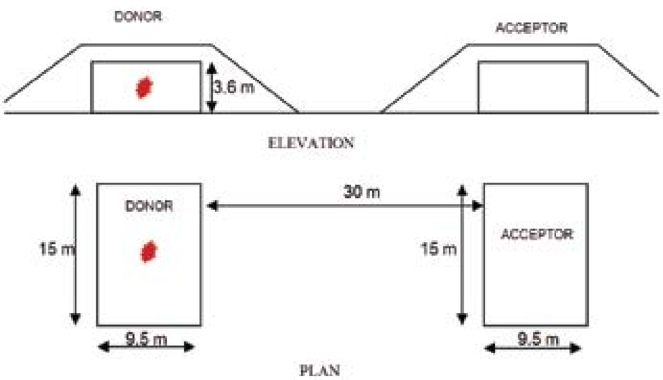

Figure 4. General arrangement of storage structures.

M25 grade concrete and Fe415 grade reinforcement steel are used. Side walls are of 350 mm thickness and are designed as one way slab. Front and rear walls are also designed as one way slabs. Roof is designed as two way slab and is of 450 mm thickness. Resistance requirement is calculated by equating the areas of the resistance-deflection and pressure-time curves. Reinforcement percentages are calculated such that the resistance provided by them is more than the demand. Percentages of main reinforcement in side walls and roof slab are 0.56 per cent and 0.39 per cent respectively. Lacings of 12 mm diameter are provided at 350 mm and 350 mm c/c in side walls and roof slabs respectively. Percentage reinforcements in secondary direction in side walls and roof slab are provided respectively as 0.19 per cent and 0.27 per cent.

5. BLAST TRIAL

Two storage structures were constructed as per the design at a separation distance of 30 m. Donor storage structure was loaded with explosive and blast trial was carried out. During this trial, performance of the acceptor storage structure was monitored. Acceptor storage structure was instrumented in order to assess its behaviour.

6. INSTRUMENTATION

Instrumentation of the acceptor storage structure was carried out with strain gages and reflectors. It was proposed to obtain the strain profile on the wall near to the donor (left wall) and deflection profiles of the left wall and roof slab. Pellets were pasted on the walls to obtain the residual strain at selected locations, where maximum strains were expected in the acceptor. Permanent strains were measured using pfender gauges. For deflection measurements, reflectors were fixed on wall and roof and total station was used for measurement.

6.1 Pellet Arrangement

On the left wall, an arrangement of pellets as shown in Fig. 5 was proposed. Initially, the expected yield line pattern was marked. Pellet locations were marked with pencils at 100 mm centre-to-centre (c/c) spacing. At the corners, pellet locations were marked perpendicular to the 45° line. After this, surface at pellet locations was smoothened with emery paper. Then, the area was cleaned with acetone solution. Pellets were pasted with the help of cyanoacrylate (CN) adhesive. After fixing the first pellet, it was allowed to set. Then, pfender gauge was used to position the next pellet in the line. Care was taken to choose the gauge spacing of pellets such that it had large range for tensile strain measurement.

6.2 Target Arrangement for Measurement of Deflection

Arrangements of targets (reflectors) on the left wall and roof are shown in Figs. 6 and 7, respectively. On the left wall, locations of targets were marked. The surface was prepared with the help of emery paper. Then, the area was cleaned with acetone solution. Reflectors were pasted with due care for the angle of reflection to the line of sight of total station.

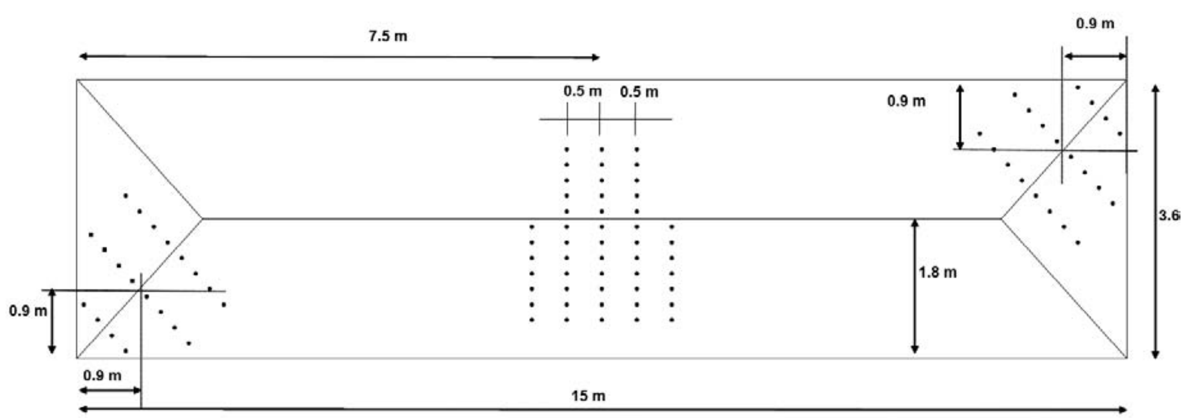

Figure 5. Arrangement of pellets on the inner surface of left wall of acceptor.

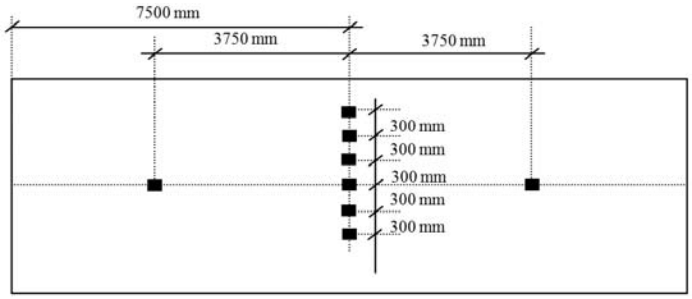

Figure 6. Location of targets (Reflectors) on left wall.

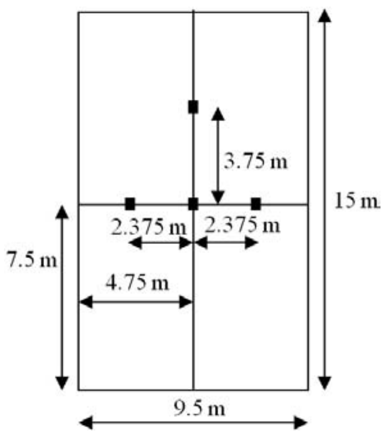

Figure 7. Location of targets (Reflectors) on the surface of roof.

Figure 8. Arrangement for target to measure deflection of roof.

For roof slab, since angle of reflection between the total station and vertical line at reflector location was more, total station could not trace the reflected ray. So, an arrangement was made by pasting a steel L-angle piece at the reflector location. Reflector was pasted on the surface of L-angle as shown in Fig. 8. Actual arrangement of reflectors in the left wall and roof slab are shown in Figs. 9 and 10, respectively.

6.3 Alternate Arrangement to Obtain Deflection Profile

An alternate arrangement for obtaining deflection at a number of points was made. Two angles were attached to the opposite walls at the same height from the floor. A string was tied between the two angles. Deflection profile was obtained by measuring the distance between roof surface and string.

Figure 9. Actual arrangement of targets in left wall.

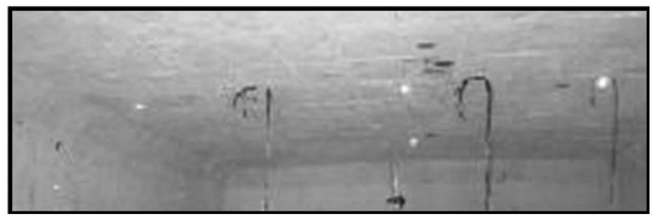

Figure 10. Arrangement of targets in roof slab.

7. DATA RECORDED

A precision theodolite/total station was used for measurement of deflection. Total station was placed inside the acceptor and initialized. The benchmark was targeted and horizontal angle was set to zero. Initial readings were noted. Then, reflectors at other places were targeted one by one and readings were recorded. Angles and distance measurements were taken before and after the trial, with respect to same reference point (benchmark).

8. RESULTS AND OBSERVATIONS

Crater of approximately 42 m in diameter and 7 m deep was formed. Fragments were found scattered in all radial directions. Acceptor was found to be intact and serviceable after the trial as seen from Fig. 11.

Initially, expected yield line pattern was mapped on

Figure 11. Intact acceptor after trial.

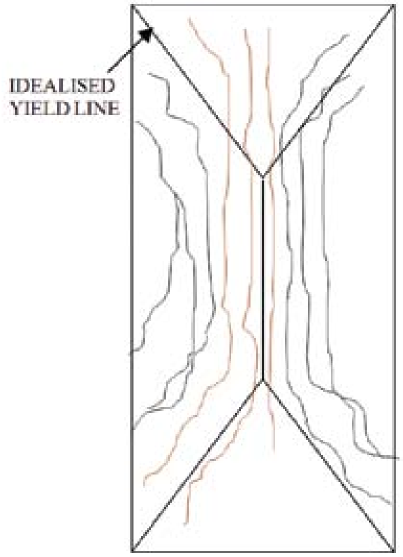

Figure 12. Mapped crack pattern on roof slab of acceptor.

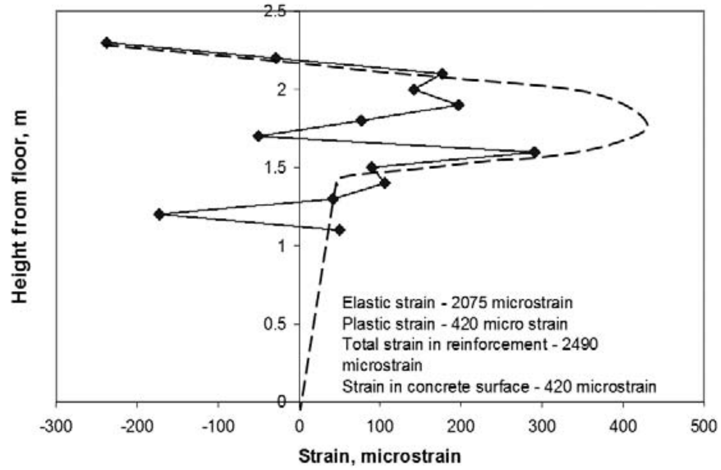

Figure 13. Average strain profile in the left wall.

the roof slab and crack pattern as observed on the roof were mapped on the sheet as shown in Fig. 12. Cracks at the middle of the roof slab were parallel to the longer span and were extending nearly to quarter spans, after which they propagated at an angle of 45°. Cracks were found to follow the expected yield line pattern.

8.1 Strain Profile

From the readings taken before and after the trial using Pfender gauge, the strain profile of the left wall was obtained. Average strain profile of left wall is shown in Fig. 13. The estimated permanent strain values on the concrete surface of the left wall was around 420 microstrains at nearly mid-height indicating the concrete has cracked. Strain values in reinforcement, at the same location, realized during testing was estimated as 2490 microstrains.

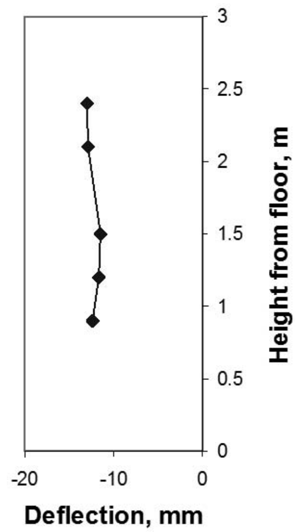

Figure 14. Deflection profile of left wall at mid span.

8.2 Deflection Profile

Deflection profile of left wall is shown in Fig. 14. Deflection variation along short and long spans is shown in Figs. 15 and 16 respectively. Maximum permanent deflection at centre of roof was measured to be around 40 mm. Residual support rotation was calculated to be 0.46°, which is much below the permissible value of 4°.

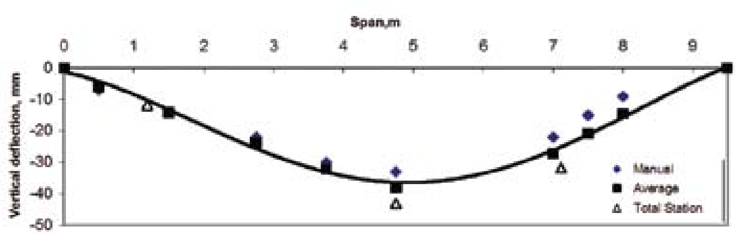

Figure 15. Deflection profile of roof along short span.

9. CONCLUSIONS

Reduction of separation distance between two explosive storage structures from the existing provision of $2.4W^{1/3}$ to $0.7W^{1/3}$ has been demonstrated with the efficient use of blast resistant LRC storage structure. Details of design of the storage structure, instrumentation for measurement of response are presented. Residual surface strains on left wall were measured using 'pfender' gauges. Deflection measurements at left wall and roof slab were taken using total station. Strain and deflection profiles were obtained from the trial data. Crack mapping on roof slab was carried out. In general, the acceptor storage structure was found to withstand the blast trial test. In addition, the acceptor structure was found to be serviceable after the blast.

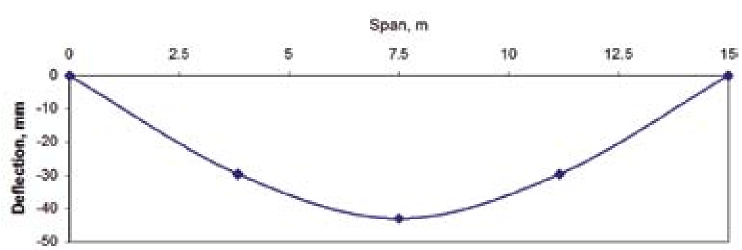

Figure 16. Deflection profile of roof along long span.

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REFERENCES

1. Parameswaran, V.S.; Lakshmanan, N.; Srinivasulu, P.; Krishnamoorthy, T.S.; Balasubramanian, K.; Thandavamoorthy, T.S. & Arumugam, M. Application of laced reinforced concrete construction techniques to blast-resistant structures. Structural Engineering Research Centre, Chennai. SERC Report No. RCC-SR-86-1. October 1986.
2. Lakshmanan, N.; Parameswaran, V.S.; Krishnamoorthy, T.S. & Balasubramanian, K. Ductility of flexural members reinforced symmetrically on the tension and compression faces. *Indian Concr. J.* 1991, 381-388.
3. Lakshmanan, N.; Balasubramanian, K.; Krishnamoorthy, T.S.; Bharatkumar, B.H.; Udhayakumar, V.; Jayaraman, R. & Natarajan, K. Analytical model for strength evaluation of laced reinforced concrete beams under shear. CSIR-Structural Engineering Research Centre, Chennai. SERC Report No. GAP 02641-RR-3. September 2007.
4. Department of Army, Navy and the Air Force. TM 5 – 1300: Structures to resist the effects of accidental explosions. Washington D.C., U.S.A. 1990.
5. Storage and Transport of Explosives Committee, Centre for Fire Explosive and Environment Safety. STEC Pamphlet No. 21: Design and construction manual for blast resistant structures using laced reinforced concrete. New Delhi. 1996.
6. Kinney, G.F. & Graham, K.J. Explosive shocks in air. Springer Verlag, New York. 1985.
7. Dusenberry, D.O. Handbook for blast resistant design of buildings. John Wiley & Sons, New Jersey, 2010.
8. Cormie, David; Mays, Geoff & Smith, Peter. Blast effect on buildings. Thomas Telford, UK, 2009.
9. Dharaneepathy, M.V.; Madheswaran, C.K. & Anandavalli, N. Investigations on shock response of structural components and structures. CSIR-Structural Engineering Research Centre, Chennai. SERC Report No. OLP06641/SVL-RR-99-1. April 1999.
10. Dharaneepathy, M.V.; Madheswaran, C.K. & Anandavalli, N. Development of design aids for shock-resistant structures. CSIR-Structural Engineering Research Centre, Chennai. SERC Rep. No. OLP-8241/SVL-RR-2000-1. March 2000.
11. Bureau of Indian Standards. Criteria for blast resistant design of structures for explosions above ground. IS: 4991-1968. New Delhi.

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