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# Analytical and Experimental Evaluation of a Buried Shelter

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**ABSTRACT**

The design, analysis, and testing of a buried circular cylindrical shelter has been described in this paper. This shelter may be used for personnel protection in emergency situations like accidental blast, terrorist attack, etc. Various criteria have been used for designing and analysing the shelter. The shelter has been analysed using a software package called ANSYS for finding out the stresses, deflections, buckling load factors, and buckled mode shapes. The shelter was buried under earthcover (1.5 m) and tested for the required loading.

**Keywords:** Buried shelter, soil-structure interaction, elastic foundation stiffness, modulus of subgrade reaction, buckling analysis

## 1. INTRODUCTION

A buried circular cylindrical shelter of corrugated steel sheets (Fig.1) (thickness: 3.15 mm, width: 460.00 mm, radius of curvature: 1250.00 mm, area of x-section: 3.04 $mm^2$ per millimeter of length, moment of inertia: 1238.57 $mm^4$ per millimeter of length) was developed by the Research & Development Establishment (Engrs), Pune. This shelter had outer diameter: 2.5 m and length: 6.0 m. The total length of the shelter was made by adding 13 circular rings. Each circular ring was having six corrugated curved segments along the circumference. These circular rings and corrugated curved segments were connected by the special fasteners. This type of arrangement is amenable for quick assembly / erection and dismantling of the shelter and manual portability of each component/segment (the maximum weight of the component is approx. 21 kg).

The line diagrams of the buried shelter and corrugated curved segment with dimensions are shown in Fig. 2.

The circular cylindrical shelter has been designed to withstand a pressure of 25 kPa due to the earthcover (1.50 m) and the surcharge pressure (external pressure) of 50 kPa on the upper surface of the earthcover. The main structural consideration in the design of this buried shelter is the ability to support both the loads. Other important items like the type of joints and protection against the environmental exposure have not been discussed in this study.

## 2. DESIGN OF SHELTER

A buried cylindrical steel shelter is a composite structure made up of steel rings and the soil envelop. Both elements played a vital role in the design of this type of structure. This shelter is made up of thin steel sheets, which may undergo large deformation. It has a large supporting capacity from the arching under passive pressure of the surrounding soil. However, the evaluation of the contribution of the soil to wall strength is difficult due to the different

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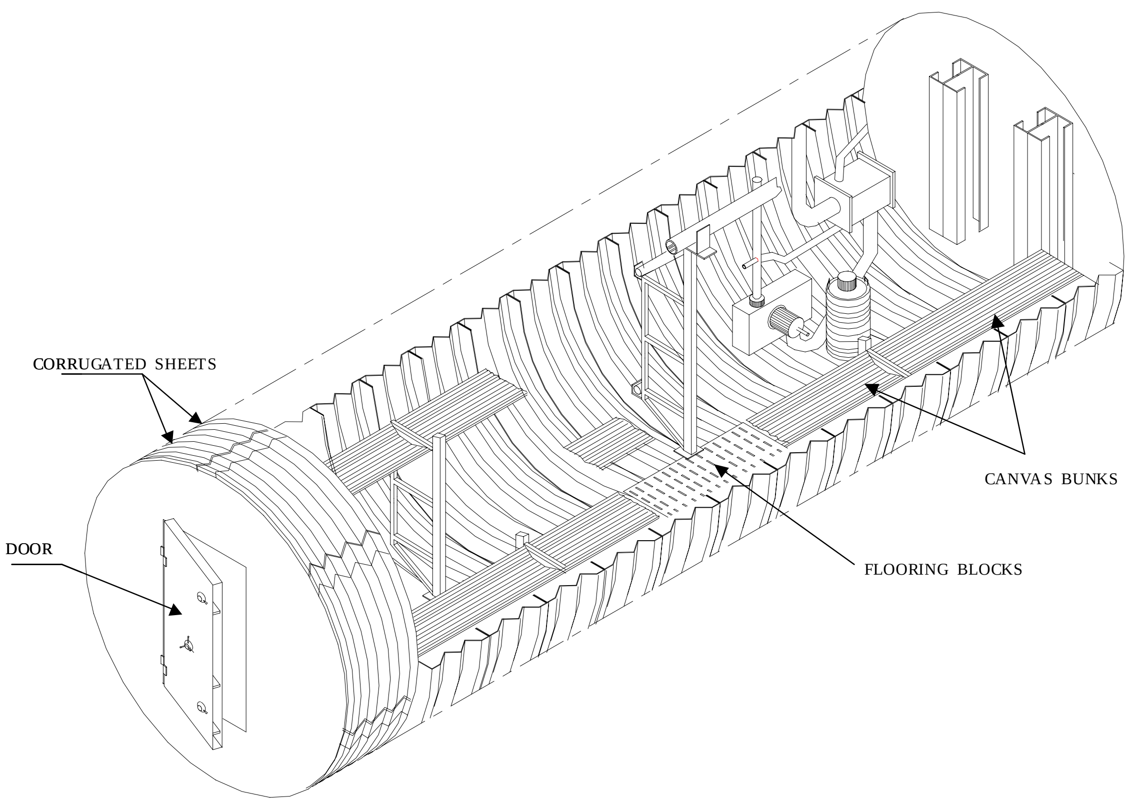



**Figure 1. Buried shelter.**

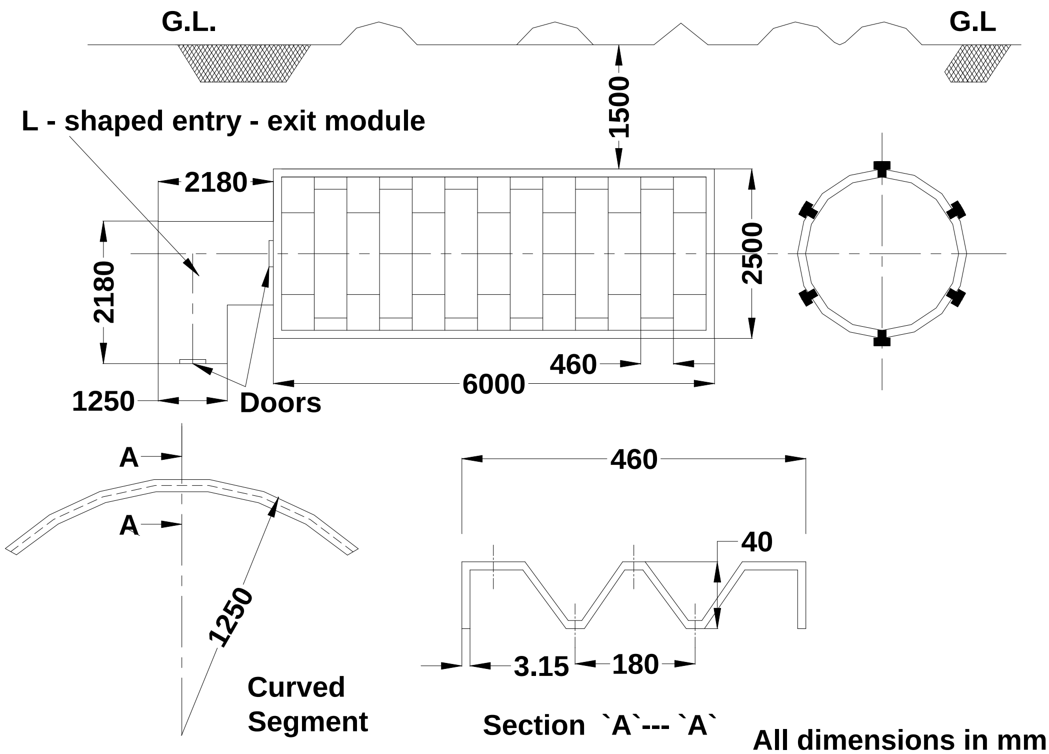



**Figure 2. Line diagrams of buried shelter and corrugated curved segment.**

conditions of shelter installation, type of soil, compaction achieved in the soil, etc. A balance between the conservatism with economic considerations has been kept for optimum design. Corrugated steel sheets have been used due to their more flexural strength per unit weight of material than the plain steel sheets.

The structural capacity of flexible shelter or thin-walled steel shelter has been evaluated on the basis of resistance to buckling and vertical diametrical deflection under load[1]. Additionally, a non-structural requirement in the form of minimum stiffness was also imposed to ensure that the shelter is not damaged during transportation and handling[2].

## 2.1 Strength-based Design

If a thin-walled circular tube of infinite length is surrounded by a well-compacted medium with elastic properties and is subjected to uniform radial pressure as shown in Fig. 3(a), the membrane compressive stress is found from the following formula[3]

$$\sigma_c = \frac{PD}{2A} \quad \text{or} \quad A = \frac{PD}{2\sigma_c} \tag{1}$$

where $P$ is the total uniform pressure on the shelter = 75 kPa, $D$ is the diameter of the shelter = 2.5 m, $\sigma_c$ is the permissible compressive stress of mild steel = $\sigma_y$ / N, $\sigma_y$ is the compressive stress of mild steel = 250 MPa (yield strength of material), and $N$ is the factor of safety (taken 3 as shelter will be used for human habitation[4]).

This factor of safety will also consider the imperfection, loss of contact of soil with the wall of the pipe and other uncertainties, and $A$ is the required cross-sectional area per unit length.

Substituting these values in Eqn (1), one has:

Required area = $1.125 \times 10^{-4}$ m$^2$/m of length
= 1.125 mm$^2$/mm of length

Provided area = 3.04 mm$^2$/mm of length.

## 2.2 Critical-buckling Pressure

In the above equation, the upper limit of the value $\sigma_c$ was considered which yielded thin wall in compression due to material failure. This is usually reached only at very low values of $D/t$. When $D/t$ has a high value (as in this case), it is necessary to calculate the elastic critical radial pressure $p_{cr}$ to cause the buckling of the wall.

### 2.2.1 *Critical-buckling Pressure without Considering Soil*

For a thin-walled long tube, the elastic critical radial pressure ($p_{cr}$) can be calculated by the following equation[5]:

$$P_{cr} = \frac{(n^2 - 1)\, EI}{(1 - \nu^2)\, R^3} \tag{2}$$

where where $n \geq 2$ and $n$ is the number of full waves formed around the circumference at buckling.

A thin-walled long tube under uniform radial pressure, but not supported in an elastic medium, will buckle into an oval shape with $n = 2$, so that Eqn (2) becomes[5]:

$$P_{cr} = \frac{3EI}{(1 - \nu^2)\, R^3} \tag{3}$$

where $E$ is the Young's modulus of elasticity of steel = 210 GPa, $I$ is the second moment of area = 1238.57 X $10^{-9}$ $m^4$ per meter, $R$ is the radius of the shelter = 1.25 m, $n$ is the Poisson's ratio of mild steel = 0.3, and $p_{cr}$ is equal to 439.02 kPa.

Allowable critical radial pressure without considering soil

$= p_{cr} / N = 219.51$ kPa > 75 kPa

Since, the allowable critical radial pressure is more than the applied pressure on the shelter, the shelter is safe in buckling. This critical radial pressure is calculated without considering the soil–structure interaction.

### 2.2.2 *Critical-Buckling Pressure Considering Soil–structure Interaction*

The soil provided the elastic radial support when the effect of a soil medium is considered on critical radial pressure[6] [Fig.3 (b)].

$$P_{cr} = (n^2 - 1)\frac{EI}{R^3} + \frac{K_z R}{(n^2 - 1)} \quad \text{when } n \geq 2 \tag{4}$$

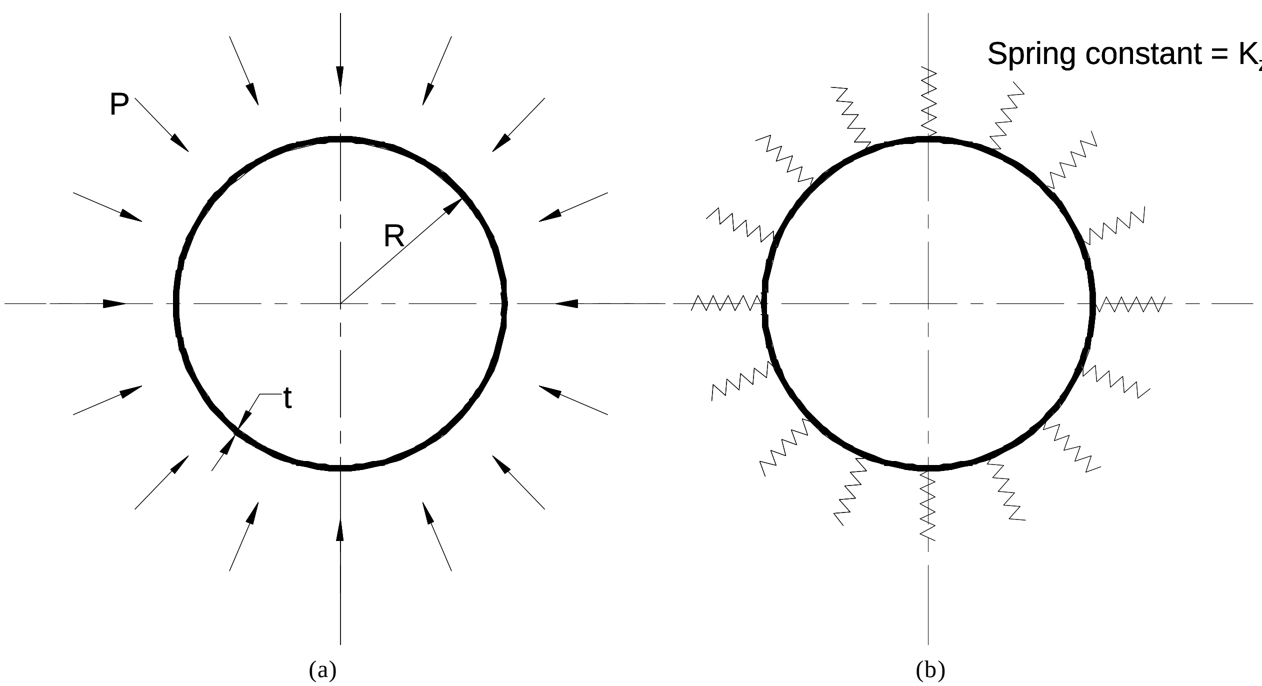



**Figure 3. Thin-walled circular tube in an elastic medium having: (a) elastic properties subjected to radial pressure, and (b) effect of the soil medium considered on critical radial pressure.**

where the buckling mode in terms of numbers of full circumferential waves are given by

$$n = [\ 1 + (\ k_z R^4 \ /\ EI\ )^{1/2}\ ]^{1/2} \qquad (5)$$

Here, $k_z$ is the spring constant (in units of pressure per unit radial deflection). If the strain in the surrounding soil is equal to the radial deflection divided by the tube radius, then

$$K_z = E_S \ /\ R \qquad (6)$$

where, $E_S$ is the soil modulus obtained from the Triaxial test. Substituting Eqns (5) and (6) in Eqn (4) and solving

$$p_{cr} = 2\ (E_S\ EI\ /\ R^3\ )^{1/2} \qquad (7)$$

Substituting $E_S$ = $10^4$ kPa (as suggested by US Federal Highway Administration), and other values

$$p_{cr} = 2307.99 \text{ kPa}$$

Allowable elastic critical radial pressure considering soil-structure interaction = $p_{cr}/N$ = 769.33 kPa > 75 kPa

Allowable elastic critical radial pressure to cause buckling further increase when the soil–structure interaction is considered.

### 2.3 Minimum Stiffness for Transportation and Handling

Design procedure requires minimum stiffness in the wall of shelter for transportation & handling. This stiffness is calculated by the flexibility factor. A flexibility factor[1] as defined by ASTM 796 is given below:

$$\text{Flexibility factor} = \frac{D^2}{EI} \qquad (8)$$

Substituting the values, one gets:

Flexibility factor = 0.024 mm/N

ASTM 796[1] has mentioned flexibility factors for different types of pipes and installations (like trench or embankment type). These values vary from 0.0315 mm/N to 0.342 mm/N. Since, 0.024 mm/N is less than the lowest value (0.0315 mm/N), this shelter can be used for different types of conditions.

### 2.4 Deflection Analysis

The deflection of the thin-walled structure was determined by the modified Spangler formula (given in American Water Works Association's Manual[2], M-11).

$$\Delta y = T_f \left( \frac{K\, W_c R^3}{EI + 0.061\, E_s\, f_d\, R^3} \right) \qquad (9)$$

where $f_d$ is the design factor = 0.5 (for conservative design), $W_c$ is the vertical load per unit length of pipe = $2PR$ =187.5 kN/m, $T_f$ is the deflection lag factor =1.5 (this factor accounts for long-term deflection as a result of consolidation or settlement of backfill material), and $K$ is the bedding constant = 0.1

Substituting these values in the above equation, one has:

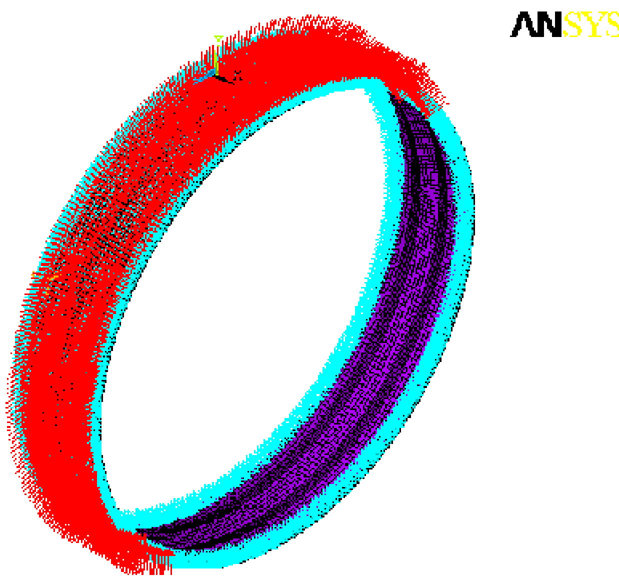
$$\Delta y = 62 \text{ mm}$$

The calculated deflection is approximately 2.48 per cent of the diameter. This is less than 5 per cent of the diameter. This limit is specified by the American Water Works Association's Manual, M–11[2] for the flexible pipe.

## 3. ANALYSIS OF SHELTER

The same shelter was analysed on the software package called ANSYS[7]. Only one ring of the shelter width (460 mm) was taken for the analysis. The ring was restrained laterally (in X - direction), ie, displacement at all nodes were re strained all around the flanges. Uniform pressure (75 kPa) was applied on the outer surface of the ring (except flanges). Finite element model and model with loading and boundary conditions are shown in Fig. 4. One node is restrained for all degree of freedoms to prevent rigid body motion. Four-noded isoparametric shell elements were used for making the finite-element model and the element size was limited to 25 mm. The following properties of material (mild steel) were taken for the analysis:


(a)




(b)

**Figure 4. Analysis of shelter: (a) Finite element model, and (b) loading and boundary conditions.**

* Young's modulus of elasticity = 210 GPa

* Poisson's ratio = 0.3

The soil is represented by the springs and the value of spring stiffness is given as elastic foundation stiffness (EFS) or the modulus of subgrade reaction of the soil. The EFS or the modulus of subgrade reaction is defined as the pressure required to produce a unit normal deflection of the foundation, ($N/mm^2$ per millimeter, ie, $N/mm^3$). Four values of the EFS as given in Table 1, are considered for the analysis.

Two types of analyses were carried out. These are: (a) static analysis to find out the stresses and deflections at various points and (b) buckling analysis for the buckling load factors (this is the ratio of the load at which buckling occurs to the load applied on the structure). Buckling analysis is used to determine the buckling loads, ie, critical loads at which a structure became unstable and buckled mode shapes, ie, the characteristic shapes associated with a structure's buckled response. However, this buckling analysis predicts the theoretical strength of an ideal elastic structure without considering imperfections and nonlinearities.

**Table 1. Values of elastic foundation stiffness for different types of soils**

| Type of soils | Bearing capacity of soil ($N/mm^2$) | Elastic foundation stiffness ($N/mm^3$) |
|---|---|---|
| Without soil | 0 | 0 |
| Weak soils | 0.1–0.2 | $2\text{-}4 \times 10^{-2}$ |
| Medium soils | 0.3–0.4 | $5\text{-}6 \times 10^{-2}$ |
| Strong soils | $\geq 0.5$ | $\geq 7 \times 10^{-2}$ |

Both the analyses were carried out for four values of elastic foundation stiffness mentioned above. Buckling load factors were found out for the first four modes. The stress plots of ring for four values of the EFS are shown in Figs 5 and 6. The first buckled mode shapes for the four values of the EFS are shown in Figs 7 and 8. Values of maximum stresses, deflections and buckling load factors are reproduced in Table 2.

## 4. EXPERIMENTAL VERIFICATION OF SHELTER

The cylindrical shelter was tested for designed pressure after puting it under earthcover (1.5 m). Figure 9 shows the circular shelter being kept in the pit. The pit was later covered with the earth.

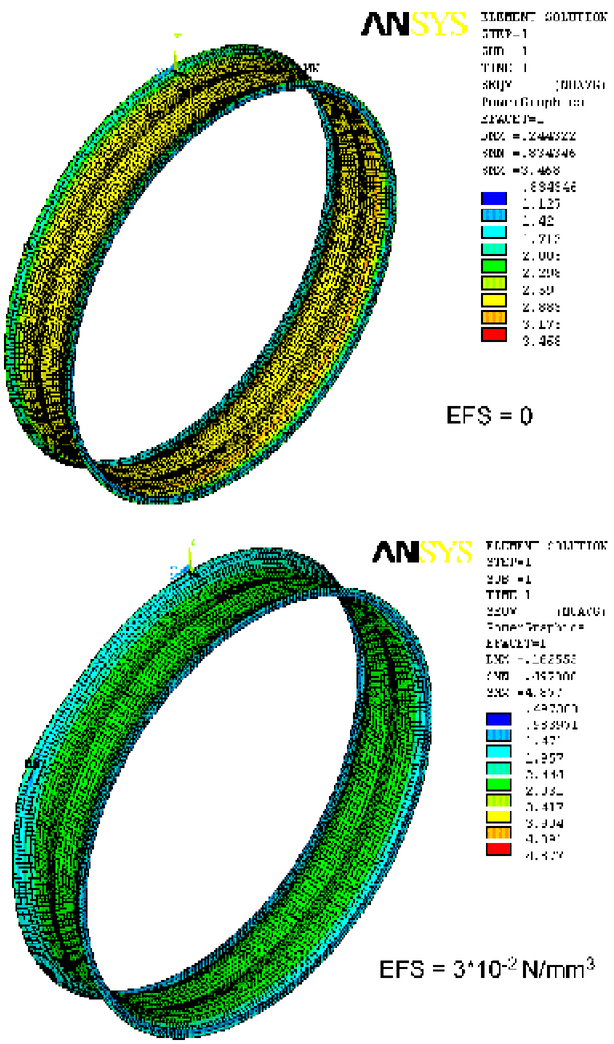



**Figure 5. Stress plots.**

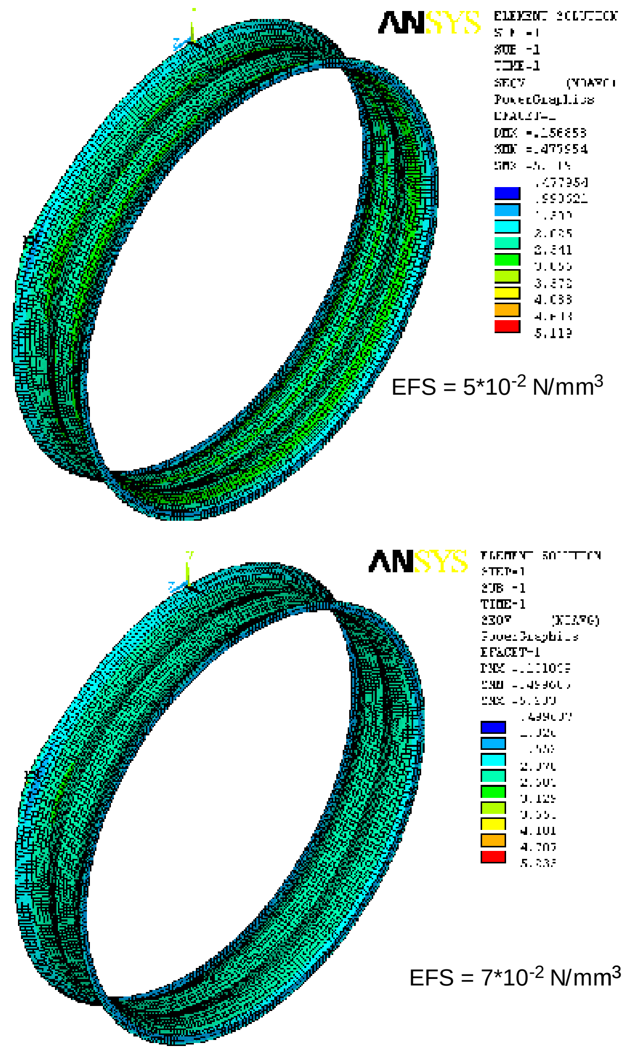



**Figure 6. Stress plots.**

Inside the shelter, strain gauges (Fig.10) and linear voltage differential transformer (LVDTs) were mounted to find out the strains in the circumferential and longitudinal directions and diametrical deflection, respectively. A shock load (50 kPa) was generated on the upper surface of earth. The values of peak strains recorded during testing in circumferential and longitudinal directions were 291.8 microstrain and 250 microstrain, respectively due to surcharge pressure only. These values corresponded to 61.28 MPa and 52.5 MPa in circumferential and longitudinal directions. These strain gauges were placed at the centre and inside top of the shelter. The strains and stresses produced due to surcharge pressure were within the elastic limit of the material (ie, mild steel). The values recorded by LVDTs showed that the central deflection is insignificant. This shows that shelter can easily carry the designed pressure and also has lot of safety margin.

**Table 2. Values of maximum stresses, deflections and buckling load factors of thin corrugated mild steel ring buried under different types of soil conditions**

| Elastic foundation stiffness | Max stress | Max deflection | Buckling load factors | | | |
|---|---|---|---|---|---|---|
| (N/mm$^3$) | (kg/mm$^2$) | (mm) | 1 | 2 | 3 | 4 |
| 0 | 3.47 | 0.244 | 3.64 | 3.65 | 8.09 | 8.10 |
| $3\times10^{-2}$ | 4.88 | 0.162 | 32.19 | 32.19 | 32.56 | 32.56 |
| $5\times10^{-2}$ | 5.12 | 0.157 | 33.49 | 33.49 | 33.96 | 33.96 |
| $7\times10^{-2}$ | 5.23 | 0.151 | 32.82 | 32.82 | 35.37 | 35.37 |

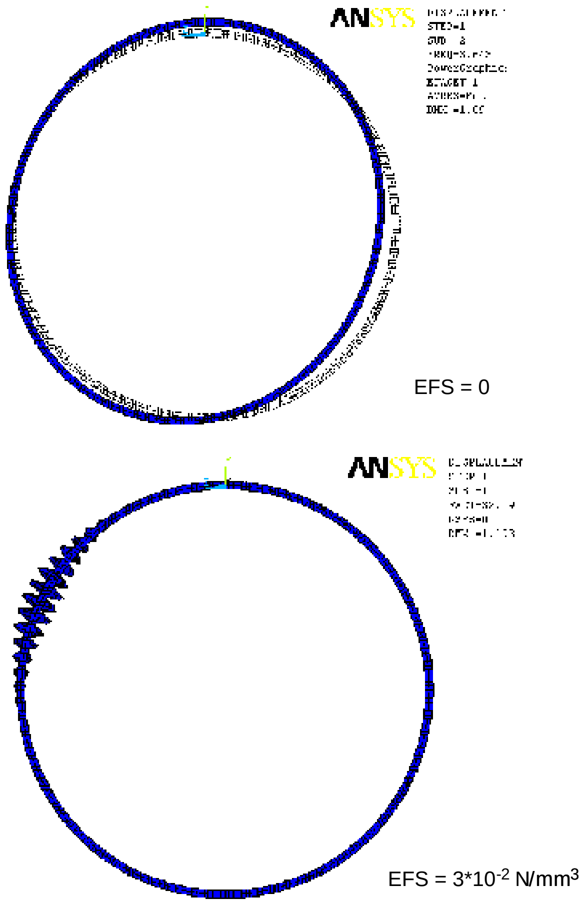



**Figure 7. Buckled mode shapes.**

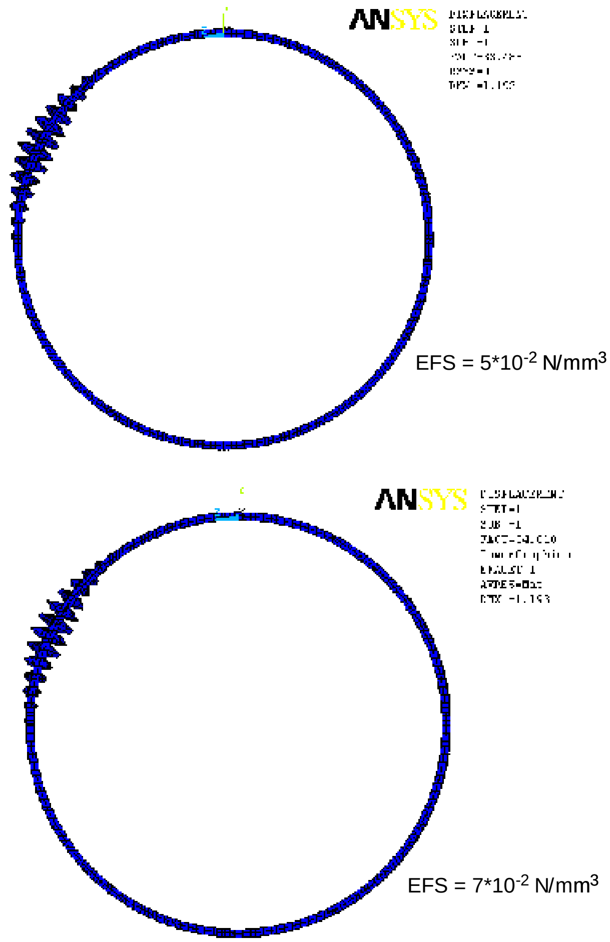



**Figure 8. Buckled mode shapes.**

## 5. RESULTS AND DISCUSSION

In this paper, the buried shelter has been designed by traditional formulae and later analysed using the software package. The main criteria of designing the thin-walled buried shelter is bucking and deflection. In both cases, the shelter is safe and show, large factor of safety. In the buckling analysis, it is clear that buckling load factors largely depends

**Figure 9. Cylindrical shelter being kept in the pit.**

**Figure 10. Instrumentation inside the shelter.**

upon the soil–structure interaction. The values of elastic foundation stiffness increased the buckling load factors significantly (from 3.64 for first buckling factor for zero EFS value to 32.82 first buckling factor for 7 X $10^{-2}$ N/mm$^3$ EFS value). Similarly, deflection of shelter reduced as the value of elastic foundation stiffness increased. The stresses produced in the shelter are less and decreased as the values of the elastic foundation stiffness increased.

Some data were also collected by the experimental testing for the same shelter. The strains, stresses and deformation produced due to surcharge pressure are very less.

## 6. CONCLUSION

A thin-walled buried shelter made up of corrugated mild steel sheets is designed, analysed and experimentally tested. It is found from all these methods that the shelter is safe for designed pressure and sufficient factor of safety is available to take care of actual field uncertainties like totally submerged or water-logged conditions, weak soil and improper compaction of soil, etc.

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