SEISMIC ANALYSIS OF FREE STANDING GLOVE BOX STRUCTURE

A. Saraswat[1], S. Ghosh[2], P.S. Somyajulu[1], G.R. Reddy[1], Arun Kumar[1], A.K. Ghosh[1]
[1]Bhabha Atomic Research Centre (BARC), Mumbai, INDIA
[2] Indian Institute of Technology Bombay, Mumbai, INDIA
E-mail of corresponding author: anupams@barc.gov.in

ABSTRACT

Nuclear fuel cycle facilities use glove boxes to handle radioactive materials. Glove box (GB) system is a leak tight freestanding stainless steel (S.S.) structure maintained at negative pressure with the help of ventilation system. In the event of earthquake such glove boxes will freely slide on the floor. Hence it is necessary to check that the displacements of the glove boxes are not excessive and there is no overturning of the boxes at design earthquake loading. Behavior of a freestanding glove box system is highly nonlinear mainly due to geometrical nonlinearities associated with the contact interface between glove box and floor (friction, gap and bounce back properties) The non-linearities associated with modeling the contact surface include modeling the friction between the two surfaces to correctly predict sliding behavior, and modeling the gap/contact surface to predict the rocking behavior.

The glove box system is analyzed by using 3D FEM model. Shake table tests were also carried out on glove box system to check its dynamic response to seismic excitation.

This paper discusses the details of methodology used for modeling and analyzing free standing glove box system under seismic loading. The behavior of the glove box under dynamic loading is benchmarked with experimental data.

INTRODUCTION

Glove box system is a leak tight freestanding S.S. structure maintained at high level of leak tightness (0.05% GB vol/ hour) and negative internal pressure at -1 inch of water column. The glove boxes can be used as standalone boxes as shown in Fig.1 or are connected to each other by a transfer tunnel as shown in Fig.2. They are provided with glove ports and gauntlets, through which process and maintenance operations may be performed. The glove boxes are anchored to a steel framework through bolts and the framework is placed on the floor with or without anchoring. In some cases the boxes are not anchored to the floor in order to facilitate the movement of boxes for maintenance. In the event of earthquake such glove boxes will freely slide on the floor. Hence it is necessary to check that the displacements of the glove boxes are not excessive and there is no overturning of the boxes at design earthquake loading.

In this paper single standalone free standing GB is analyzed for its dynamic response to three directional seismic loading. 2D idealized GB model is considered for developing the equations of motion. Further, 3D finite element model has been developed and analyzed for orthogonal seismic loading. The analysis results have been verified by the test data generated by BARC in collaboration with Central Power Research Institute (CPRI) during shake table testing [1].

Fig.1: Typical Glove Box

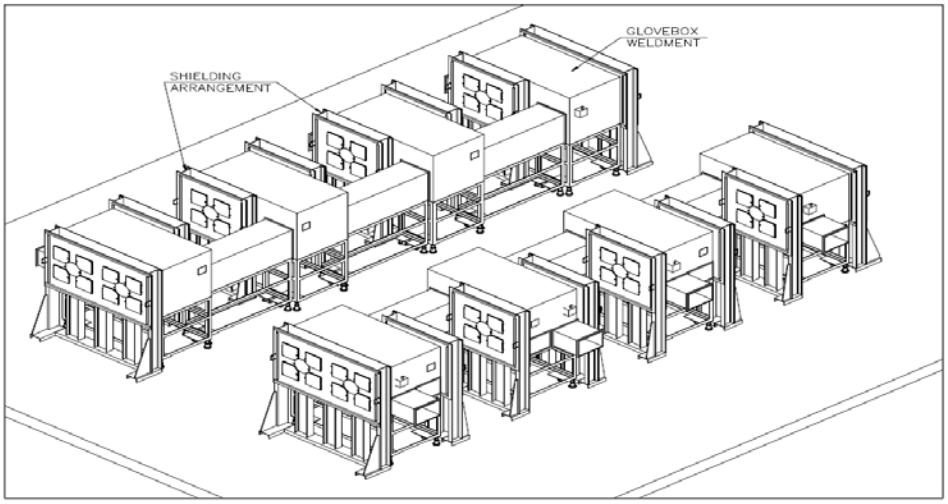


Fig.2: Automated Glove Box Train Layout

MODELLING OF GLOVE BOX

This problem is modeled using two rigid beams, one which models the height (H) of the centre of gravity (C.G.) above the contact surface and the other, which spans across the width (W) of the glove box as shown in Fig.3. The model is an idealized 2-D representation of the GB. The width chosen is the dimension where the anticipated rocking is of interest. GB structure is considered as linear rigid body with limited nonlinearity at the contact surface between GB and floor on which it is standing freely. The dynamic interaction of GB with floor includes translation in horizontal direction(X), rocking in XZ plane and vertical motion (impact or free flight/gap) along Z axis. In the 2D model, sliding between the floor and GB interface is represented by discrete friction spring representing coulomb friction. Discrete vertical dampers are introduced at the base to properly represent the energy absorption due to vertical impact. Compression only springs are used to model the gap behavior.

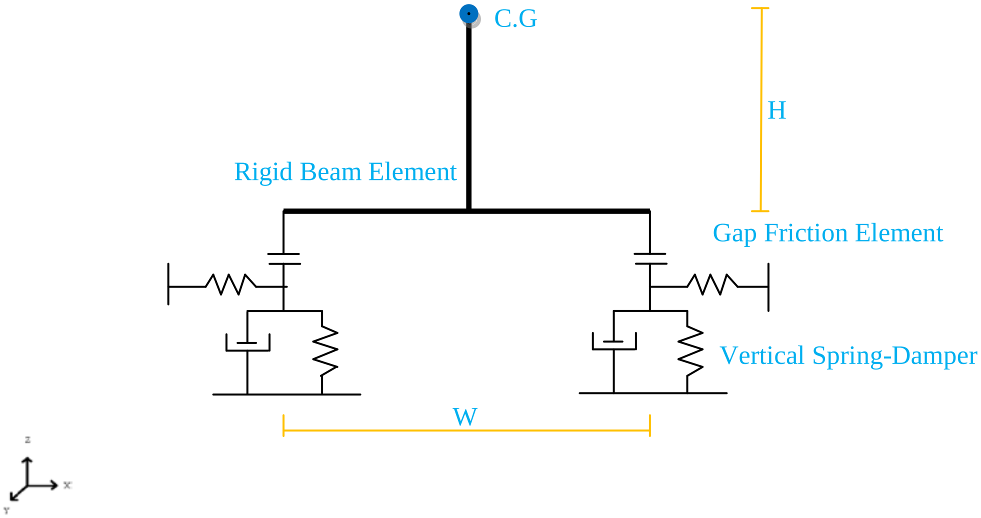


Fig.3: Simplified Mathematical Model for Glove Box Structure

The governing equations of motion are derived using the classical Lagrangian method [2, 3] wherein Lagrangian (L) is a scalar function of the kinetic energy (T) and potential energy (V) of the system which are written in terms of the independent generalized coordinates (q_k) of the problem. Performing partial differentiation operations on the

Lagrangian, and equating the results of the operations to the appropriate generalized forces associated with each degree of freedom, yields the appropriate system equations of motion.
In this problem 3DOFs are taken for formulating equations of motion. They are 1- Translation along X axis – represented by q_1, 2- Translation along Z axis – represented by q_2, 3- Rotation in XZ plane – represented by q_3.
Similarly generalized forces (Q_k) are associated with generalized masses, M (mass of GB) and I (mass moment of inertia of GB about Y axis through the centroid).The equations of motion for the GB system with dissipative forces can be written in terms of generalized coordinates, by using Lagrangian equation as described below.

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_k}\right) - \frac{\partial L}{\partial q_k} + \frac{\partial F}{\partial \dot{q}_k} = Q_k \ , \quad k = 1,2,\dots\dots,n \tag{1}$$

Here n represents number of degrees of freedom (DOF) of system (3 for GB), L= (T-V) & F- Rayleigh's dissipation function which represents dissipative force due to damping in the system (Coulomb damping), is given by the following equation:

$$F = \sum_{k=1}^{n} 1/2\left(c_{xk}\dot{x}_k^2 + c_{yk}\dot{y}_k^2 + c_{zk}\dot{z}_k^2\right) \tag{2}$$

The Lagrangian (L) for the GB system shown in Fig.2 is derived below:

a) Kinetic Energy(T) for the GB system

$$T = \frac{1}{2}M(\dot{q}_1^2 + \dot{q}_2^2) + \frac{1}{2}I\dot{q}_3^2 \tag{3}$$

b) Potential Energy(V) for the GB system

$$V = \frac{1}{2}\left(k_{f1} + k_{f2}\right)\dot{q}_1^2 + \frac{1}{2}(k_{v1} + k_{v2})\dot{q}_2^2 \tag{4}$$

c) Dissipative Force for the GB system

$$F = \frac{1}{2}(c_{v1} + c_{v2})\dot{q}_2^2 \tag{5}$$

Here k_{f1} and k_{f2} are the spring constants for the friction springs and represents shear stiffness in X direction, k_{v1} and k_{v2} are spring constants for vertical springs and represents contact stiffness in vertical downward direction, c_{v1} and c_{v2} are the velocity proportional damping constants which represents energy loss due to impact.

d) Lagrangian (L) for the GB system

$$\text{L} = \text{T} - \text{V} = \frac{1}{2}M(\dot{q}_1^2 + \dot{q}_2^2) + \frac{1}{2}I\dot{q}_3^2 - \left\{\frac{1}{2}\left(k_{f1} + k_{f2}\right)\dot{q}_1^2 + \frac{1}{2}(k_{v1} + k_{v2})\dot{q}_2^2\right\} \tag{6}$$

e) External forces (Q_k) for the GB system

Q_1= F_x, Seismic force acting at C.G in X direction
Q_2= F_y, Seismic force acting at C.G in Z direction
Q_3= F_xH, Torque due to F_x

$$\{Q1 = \ Fx, Q2 = \ Fy, Q3 = \ FxH \ \} \tag{7}$$

Now substituting values of "Eq.5, 6 & 7" in "Eq.1", we get 3 uncoupled equations of motions for the system which can be written in matrix form as below:

$$[M]\{\ddot{q}_k\} + [C]\{\dot{q}_k\} + [K]\{q_k\} = \{Q_k\} \tag{8}$$

The equations can be solved using numerical time integration methods like Newmark β method to get the dynamic response of the system.

SHAKE TABLE TEST RESULTS

Shake table tests were carried out on full scale glove box (1m x 1m x 1m , 3.92 tons) bolted to carriage and resting on PVC floor as shown in Fig. 4(a,b). The test floor was prepared such that it represents the actual lab conditions in which the glove box is kept. The Glove boxes were subjected to series of design spectrum compatible time histories of Tarapur (Mumbai) with peak acceleration from 0.1g to 0.4 g in steps of 0.1g in all the three directions. The applied vertical acceleration was 2/3rd the horizontal acceleration. Tests were conducted on glove boxes for 5% damped design response spectrum compatible time histories in all three directions as shown in Fig.5. The test response spectra generated is shown in Fig.6 in X-direction, Z-direction and Y (vertical)-direction respectively. These spectrum compatible time histories were applied to the model in X, Z and Y directions simultaneously. The integrity of pressure boundary is checked during tests by actually monitoring the pressure changes inside the box during shake table testing. Leak testing was carried out after each test for two hours at the pressure of -1" water column, and thereafter, -3"water column for two hours. The acceleration and displacement time histories at the top of the boxes and the strains at various locations of the glove boxes were measured during the tests. Displacement test responses of GB to 0.1g, 0.2g, 0.3g and 0.4g PGA values are shown in Fig. 7 to 10.


Figure 4a Shake table test setup of single GB


Figure 4b Shake table test setup of two GB

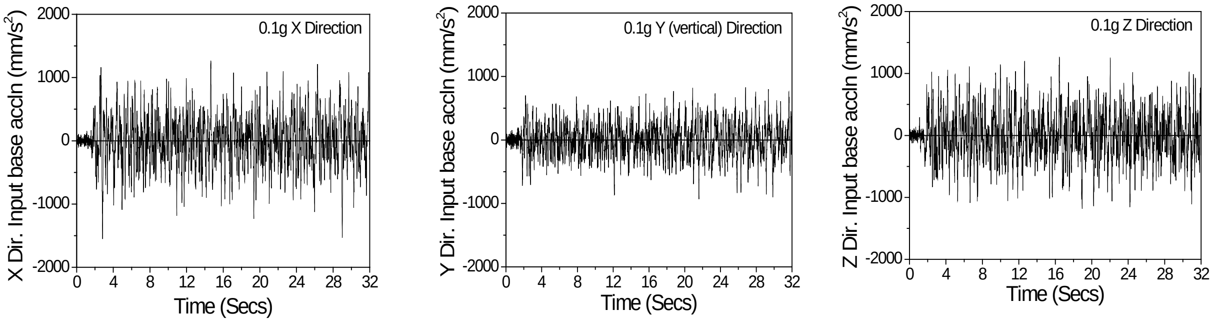


Fig. 5 Spectrum Compatible Time Histories in 3 directions

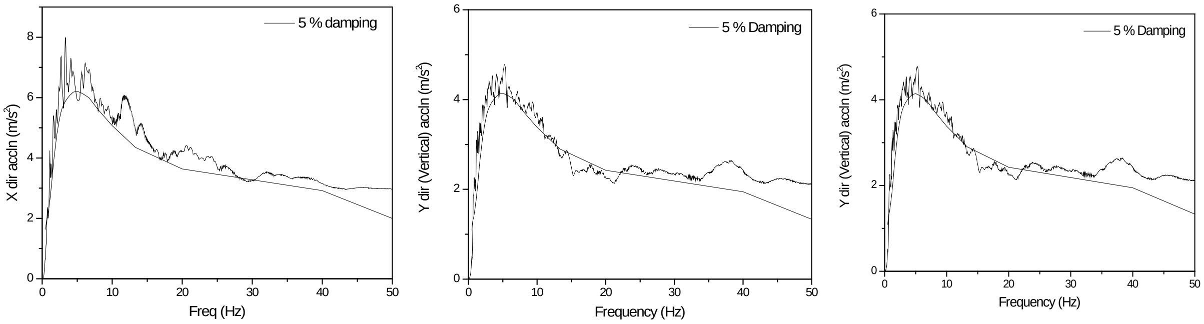


Fig. 6 Comparison of Test and Required Response Spectrum in the 3 directions

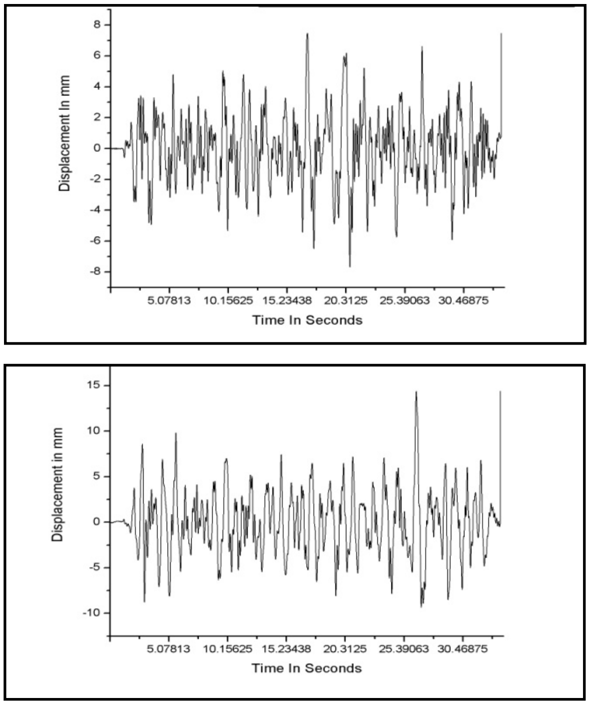


Fig. 7 Displacement in Z & X direction for 0.1g PGA

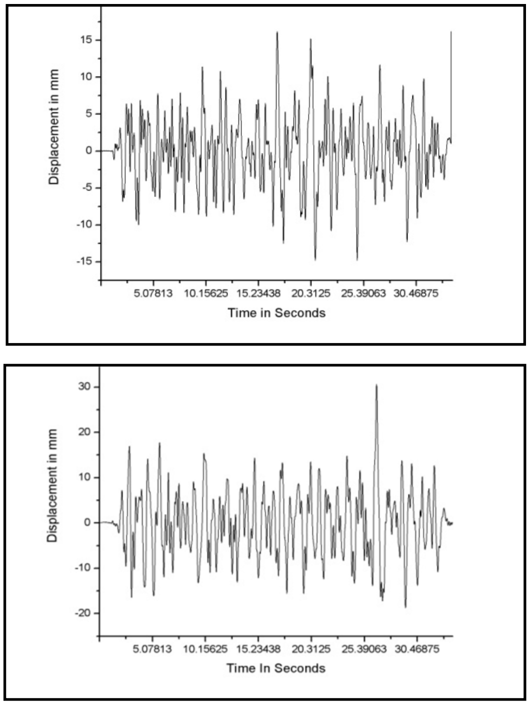
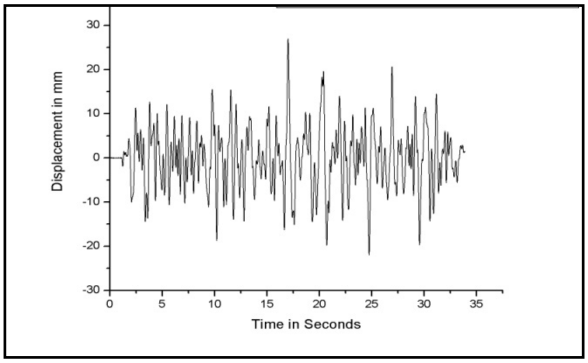
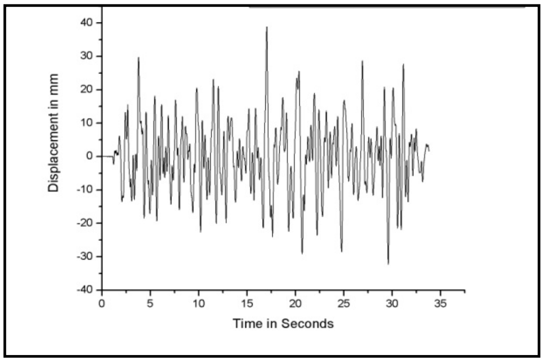


Fig. 8 Displacement in Z & X direction for 0.2g PGA





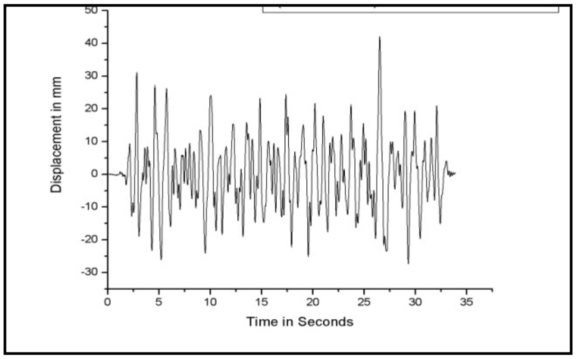


Fig. 9 Displacement in Z & X direction for 0.3g PGA

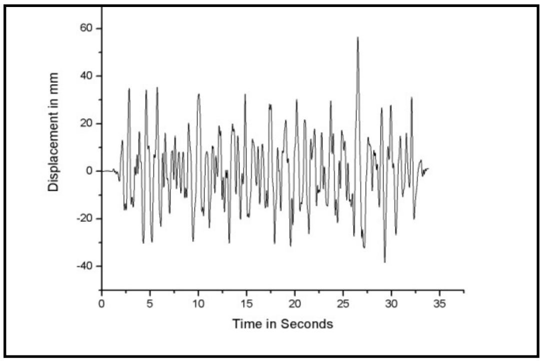


Fig. 10 Displacement in Z & X direction for 0.4g PGA

FINITE ELEMENT ANALYSIS OF GLOVE BOX

Dynamic analysis has been carried out for determining the stability of GB system subjected to orthogonal seismic loading. Main concern is to find out the sliding displacement and overturning of the GB. Single glove box without mass and with free condition of ventilation pipe was modeled using finite elements (FE) with friction between the legs and the PVC floor. The Glove box is modeled as 4 nodes shell elements and supporting structure is modeled as 3 nodes quadratic beam elements with 6 degrees of freedom at each node. Ventilation pipes connected to the glove box are assumed to be flexible enough to allow the free movement of GB on the floor. Contact between GB and floor has been modeled by suitable contact element which considers Gap and friction properties of contact surfaces. Analysis is carried out with the assumptions that GB behaves linearly except at the contact surface where non linearity due to friction exists. The coefficient of friction between the floor and legs of the glove box is assumed as 0.15. This is a realistic assumption from the observations of the tests that the glove box started sliding when the base acceleration changed from 0.1g to 0.2g. Damping is assumed as 2 % in the analysis. This assumption is based on the value mentioned in ASCE 4-98 [4] for welded steel structures. Mass of the filter box, regulating valve, clamping strips, glove ports, gauntlet etc. are lumped at appropriate places and are effective in three translational degrees of freedom. The FE model of the glove box is shown in Fig. 11. Prior to carrying out dynamic analysis a static analysis and a modal analysis is done so as to eliminate the possibility of any errors and to determine the natural frequencies of the model.

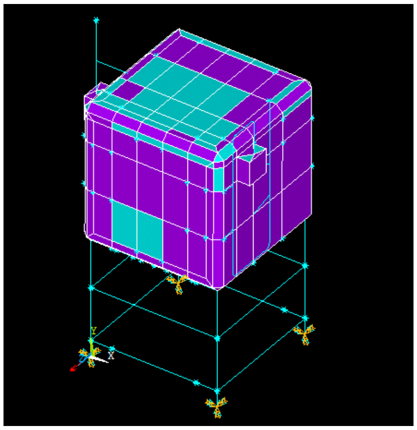


Fig.11 GB FEM model

Results

The displacement-time history of the glove box (at the place where sensors were mounted during the experiment) for the input excitation same as that in the Experiment (at CPRI Bangalore), are shown in the following figures from Fig. 12 to17.

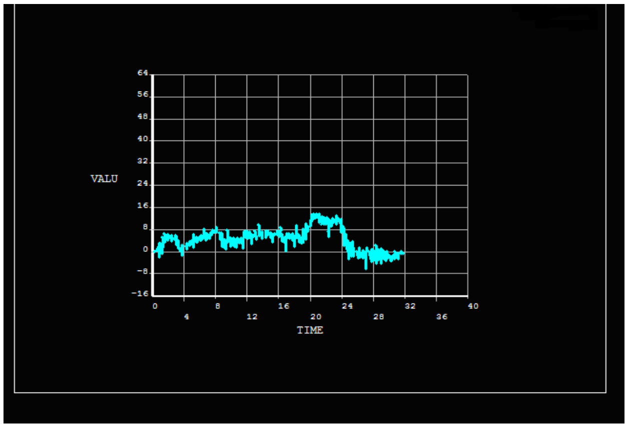


Fig. 12 Displacement in X-Direction for .1g

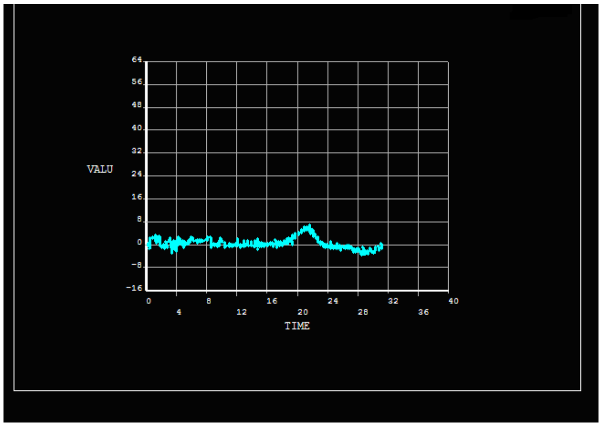


Fig. 13 Displacement in Z-Direction for .1g

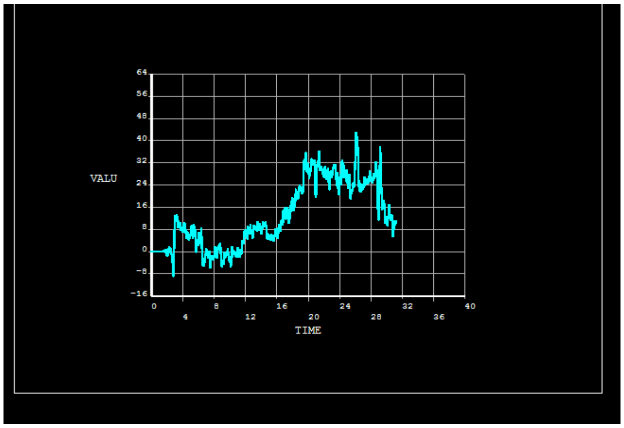


Fig. 14 Displacement in X-Direction for .2g

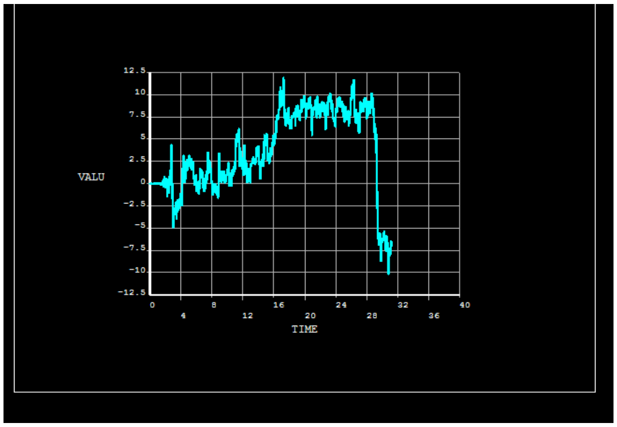


Fig 15 Displacement in Z-Direction for .2g

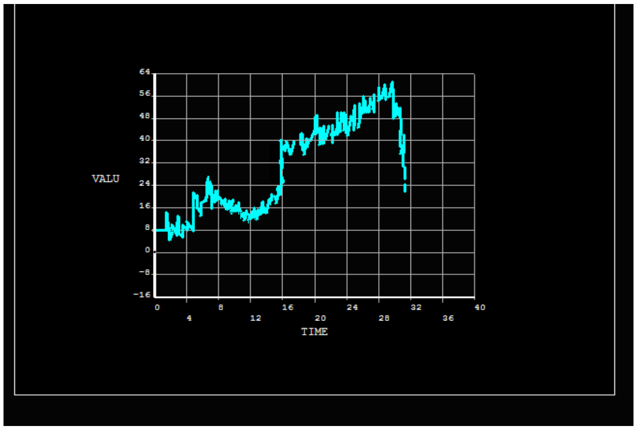


Fig 16 Displacement in X-Direction for .3g

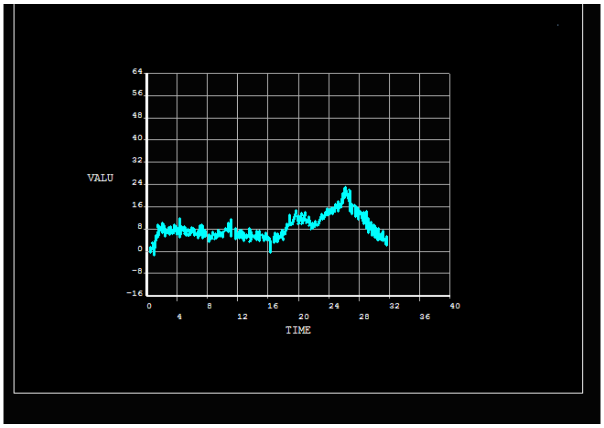


Fig 17 Displacement in Z-Direction for .3g

OBSERVATIONS AND CONCLUSION

Free standing glove box structure has been subjected to orthogonal seismic excitation. Results of finite element analysis and shake table testing commensurate with each other. Although it has been observed that at high level of excitation (PGA$\geq$0.3g) GB structure deviates from the results generated by the finite element analysis. This is mainly due to the nonlinearity introduced by rocking and impact of GB at PVC floor and subsequent deformation of floor.

To account for the above mentioned nonlinear behavior, simplified mathematical model of the glove box structure as suggested by the author in the paper can be utilized. Model can further be improved to incorporate elastic plastic behavior of the PVC floor by suitable addition of nonlinear elements. More realistic 3D model having 6 DOF's can be developed to accommodate energy dissipation via impact, rocking & rotation. Author's future course of work is to analyze the results obtained from time integration of mathematical 2-D model and compare them with FEM and experimental values.

Acknowledgement: *Author sincerely acknowledges the support of Ms. Y.M. Parulekar of B.A.R.C, for providing useful shake table test data and guidance.*

REFERENCES

[1] Y. M. Parulekar, G.R. Reddy, C. UmaShankar, K.K. Vaze, A.K. Ghosh, H.S. Kushwaha,K.N. Mahule, R. Ramesh babu, "Seismic Stability of Glove Boxes - Experiments and Analysis", *20th International Conference on Structural Mechanics in Reactor Technology (SMiRT 20)Espoo, Finland, August 9-14, 2009*

[2] Samuel Levy and John P.D. Wilkinson, "The Component Element Method in Dynamics" (*McGraw-Hill, New York, 1976)*

[3] Leonard Meirovitch, "Methods of Analytical Dynamics" (*McGraw-Hill, New York, 1970)*

[4] ASCE standard 4 – 98, Seismic analysis of safety – related nuclear structures.