

Design and Validation of Blast Non-propagation Wall for Multi-compartmented Explosive Storage Structure of Capacity 5 T NEC per Compartment

Prabhanjan Thakur*, Rajesh Mishra, R.K. Tanwar, G.K. Mishra, and Rajiv Narang

DRDO-Centre for Fire, Explosive and Environment Safety, Delhi - 110 054, India

**E-mail: prabhanjankthakur@gmail.com*

ABSTRACT

Conventional magazines for mass explosion hazard (hazard division 1.1) are constructed using bricks and reinforced cement concrete. For such magazines, magazine inter separation distance or storage inside quantity distance (SIQD) is $2.4 W^{1/3}$ m, where W is net explosive content in kg. New composite material called laced reinforced concrete (LRC) has been developed recently, for which the SIQD has been reduced upto $0.5 W^{1/3}$ m. Due to substantial reduction in inter magazine separation distances, the requirement of storage land area has been reduced significantly. Although SIQD has been reduced drastically due to development of the new composite LRC, the other quantity distances like process inside quantity distance (PIQD) and outside quantity distance (OQD) reduced marginally. To reduce these quantity distances, one solution is multi-compartmented structures based on Unit Risk Principle. The application of unit risk principle enables the separation of explosives into compartments in such a manner that initiation of explosives in one compartment does not result in initiation of explosives in adjacent compartments. This is achieved by special design of explosive storage buildings incorporating blast non-propagation wall between adjacent compartments storing explosives. Quantity distances are reduced for such magazines because maximum credible limit corresponds to the quantity of explosive in one compartment. Present paper describes design and full scale testing of blast non-propagation wall to be constructed between two adjacent compartments of a multi-compartmented explosive storage structure with storage capacity of 5 T net explosive content of HD 1.1 per compartment. The blast non-propagation wall comprising of sand filling and air gap between LRC walls has been designed for desired attenuation of blast parameters as well as for arresting high velocity fragments/debris. The design has been validated by fully instrumented design validation field trial. The conduct of the trial as well as the trial results one discussed.

Keywords: Hazard divisions; Quantity distances; URP; Laced reinforcement concrete, LRC; Blast non-propagation wall; Composite elements

1. INTRODUCTION

The Orange Book issued by United Nations contains the detailed classification of dangerous goods. As per this classification, the dangerous goods are classified into 9 classes (1 - 9), out of which class 1 comprises of explosive substances and articles. Class 1 is further divided into 6 hazard divisions (HDs). The first hazard division, HD 1.1 comprises of mass explosion hazard¹.

1.1 Principles of Quantity Distances

Potential explosion sites which permit explosives are a potential risk to individuals and property. Such sites should be located sufficiently clear of other buildings, stacks, vehicles or places frequented by persons so as to ensure the minimum reasonably practicable risk to life and property. This distance usually depends on the maximum net explosive quantity permitted at the potential explosion site and is therefore called the quantity distance (Q-D). Quantity distances are of four

kinds; storage inside quantity distances (SIQD), process inside quantity distance (PIQD), public traffic route distances (PTRD) and outside quantity distances (OQD)^{1,2}. The QDs are based on series of trials and analysis of trial results and all available data on accidental explosion in different countries. All QDs for HD 1.1 class of explosive except OQD are function of overpressure, however OQD is a function of both overpressure and number density of lethal fragments (number of lethal fragments per unit area). A fragment is called lethal if its kinetic energy is 79 J or more^{3,4}.

1.2 Construction of Explosive Storage Structures

Conventional explosive storage buildings are constructed using bricks and reinforced cement concrete (RCC)^{5,6}. Scaled distances and overpressure values at various QDs for such high explosive magazines are as given in Table 1.

It is desired to design and develop such explosive storage buildings which require lesser quantity distances and therefore lesser land area.

Table 1. Scaled distances and overpressure values for Q-Ds^{1,3,7}

| Quantity distances | Scaled distances (m/kg ^{1/3}) | Overpressure (bar) |
|--------------------|-----------------------------------------|--------------------|
| SIQD | 2.4 | 1.81 |
| PIQD | 8.0 | 0.21 |
| PTRD | 14.8 | 0.09 |
| OQD | 22.2 | 0.05 |

1.3 Development of Laced Reinforcement Concrete

In laced reinforcement concrete (LRC), two layers of reinforcement and core concrete are tied together by truss action of continuous bent shear lacing. The arrangement of reinforcement bars and truss members (lacing elements) is as shown in Fig. 1.

Compared to conventional RCC, LRC technique is very useful for blast resistant structures subjected to close-in detonations. LRC structural elements exhibit larger ductility/energy absorption and excellent concrete confinement⁸⁻¹⁰.

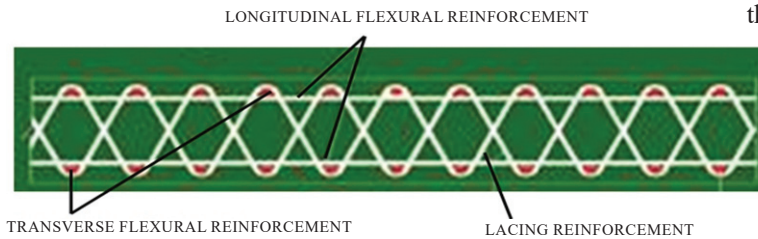


Figure 1. Reinforcement details of a LRC slab.

1.3.1 Development of Structures-based on Unit Risk Principle

The application of unit risk principle enables the separation of explosives into compartments in such a manner that initiation of explosives in one compartment does not result in initiation of the explosives in adjacent compartments. This is achieved by special design of the storage buildings incorporating blast non-propagation walls between adjacent compartments storing explosives. All quantity distances are reduced and correspond to the quantity of explosive in one compartment called maximum credible limit. Reduction in QDs due to reduction in maximum credible limit for a 10 compartmented storage structure with per compartment storage capacity of 5 T NEC HD 1.1 as per QD table¹ can be as shown in the following Table 2.

Table 2 . Difference in Q-Ds for a multi-compartmented and a non-compartmented structure

| Type of structure | SIQD (m) | PIQD (m) | OQD (m) |
|---------------------------------------------------------------|----------|----------|---------|
| Non-compartmented structure of 50T NEC Capacity | 89 | 295 | 820 |
| 10-Compartmented structure of 5T NEC capacity per compartment | 41 | 140 | 380 |

In case of multiple explosions i.e. explosions in different compartments of the explosive storage structure, if the time

delay between two explosions is sufficiently large, the effects of the two detonations do not superimpose/coalesce, otherwise due to coalition of the two effects, the damage increases exponentially. If this induced detonation takes place after a critical period so that superposition of positive phases of two blast waves does not take place, then it is called delayed detonation¹¹. The superposition of positive phases of two blast waves is as shown in Fig. 2.

The blast non-propagation wall between two compartments of a multi-compartmented explosive storage building having a storage capacity of 5 T NEC HD 1.1 per compartment has been designed and tested. The possibility of delayed detonation has been taken into account. This specially designed blast non-propagation wall comprises of a series of LRC panels separated by sand-filling and air gap.

2. DESIGN OF BLAST NON-PROPAGATION WALL

2.1 Blast-Wave Phenomena

Sudden release of energy is called an explosion. Due to the sudden release of energy, a disturbance (pressure front) is generated which propagates in the outside material medium. This disturbance or shock front while travelling in the surrounding atmosphere is called blast wave and is characterised by an instantaneous rise in pressure with respect to ambient. The peak value of overpressure associated with a blast wave is called peak incident pressure and is denoted by P_p ^{9,10,12-14}. An ideal pressure profile with respect to time of a blast wave can be as shown in Fig. 3.

2.2 Estimation of Blast Loading Parameters for Surface Burst

Detonation of a charge located on or very near to the ground surface is considered to be a surface blast. The variation of positive phase pressure, impulse, duration, negative phase pressure, time of arrival and other blast parameters with scaled distance for both surface and air blast have been plotted by DoD, USA^{9,10}. The scaled distance (Z) is mathematically defined as the ratio of standoff distance (R) to the cubic root

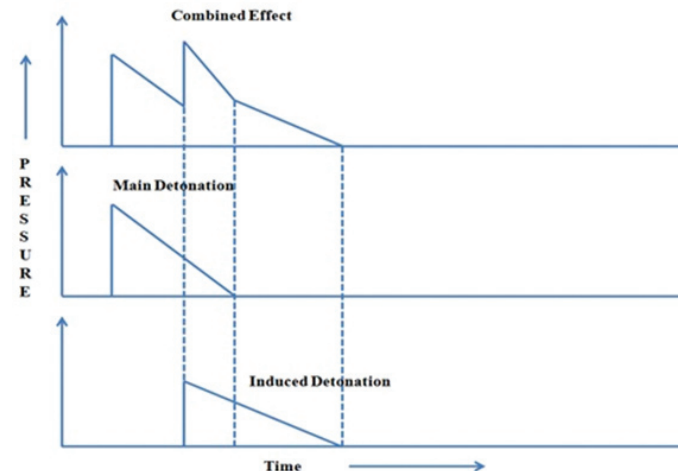


Figure 2. Superposition of positive phase of two blast waves.

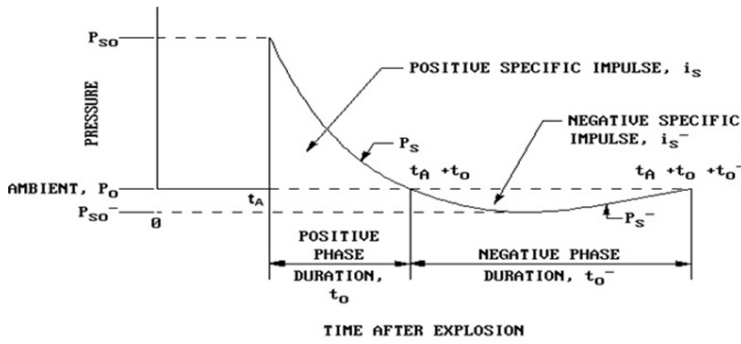


Figure 3. Blast wave profile ^{9,10,12,15-19}.

of net explosive weight (W) in terms of TNT or its equivalent ($Z=R/W^{1/3}$)^{9,10,13-16,20}.

2.3 Estimation of Blast Loading Parameters for Confined Explosion

When an explosion takes place inside a structure, the peak value of blast overpressure associated with the initial shock front is extremely high. This blast overpressure is further amplified by its reflections from various reflecting surfaces like walls, floor and roof of the structure. The maximum number of reflecting surfaces in a fully confined cubicle can be four. Due to increase in the overpressure and duration of load, the impulse also increases. An approximate method for calculation of the internal blast pressures and impulses has been developed by DoD, USA using theoretical method. This method is based on semi-empirical blast data and the results of response tests on slabs.

2.4 Attenuation of Blast in Air

Attenuation of blast in an air gap can be calculated using following sequential steps.

- (i) Scaled distances of the two extremes are determined
- (ii) Scaled blast impulses are estimated for both scaled distances using figure 2-15 of ref 10
- (iii) Absolute blast impulses are determined
- (iv) Difference in absolute blast impulses gives the attenuation of blast impulse in air gap.

These steps are as shown in the Fig. 4.

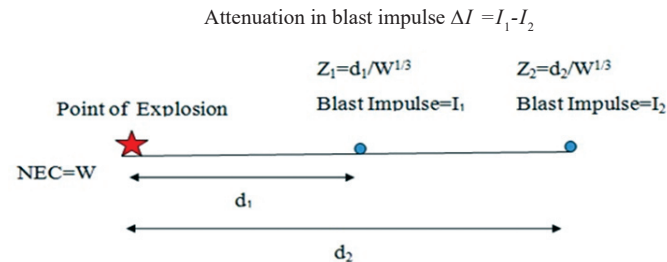


Figure 4. Attenuation of blast impulse in air.

2.5 Blast Attenuating Composite wall

Composite walls consist of two concrete panels filled with sand in between. The concrete panels may be made of reinforced cement concrete (RCC) or laced cement concrete (LRC). The composite walls are having the quality of attenuating the effects of close-in detonation. Composite walls

are generally used as blast non-propagation wall which does not allow the blast to propagate from one stack of explosive to other stack of explosive kept on either sides of the wall. Hence, construction of blast non-propagation wall comprising of composite walls is a solution to prevent sympathetic detonation. Apart from blast attenuation capability, the composite walls are very good fragment arrester^{9,10,21}.

A composite wall comprising of two LRC panels separated by sand filling is as shown in the Fig. 5. A blast load having impulse I is incident on this composite wall. If the residual impulse I' will be transmitted to the surrounding, then blast impulse attenuated in the composite wall equals $\Delta I = I - I'$. ΔI is called the blast impulse capacity of the composite wall. Blast impulse capacity of composite wall is calculated as mentioned above. For design of a composite wall to be acceptable, its blast impulse capacity should be greater than the impulse of the incident blast load.

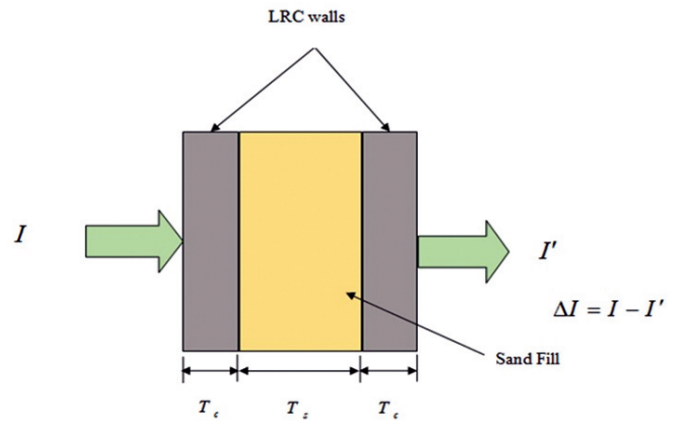


Figure 5. Attenuation of blast impulse in a composite element.

3. TRIAL SET-UP

A three compartmented explosive storage structure named high performance magazine (HPM) was designed and constructed at the Test Range. It consists of three identical storage compartments having size 10 m X 8 m X 3.6 m each. Blast non-propagation composite walls comprising of sand filling and air gaps between LRC walls were constructed between two storage compartments. Two configurations of composite walls were used on either side of the central compartment. The first configuration comprised of sand (2m) - air (1m)-sand (2m) (S-A-S) while the second configuration was comprised of air (1m) -sand (3m) - air (1m) (A-S-A). Blast attenuation capabilities of both configurations were found comparable as per calculations & simulations and were needed to test experimentally for deciding better of the two. For this purpose, one compartment on either side of the central compartment was constructed incorporating both configurations (S-A-S and A-S-A). The central compartment was named as Donor Compartment as 5 T NEC HD 1.1 was to be initiated in that compartment during the Trial and the compartment was supposed to be sacrificed. Adjacent compartments on either side of the Donor Compartment were named Acceptor Compartments as the ammunitions kept in these compartments

were supposed to be safe in case of accidental initiation of 5 T NEC HD 1.1 in Donor Compartment. VIFTs (Vertical Inner Face Traverse) were constructed on both front and rear sides of the donor compartment for arresting the fragments /debris generated due to explosion. The layout of the experimental structure comprising of one Donor and two Acceptor chambers is shown in Fig. 6.

The actual test structure constructed at the Test Range to validate the design is as shown in Fig. 7.

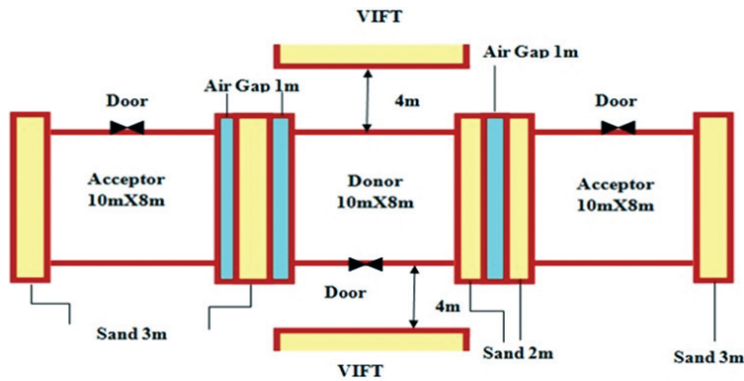


Figure 6. Layout of trial set-up.



Figure 7. Test structure.

4. DESIGN VALIDATION FIELD TRIAL

Fully instrumented blast trial with 5 Ton TNT was conducted successfully. 5 T of TNT was stacked in the central compartment (Donor) as per the stacking pattern. The stacking pattern has been finalised based on the series of detonability trials. The stacked TNT boxes in the Donor compartment are as shown in Fig. 8. Four numbers of fuzes, 10 kg plastic explosives, 10 electrical detonators and two anti-tank mines of 6.8 kg NEC each were kept in both acceptor chambers.



Figure 8. Explosive stacked in HPM donor compartment.

To capture the real time structural response against blast load and to assess effect of blast up to OQD, numbers of sensors were deployed inside acceptor compartments as well as at various scaled distances in the field. Following parameters were measured during the blast field trial. Figure 9 shows strain gauges deployed inside the acceptor compartments to capture the responses of the acceptor compartments against the blast load generated due to detonation of 5 T TNT inside the donor compartment.

Sensors like pressure probes, accelerometers and geophones were deployed in the field as shown in Fig. 10 for measuring overpressure, ground acceleration and ground peak particle velocity, respectively.

5. TRIAL RESULTS

Both the acceptor compartments remained intact after the blast. Except the side wall of the acceptor compartments facing donor, all other walls including the acceptor roof remained intact and did not suffer any damage. The side wall facing donor sustained heavy damage but did not generate lethal fragments that could initiate an explosive stack. The reinforcement of the damaged side wall remained intact to the core concrete thereby proving the efficacy of LRC walls to take up huge deflections without failure. Figure 11 shows post trial photograph of the structure. The doors of both the acceptors remained intact and did not sustain any kind of damage.

Overpressure values, arrival time and positive duration of blast load measured at various quantity distances in the field are mentioned in Table 3.



Figure 9. Deployment of sensors inside acceptor compartment.



Figure 10. Deployment of Sensors in the field.



Figure 11. Structure after the blast.

Table 3. Blast parameters at various quantity distances

| Location | Pressure recorded (Bar) | Arrival time (ms) | Positive duration (ms) |
|----------|-------------------------|-------------------|------------------------|
| SIQD | 1.18 | 75.6 | 32 |
| PIQD | 0.147 | 325 | 50 |
| PTRD | 0.065 | 628 | 56 |
| OQD | 0.04 | 980 | 60 |

QD reductions based on recorded overpressure were obtained by extrapolating the values of overpressure at various quantity distances on log-log plot. These reductions are as shown in Table 4.

Table 4. QD reductions based on recorded overpressure

| Quantity distances | Scaled distance (STEC) (Z) | Scaled distance (Design validation trial) (Z) | Reduction (per cent) |
|--------------------|----------------------------|-----------------------------------------------|----------------------|
| SIQD | 2.4 | 1.85 | 28.0 |
| PIQD | 8 | 6.7 | 19.6 |
| PTRD | 14.8 | 11.8 | 25.0 |
| OQD | 22.2 | 20.1 | 10.4 |

These reductions in Q-Ds are in addition to the reduction due to decrease in maximum credible limit as shown in Table 2.

6. SUMMARY AND CONCLUSIONS

For reducing PIQD and OQD, multi-compartmented explosive storage structures based on Unit Risk Principle is the solution. But the design of blast non-propagation wall between two adjacent compartments is a big challenge. The blast non-propagation wall comprising of sand filling and air gap between LRC walls has been designed to withstand the blast effects of 5T NEC HD 1.1. The design has been tested by full scale instrumented field trial. Based on instruments readings, videography and visual observation, the design was validated. No sympathetic detonation occurred in the adjacent compartments. Ammunition/ explosives stored inside the adjacent compartments were found safe and serviceable. Out of the two proposed configurations of blast non-propagation wall, the Sand-Air-Sand configuration sustained less damage as compared to Air-Sand-Air configuration and hence has been recommended for the future design. The pressure recorded

during the field trial at SIQD, PIQD, PTRD and OQD in all directions were substantially lower than the corresponding values for conventional explosive storage buildings. The reduction in QDs was directional and was over and above the reduction resulting from limitation of maximum credible event (MCE) to 5 T NEC per compartment. The number density of the lethal fragments at OQD was found lesser than its critical value (1 lethal fragment in 56 square metres). The en-masse detonation of 5 T NEC represents the worst case scenario with maximum blast, fragmentation and ground vibrations resulting in maximum possible damage to surrounding structures. In real scenario, where ammunition is stored in separate stacks, en-masse detonation is a low probability event and thus the effects would be considerably less severe.

REFERENCES

1. STEC Pamphlet No. 1: Quantity Distance Regulations for Military Explosives. Storage & Transport of Explosives Committee 2011, Centre for Fire, Explosives & Environment Safety, Brig S K Mazumdar Road, Delhi - 110054.
2. Guidelines for Bulk Explosive Facilities. G05-01, Revision # 6, February 2014 (no.: G05-01).
3. Manual of NATO Safety Principles. Reference of decision for release: AC/326-N(2007)0001-AS1 05-09-2007.
4. Kummer, Peter O. Debris Hazard from Accidental Explosions in Underground storage facilities: A Case Study on Modeling of Debris throw (Chapter 26).
5. STEC Pamphlet No. 3: Construction of Building and Traverses for Military Explosives Storage & Transport of Explosives Committee 2011, Centre for Fire, Explosives & Environment Safety, Brig S K Mazumdar Road, Delhi-110054.
6. JSP 482 Edition 4, Explosives Regulations: Buildings Associated with Military Explosives (Chapter 6), Ministry of Defence, Published by DSEA-DOSR-Policy, Part of Defence Safety and Environment Authority, Bristol, UK. Jan 2013.
7. International Ammunition Technical Guideline, IATG 05.20, Types of Buildings for Explosive Facilities. Second Edition 2015-02-01.
8. STEC Pamphlet No. 21: Design and Construction Manual for Blast Resistant Structures using Laced Reinforced Concrete. Storage & Transport of Explosives Committee 2011, Centre for Fire, Explosives & Environment Safety, Delhi.
9. TM 5-1300/ NAVFAC P-397/ AFR 88-22, Department of the Army, the Navy and the Air Force November 1990.
10. Unified Facility Criteria: Structures to resist the effects of accidental explosions: 3-340-02, 5 December 2008.
11. Chen, Lang; Chen, Wang; Fenz, Chang-gen; Fenj, L.U.; Jian-ying, L.U.; Xiao-feng, Wang & Guo, Xin. Study on random initiation phenomenon for sympathetic detonation of explosive. *Sci. Direct, Def. Technol.*, 2013, 9(4), 224- 228. doi: 10.1016/j.dt.2013.12.002
12. Lofquist, Carl. Response of buildings exposed to blast load. Division of Structural Mechanics, Lund University,

- Sweden, 2016 (ISRN LUTVDG/TVSM--16/5216--SE (1-88).
13. Cooper, Paul W. Explosive Engineering. WILEY-VCH, 424 Girard Blvd, SE, Albuquerque, NM 87106, ISBN 0-471-18636-8 Wiley VCH, Inc.
 14. Ramamurthy, K. Explosions and Explosion Safety. Tata McGraw Hill Education Private Limited, 7 West Patel Nagar, New Delhi.
 15. Ngo, T.; Mendis, P.; Gupta, A. & Ramsay, J. Blast loading and blast effects on structures. ESJE Special Issue: Loading on Structures, 2007, pp. 76-91.
 16. Demin, George & Varnitha, M.S. Structural analysis of blast resistant structures. *Int. J. Sci. Res. Develop.*, 2016, **4**(5), 1310-1316.
 17. Hrvoje, Draganic & Sigmund, Vladimir. Blast loading on structures. UDC/UDK 624.01.04.662.15
 18. Karlos, Vasilis & Solomos, George. Calculation of blast loads for application to structural components. JRC Technical Reports, 2013, doi: 10.2788/61866
 19. Design, materials and connections for blast-loaded structures. Research Report 405, ABS Consulting Ltd, Health and Safety Executive 2006.
 20. Smith, P D. Blast and ballistic loading of structures. Butterworth-Heinemann Ltd, Linacre House, Jordan Hill, Oxford OX2 8DP.
 21. Guo, Y.B.; Rao, G.F.; Jing, L. & Shim, V.P.W. Response of high strength concrete to dynamic Compressive loading. *Int. J. Impact Eng.*, 2017, **108**, 114-135. doi: 10.1016/j.ijimpeng.2017.04.015

CONTRIBUTORS

Mr Prabhanjan Thakur joined DRDO in 2004 and is presently working as Scientist 'D' at CFEES. His areas of research include design, development and validation of new types of explosive storage buildings.

He has been involved in the design of blast non-propagation wall and instrumentation during design validation blast field trial.

Mr Rajesh Mishra joined DRDO in 2008 and is presently working as Scientist "D" at CFEES. His areas of research include design, development and validation of new types of explosive storage buildings.

He has been involved in modelling and simulation of the structure and instrumentation during design validation blast field trial.

Mr R.K. Tanwar is presently working as Scientist 'G' at CFEES. His areas of research include design, development and validation of new types of explosive storage buildings and design of hardened aircraft shelter.

He has been involved as trial officer during design validation blast field trial.

Dr G.K. Mishra is presently working as Scientist 'G' at CFEES. His areas of research include design, development and validation of new types of explosive storage buildings and safety engineering works.

He has been involved in conceptual design of blast non-propagation wall and review of the structure design.

Mr Rajiv Narang is Director, CFEES since January 2017. He has been associated with various R&D projects related to design & development of innovative explosive storage structures with reduced land requirement.

He has been involved in the analysis of the trial results and review of structure design and trial instrumentation.