Defence Science Journal, Vol 47, No 2, April 1997, pp. 139-148

Design of Blast Resistant Structure

C.K. Gautam and R.C. Pathak
Research & Development Establishment (Engineers), Pune-41 015.

ABSTRACT

A shock/blast resistant structure designed, developed and experimentally evaluated by the authors is described. The structure, capable of withstanding dynamic loading (≈12 psi and a static pressure of 1.5 m earth cover) due to blast or any other explosion, also gives protection against radiation, chemical and thermal hazards. Some results and details of analysis and experimentation are presented.

1. INTRODUCTION

An extensive programme to develop and experimentally evaluate a number of shock resistant structures was undertaken by the Research & Development Estt (Engineers) (R&DE (Engrs)), Pune. The design of such structures capable of resisting shock and vibrations arising due to blast or any other explosion, is a complex and challenging task. In this paper, analytical approach and experimental analysis in respect of one such shelter are discussed.

Slawson, *et al*[1] developed an underground reinforced concrete blast shelter for 100 men to resist the air blast (peak overpressure of 50 psi) and radiation effects of 1 Mt nuclear surface detonation. The design was validated by conducting small scale static and dynamic tests. Holmes, *et al*[2]. tested an 18-man blast shelter for 200 psi peak overpressure level generated by 8 Kt high explosive detonation. The shelter was made of 10 gauge galvanised corrugated steel sheets. Study of shock spectra indicated that occupant's survivability was highly probable with little or no injuries and that the survivability of generators and communication equipment could be achieved by shock isolation.

Need was felt to indigenously develop and test an underground shelter to take care of all the effects of atomic detonation of 20 Kt at a distance of 1.5 km. This detonation will generate a pressure of 12 psi (7.5 t/m^2) on the top of the earth. However, after including the weight of 1.5 m earth cover, the shelter was designed to withstand a total pressure of 10.1 t/m^2 (7.5 t/m^2 + 2.6 t/m^2).

The shelter developed by R&DE (Engrs) is an underground structure made of light weight segments of steel sheets. These segments can be carried by man and assembled at site in a very short time (3 to 4 hours by 10 men). The shelter, which is modular in construction, is capable of meeting changing requirements (i.e. increase in length, etc). In addition to the blast effect, the shelter also prevents ingress of gas leakage/radioactive dusts.

2. GENERAL DESCRIPTION

The shelter is made for personal protection from blast, thermal and radiation effects in case of accidental explosion or war scenario. It can also be used for communication, first aid, command or control centres. The shelter can be further utilised for the storage of materials, such as food, fuel,

Received 10 June 1996, revised 20 December 1996

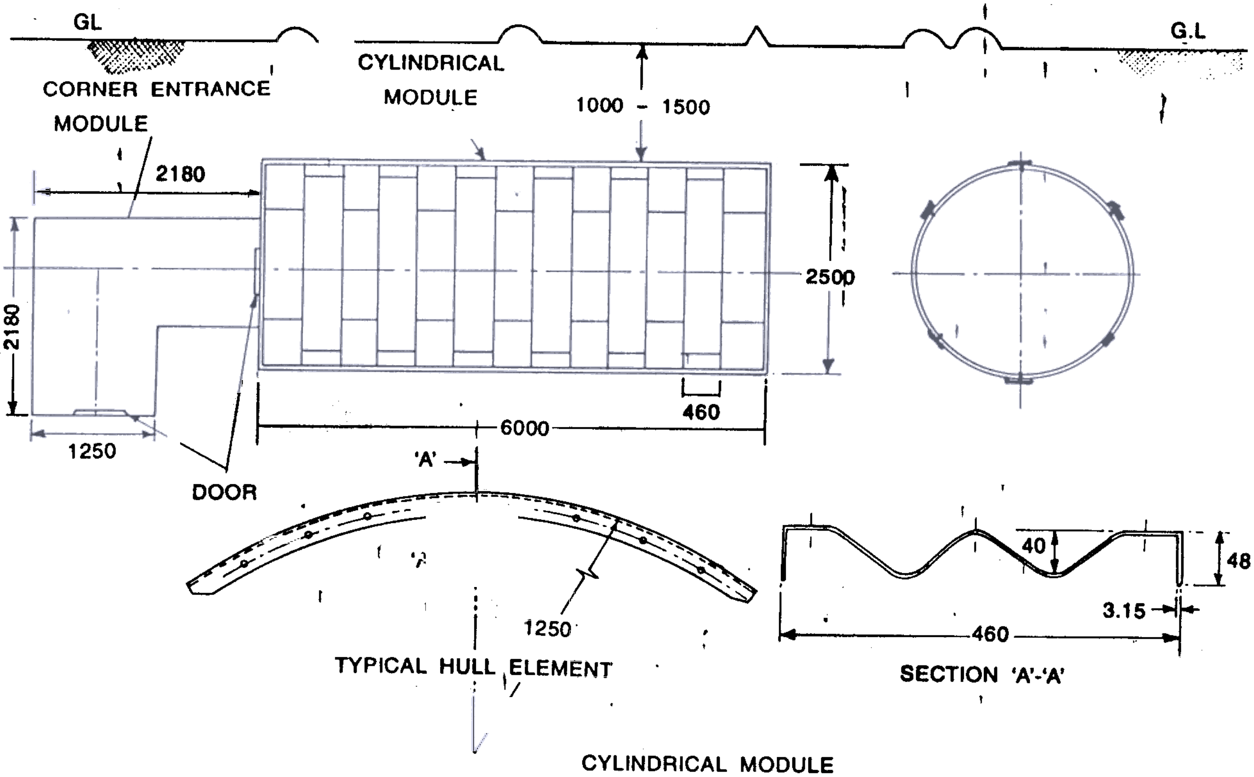


Figure 1. Cylindrical module

medical supplies, etc. It can be modified according to the actual requirement/purpose/utility. Some of the salient features of the shock/blast resistant shelter are discussed here.

2.1 Cylindrical Module

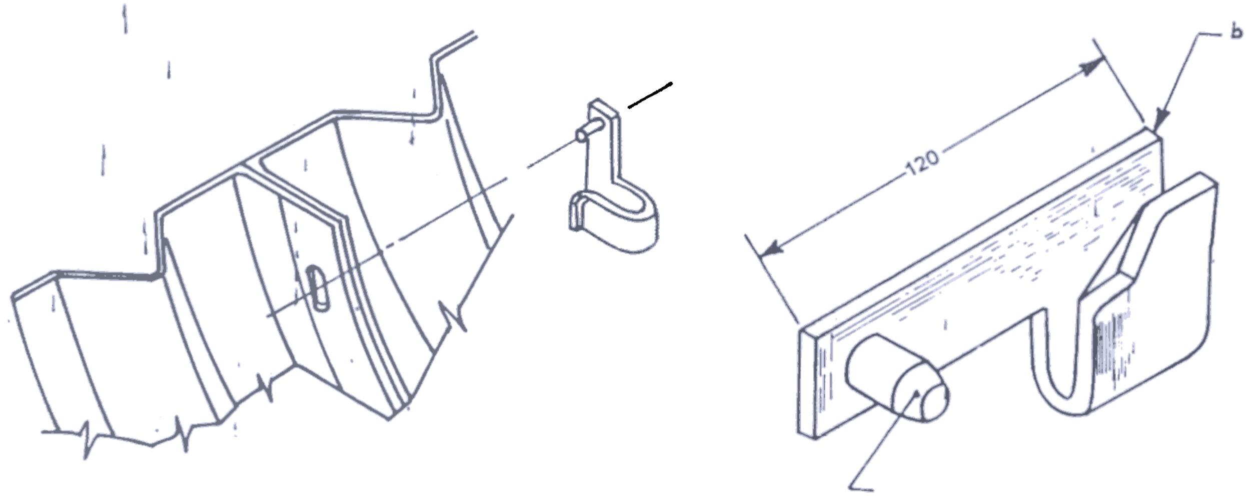
A cylindrical module of 2.5 m diameter and 6 m length made of galvanised corrugated steel sheet segments of 3.0 mm thickness has been designed and developed. Later, other materials like fiber reinforced plastic (FRP) composite, aluminium alloys, high strength low alloy (HSLA) steel will also be tried to reduce the weight and assembly time and to increase its corrosion resistance. The module is buried under a minimum earth cover of 1 m. It is designed to withstand an overpressure of 7.5 t/m^2 (12 psi) plus the overburden pressure due to 1.5 m of compacted soil having density of 1.7 t/m^3 on the circumference. The detailed dimensions of the module and one segment are shown in Fig. 1. It also has a filtration/ventilation unit which provides contamination-free air to the inhabitants of the module. This unit has a composite filter [having activated charcoal and high efficiency particulate air (HEPA) media] for cleaning the air and a blower unit for sucking the air from outside.

2.2 Corner Entrance Module

The cylindrical module is connected with a corner entrance module on one side for entry/exit. The other end of the corner entrance is having a gable end assembly along with a door. The size of the corner entrance is 1.25 m × 1.8 m (height) × 2.2 m ('L' shape). Its segments are similar to the cylindrical module, but they have smaller radius (625 mm). The gable end assembly is designed for 15 t/m^2 (23 psi) pressure. A proper 'L' type of stair is made for going up to the ground level.

2.3 Constructional Details

The shelter consists of prefabricated, galvanised steel components and is assembled with special fasteners (refer to Fig. 1(a) for type, size,



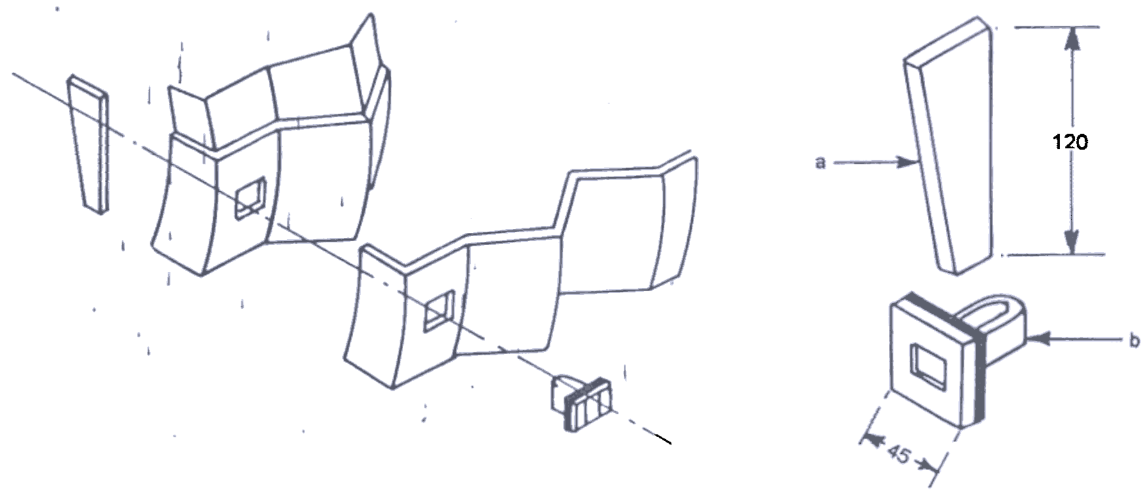


Figure 1(a). Special fasteners : (i) Pin clamp (length - 120 mm, thickness - 5 mm, material - (a) carbon steel 'C 40' as per IS-2073 (b) spring steel '45 C 8' as per IS-2507) (ii) Staple wedge (thickness - 5 mm, material - (a) carbon steel 'C 40' as per IS-2073 (b) spring steel '45 C 8' as per IS-2507).

shape and material) for quick erection by unskilled persons. The components are transportable in a vehicle and are also man-portable. Six curved segments (460 mm wide) with flanges on both sides and joggling at one end are joined together by fasteners to form a hoop. Thirteen such hoops are joined at flanges by pin clamps to form a cylindrical module about 6 m long. Front and back walls are fitted to the cylindrical module. The front wall also has a door. The corner entrance module is assembled in the same way. However, in this module, hair pin shape is formed by joining floor plate, vertical plate and one circular segment. Each joint of the shelter is sealed with rubber gaskets and flash strips to make it completely air leak-proof.

3. ANALYTICAL APPROACH

These modules were designed using finite element solution technique. In finite element idealization[3], two basic element types are

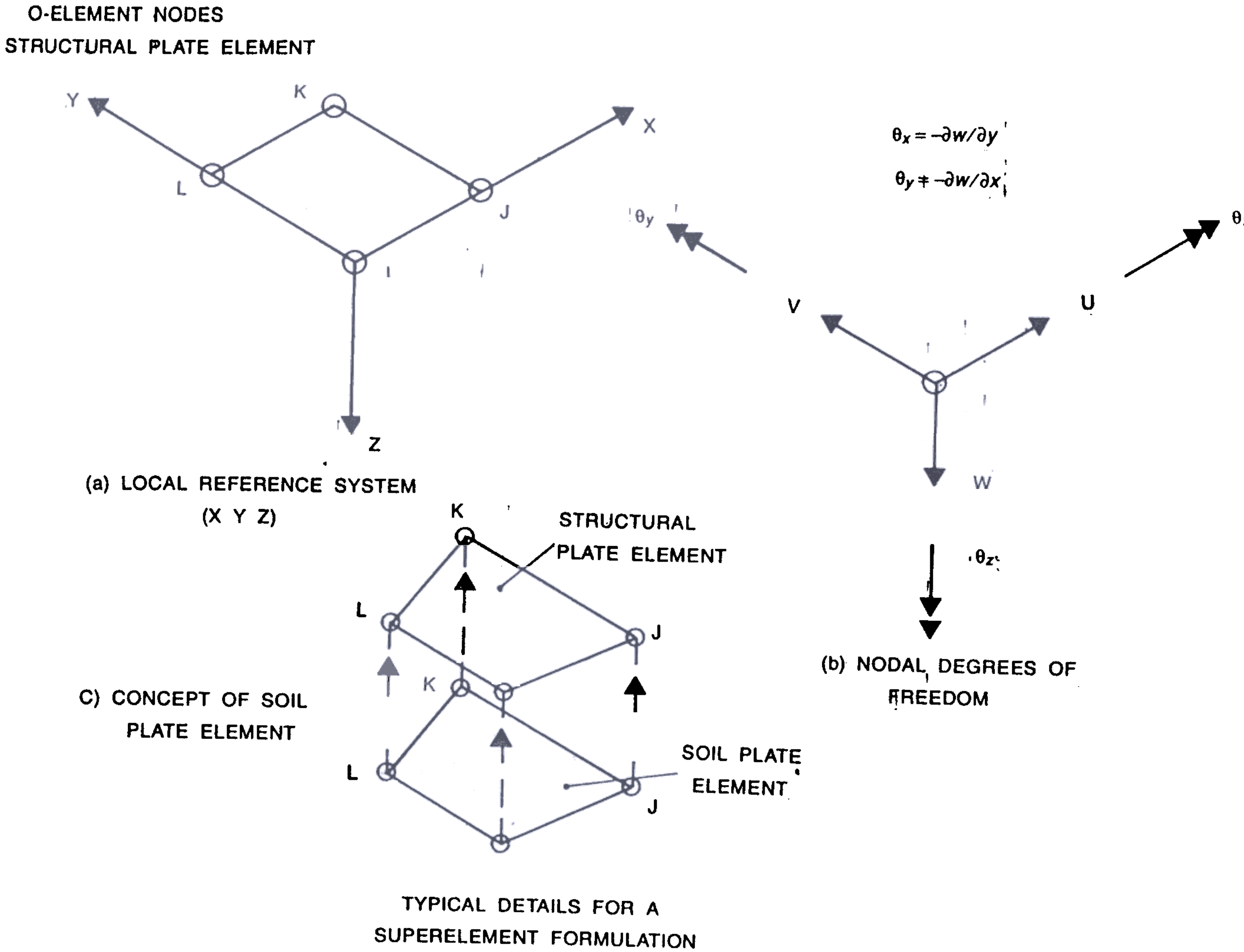


Figure 2. Typical details for a superelement formulation

employed: (a) structural plate elements to represent shelter body, and (b) compatible soil plate elements for simulating the soil continuum, in which the shelter body is buried. These elements have the following characteristics :

3.1 Structural Plate Element

The structural plate element is a flat plate-shell element. Its stiffness characteristics are derived through superpositioning of the characteristics arising from membrane, flexural and torsional actions. The element is referred to as local (x, y, z) reference system wherein meridional plane of the plate is confined to (x, y) plane and z axis is normal to the plane. A typical structural plate element details is shown in Fig. 2(a). Each node of the element has six degrees of freedom, as shown in Fig. 2(b). These are :

(a) Translations u, v, w in x, y, z directions, respectively, and

(b) Rotations $\theta_x, \theta_y, \theta_z$ around x, y, z axes, respectively.

3.2 Soil Plate Element

The soil plate element represents the additional stiffness derived by the structural plate element by virtue of the support offered by the soil continuum. This aspect is shown in Fig. 2(c). The soil plate element has its stiffness characteristics, governed by a set of subgrade moduli: (a) normal

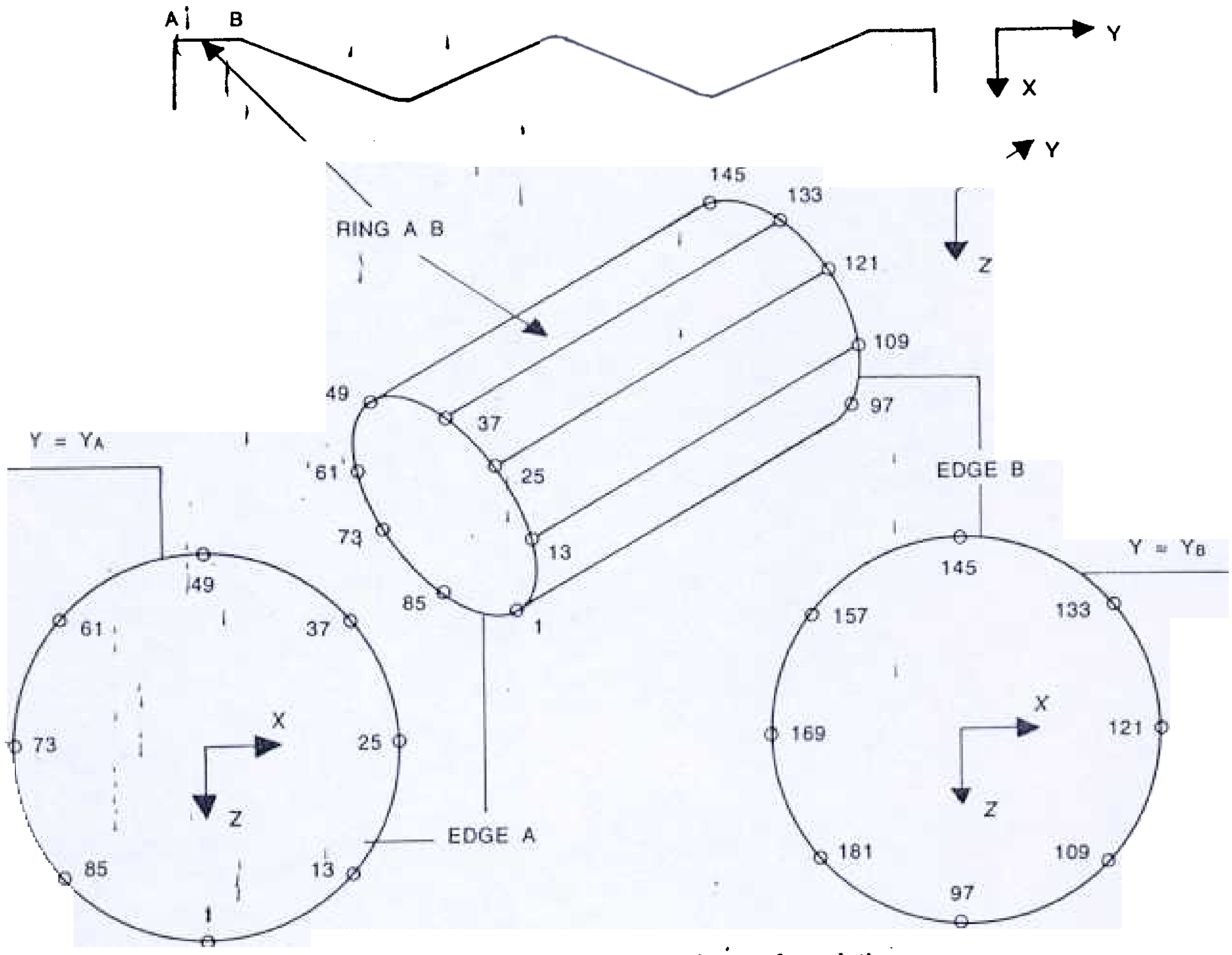


Figure 3. Typical details for a superelement formulation

subgrade modulus - Kn, (b) shear subgrade modulus - Ks and (c) torsional subgrade modulus - Kt. The details governing stiffness characteristics of the structural plate element and the compatible soil plate element are presented in Table 1.

3.3 Discretization of Structure

A ring 'AB' (Fig. 3) which is the segment of a corrugated sheet of cylindrical module is considered. For providing a mesh of enough degree of fineness, the ring is divided into 96 segments of equal size. The idealised ring, therefore, comprises an assembly of 96, four-noded elements, interconnected through 192 nodes. Further, the group of 96 four-noded elements is transformed into a 16-noded super-element. The super-element nodes, shown by thickened dots, are referred to as master nodes. Repeated application of the concept of super-elements leads to the development of various sub-structures. For a cylindrical module

Table 1. Stiffness characteristics

Mode of deformation	Active nodal D.O.M.	Variation of D.O.M. with respect to (x, y)	Active subgrade modulus	Values of subgrades (t/m^2)
Membrane action	u and v	Linear variation of u and v	Ks	0.132
Flexural action	(w, θ_x, θ_y) & $\theta x = (-\partial w/\partial y)$ & $\theta y = (\partial w/\partial x)$	Cubic variation of ω	Kn	0.196
Torsional action		Linear variation of θ_z	Kt	0.098

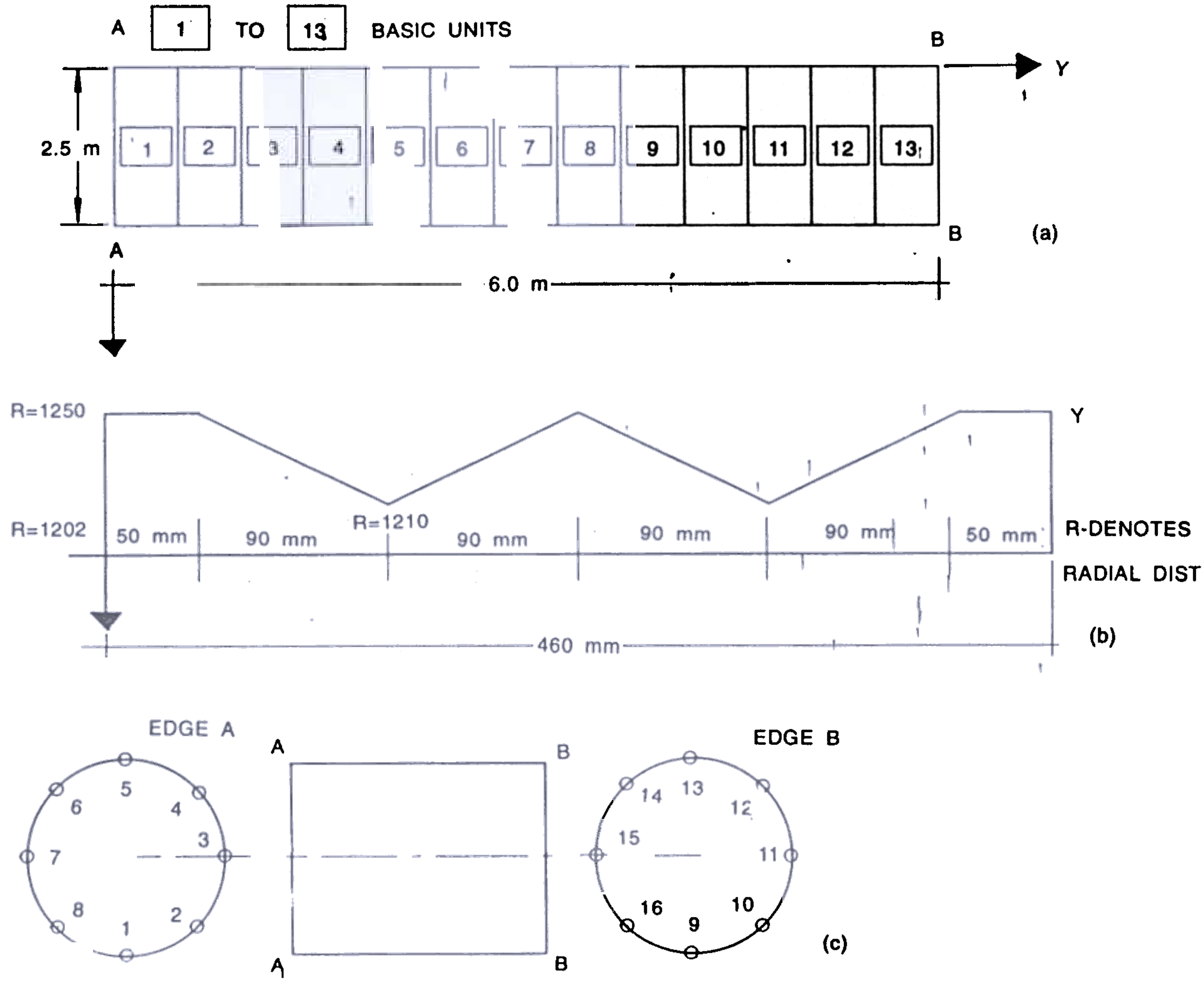


Figure 4. Typical details for substructural formulation (a) Composition of main module, (b) Part section through a basic unit of master nodes defining substructural element, (c) Substructural element representing main module.

composed of 13 basic units, the details of the finally developed 16-noded element representing the sub-structural unit are shown in Fig. 4.

3.4 Results of Analysis

With the help of two normal stresses (S_1 - in axial direction and S_2 - in circumferential direction) and one shear stress (S_3) and employing Von Mises failure criteria[4], S_E. The equivalent uniaxial stress is calculated as follows :

$$S_E = (S_1^2 + S_2^2 - S_1 S_2 + 3S_3^2)^{1/2}$$

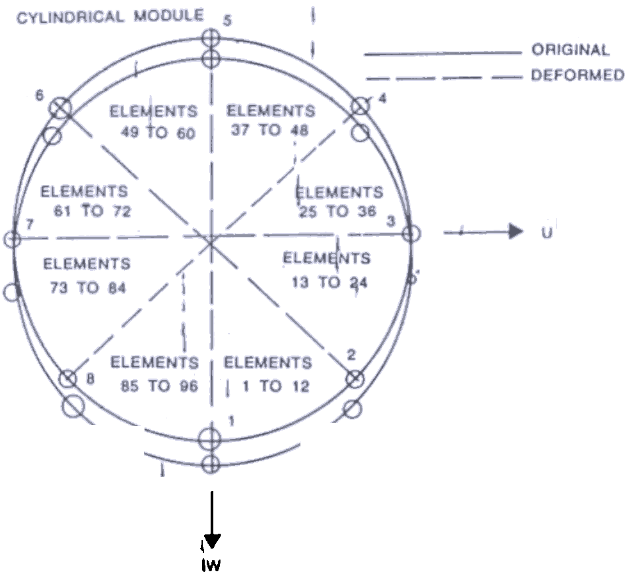
The parameter FACTOR representing safety factor is given by

$$\text{FACTOR} = S_E / f_y$$

where

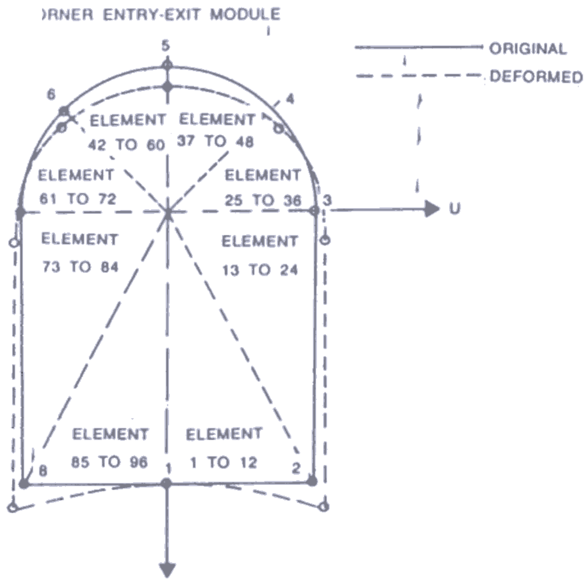
f_y is the permissible stress. Yield stress as per IS: 226/IS: 1079 (structural steel which has been used) is 250 N/m^2. However, a safety factor of 1.25 has been taken and the value of f_y has been restricted to 200 N/m^2.

The deflected shapes with the displacement values in u and w directions (i.e. along the radial and vertical downward directions) for cylindrical module, corner entrance module and gable end are shown in Figs 5, 6 and 7, respectively. The deflections and stresses are found to be reasonable from the design safety point of view. Safety



NODE	u (mm)	W (mm)
1	0.18	19.9
[redacted]	2.24	34.9
	31.30	66.60
	25.30	92.10
	1.56	118.00
	18.50	87.00
	27.20	59.40
	3.77	36.40

Figure 5. Structural deformations for cylindrical module (a) Overburden of - 1.5 m, (b) Overpressure - 12 psi, (c) Max vertical deflection at node 5 - 118 mm.



NODE	u (mm)	W (mm)
1	0.0	0.0
2	2.36	60.30
3	9.11	60.30
4	2.89	63.20
5	0.0	70.10
6	- 2.96	63.30
7	- 9.15	60.40
8	2.39	60.40

Figure 6. Structural deformations for corner entry-exit module (a) Overburden of - 1.5 m, (b) Overpressure - 12 psi, (c) Max vertical deflection at node 5 - 70.1 mm.

FACTORS by Von Mises failure criteria for each element were calculated. Values of the FACTORS are less than 1, which shows safety of the design.

4. EXPERIMENTAL ANALYSIS

The experimental testing were carried out on the completed shelter (cylindrical and corner entrance modules) while it was buried under 1.5 m earth cover.

4.1 Blast Testing

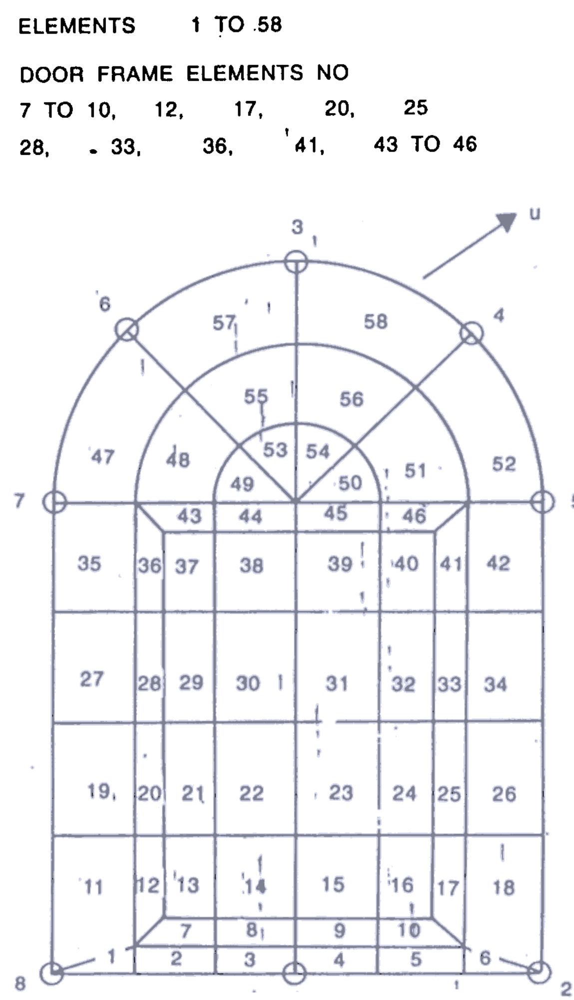
The blast testing on the shelter was done for a designed circular pressure of 7.5 t/m^2 (12 psi) on earth covered parts and a longitudinal pressure of 15 t/m^2 (23 psi) on non-covered gable end of the entrance module. Blast testing was done under simulated conditions by exploding a trinitrotoluene (TNT) cylindrical charge. Pressure gauges were kept at various places to monitor the blast pressure. Free air blast trials were conducted at pre-determined standoffs from the buried shelter. Strain gauges were fixed to record strains in circumferential and meridional directions. Locations of charges and other aspects of trials are given in Fig. 8. Some details of blast trials are given in Table 2. Blast trials were carried out for higher charge (more than 10 kg) for underground shelters of other shapes and sizes, which are not included in the scope of this shelter. The shelter withstood design pressure.

4.2 Radiation Test

The shelter buried under 1.5 m of earth cover was tested for protection factor against radiation effect by using a radioactive source *Cs*-137 emitting gamma rays. The protection factor was found to be 300 for gamma radiation. This protection factor was achieved due to the earth cover of 1.5 m. The protection factor due to the steel sheet of 3 mm thickness is negligible. Earth cover of 0.66 m has a protection factor of 10 (tenth value thickness)[5]. The expected radiation intensity (designed value) over the shelter is 290 rad. After passing through the earth cover, less than 1 rad of radiation will reach inside the shelter. This is a very safe value. Biological effects on humans resulting from exposure to radiation has negligible effects if dose is less than 50 rad.

Table 2. Blast testing of the shelter

	Trial 1	Trial 2
Position of charge	Charge above the centre of the buried shelter	Charge on non-covered portion of the shelter
Weight of cylindrical charge (TNT)	10 kg	10 kg
Charge position	In free air	In free air
Distance	3.5 m from the earth cover	5 m from centre of entrance
Max. strain recorded	291.8 μ strain circumferential, 250 μ strain meridional	Not recorded
Pressure recorded	11.1 psi* at the centre of the shelter	23 psi at the centre of entry
Observations	(i) No perceptible damage. (ii) Only a few fasteners and floor blocks became loose	



NODE	μ(mm)
1	7.35
2	71.90
3	31.30
4	6.79
5	15.40
6	14.70
7	29.30
8	51.30

Figure 7. Idealisation and response details for end gate (a) Applied pressure perpendicular to the door-23 psi, (b) Max deflection normal to the door at node 2: 71.9 mm.

4.3 Smoke Test

The underground shelter consisting of cylindrical and corner entrance modules was made

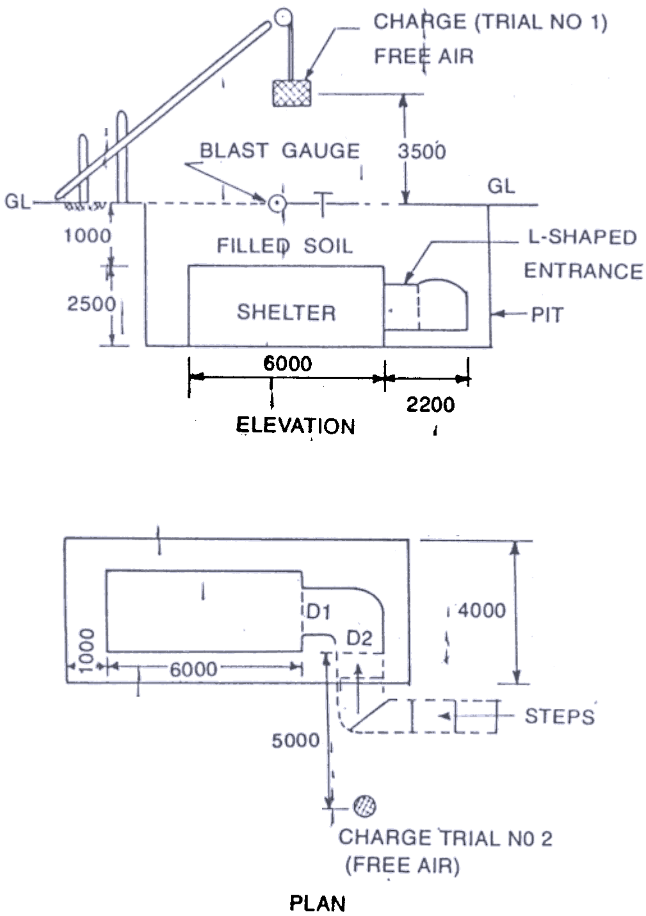


Figure 8. Location of charges for different trials D1, D2 doors

leak-proof by using rubber gaskets, flash strips and polyethylene sheets. An overpressure of 12 mm water gauge was developed with the help of a filtration/ventilation unit. Tear gas shells were burst in the inlet of the ventilation system and passed through the filter unit and then air was checked for its harmful effects in the shelter. No smoke or tear gas effect was observed in the shelter.

5. DISCUSSION

The blast structure developed can be used for different types of disaster management. The cylindrical module alongwith hair pin module (corner entrance) so developed can be used near nuclear power plants or chemical industries, so that in emergency, persons can easily protect themselves by taking shelter inside the module. The module, which has been experimentally tested, gives protection against shock, radiation and chemical agents.

6. CONCLUSIONS

(a) The cylindrical module as well as corner entrance module are safe against design pressures of 12 psi and 23 psi, respectively.

(b) The shelter can be used against shock, gas leakage, chemical or radioactive hazards.

(c) It can be used for personal protection, storage of fuel, food, medical supplies and communication and control centres, etc., in contaminated environment or during war scenario.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the guidance and encouragement given by the Director, Shri M.R. Joshi, R & DE (Engrs), Pune.

REFERENCES

1 Slawson, T. R. & Davis, J.L. Behaviour of a reinforced concrete blast shelter in an overload environment. 59th Shock and Vibration Symposium, Vol 3, USA, 1988. pp. 231-42.

2. Homes, R. L.; Woodson, S.C. & Slawson, T. R. Shelter response in a simulated eight Kt nuclear blast environment. 59th Shock and Vibration Symposium, Vol 3, USA, 1988. pp. 243-57.

3. Cook, R.D. Concepts and application of finite element analysis. John Wiley, New York, 1974. pp. 10-150.

4. Timoshenko, S. Strength of materials. Vol. 2, Advanced theory and problems, Part -II. CBS Publishers and Distributors, New Delhi, 1986. pp. 258-558.

5. Ormerod, R. N. Nuclear shelters A guide to design. The Architectural Press Ltd, London, 1983. pp. 52-119.

Mr CK Gautam received his BE (Civil Engg) in 1985 from Regional Engineering College, Kurukshetra and MTech (Material Science) in 1995 from Indian Institute of Technology, Bombay. At SASE, Manali, he worked in the design and development of many avalanche control structures on various axes in northern India. Currently, he is working as Scientist C at R&DE (Engrs), Pune, where he is mainly involved in research on blast resistant structures.

Col (Dr) RC Pathak obtained his BSc (Civil Engg) in 1956 from Birla Institute of Technology, Ranchi, MTech and PhD in Geotechnical Engineering in 1984 and 1988, respectively from Indian Institute of Technology, Delhi. The areas of his specialisation are geotechnical engineering, blast-proof structures and cold region engineering. He also participated in one of the Indian Antarctica Expeditions. He has published more than 57 research papers in national/international journals and also attended many conferences/seminars in India and abroad. Currently, he is heading Field and Cold Region Engineering Group at the Research & Development Establishment (Engineers) (R&DE (Engrs)), Pune.