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Seismic Stability of Glove Boxes - Experiments and Analysis

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1 ABSTRACT

In a nuclear facility radiotoxic materials are being handled in leak tight enclosures called glove boxes. These glove boxes serve as primary confinement for these radiotoxic materials. Hence there is a need to check the structural integrity and leak tightness of the glove boxes when subjected to earthquake loads. For this requirement, extensive shake table experiments for design earthquake loads were carried out on a single glove box with and without heavy mass of machinery. Shake table tests were also carried out on two glove boxes connected by transfer tunnel held by o-rings. Detailed nonlinear sliding analysis of the glove boxes is also carried out using Newmark–beta time integration technique in order to confirm that the analysis methods are appropriate.

2 INTRODUCTION

The risk of seismic hazard on a nuclear facility necessitates the detailed seismic evaluation of its structures, systems and equipments. Equipments such as glove boxes can be seismically qualified by analysis, testing or using past earthquake data experienced by identical equipments. Earlier full scale tests have been carried out in Japan by Fugita et. al [1],1989 and Miura et. al.[2],2003. These tests were conducted on glove boxes fixed to the floor and it was concluded from the tests that the glove boxes kept working when subjected acceleration of safe shut down earthquake (SSE) level and operation basis earthquake (OBE) level. In the nuclear facilities in India, there are many free standing glove boxes and seismic evaluation of such type of glove boxes is essential. Hence shake table tests were carried out on free standing glove boxes subjected to SSE level earthquake in which sliding and overturning of the boxes is a big concern. Nonlinear sliding analysis of a single glove box subjected to design spectrum compatible time history is also performed and the analysis is validated by comparing the response of the boxes with those obtained in the tests.

Initially general guidelines stated by U.S. Department of Energy (DOE) were used for evaluating and upgrading the seismic adequacy of glove boxes. The glove box system shown in Fig. 1 is a series of physical barriers provided with glove ports and gauntlets, through which process and maintenance operations may be performed, together with an operating ventilation system. 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. The stresses in the bolts, connections and the supporting structure should also be within the allowable limits and attached tubing conduits should have enough flexibility to accommodate the seismic motion. Moreover it should be checked that internally placed free standing objects such as bottles, machining tools etc. does not slide and tear gloves and break windows of the glove boxes. Glove boxes are maintained at high level of air tightness and negative internal pressure at about -1 inch of water column. It should be confirmed that during design earthquake excitation this pressure is maintained and the leak tightness of the glove boxes is maintained according to design standards [3,4]. The allowable rate of air leakage is 0.05 % of air vol/hr or less at pre-service inspection according to relevant standards [4]. In order to check all these aspects series of shake table tests were very essential along with analysis to check the seismic adequacy of the glove boxes. Tests were carried out on full scale single glove boxes and train of two glove boxes connected by transfer tunnel.

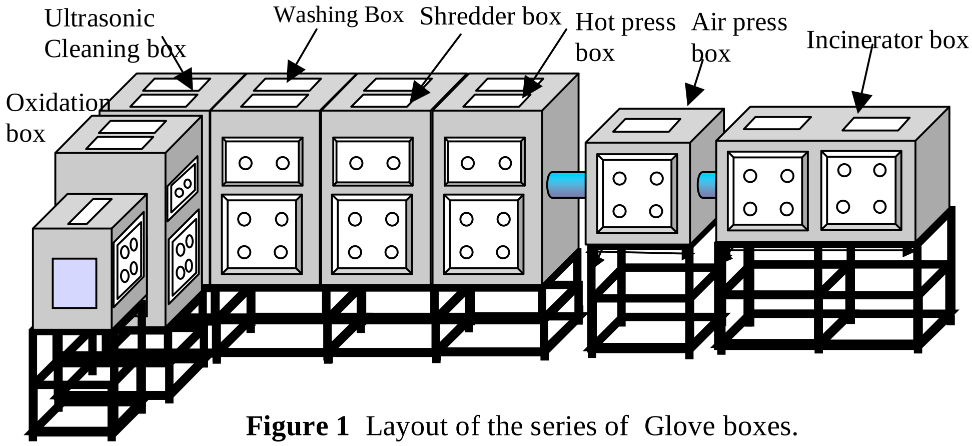

Figure 1 Layout of the series of Glove boxes.

3. TESTING MODELS OF GLOVE BOXES

Shake table tests were carried out on full scale Type IV glove box (1m x 1m x 1m , 3.92 tons) bolted to carriage and resting on PVC floor as shown in Fig. 2a. The test floor was prepared such that it represents the

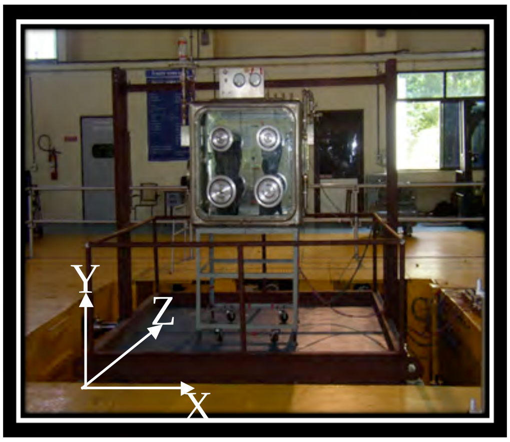

Figure 2a Shake table test setup of single type IV Glove box

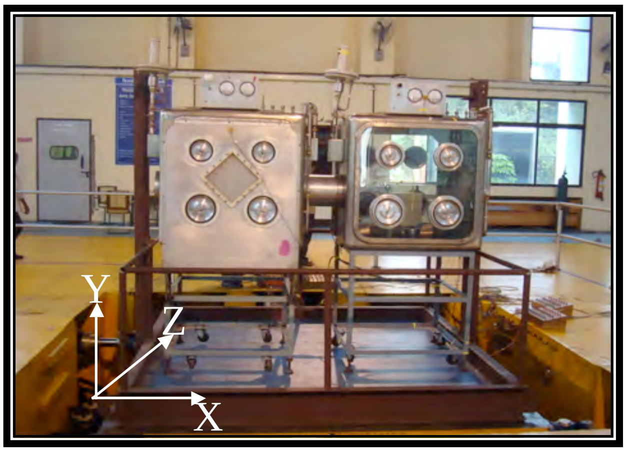

Figure 2b Shake table test setup of two type IV Glove boxes connected by transfer

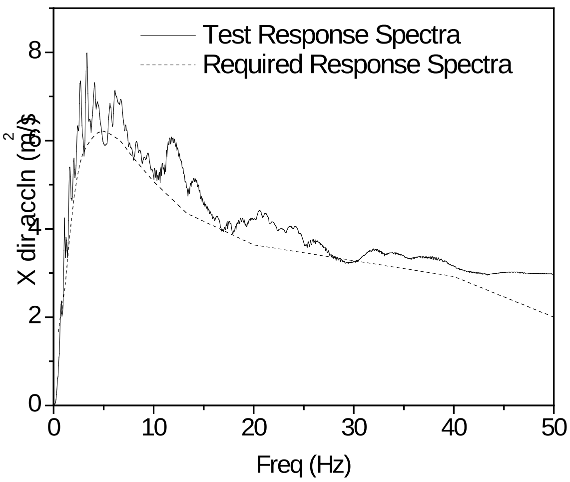

Figure 3 Comparison of test and required response spectra (5 % damping)

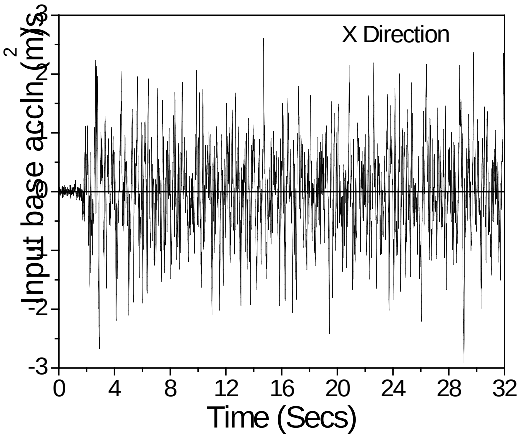

Figure 4 Input base acceleration Time history in X direction

actual lab conditions in which the glove box is kept. Tests were carried out on the glove boxes for three cases viz. single glove box without mass, single glove box with central mass of 250 kg representing heavy machinery kept inside the box and single glove box with eccentric mass of 96 kg radiation shield on one of its side. For each case the glove box was tested for two conditions: one with one inch pipe at the top of the box kept free and the other with 1 inch pipe at the top of the box fixed to a rigid beam. These two conditions simulate the actual two field conditions, one in which the glove box is having long flexible ventilation system and the other in which the ventilation system at a small length is rigidly connected to a support. Tests were also carried out on two glove boxes connected by a transfer tunnel as shown in Fig. 2b. In this test one glove box had an eccentric mass of 96 kg and other glove box had 250 kg fixed mass. The transfer port is kept between the two glove boxes without any anchorage and is held with the o-rings.

The Glove boxes were subjected to series of design spectrum compatible time histories (Fig 4) 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. The glove boxes are situated in ground storeyed RCC building. Hence 5 % damped ground response spectrum of safe shut down earthquake shown in Fig. 3 is used for testing. The comparison of required response spectrum and the test response spectrum is also shown in Fig. 3. 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.

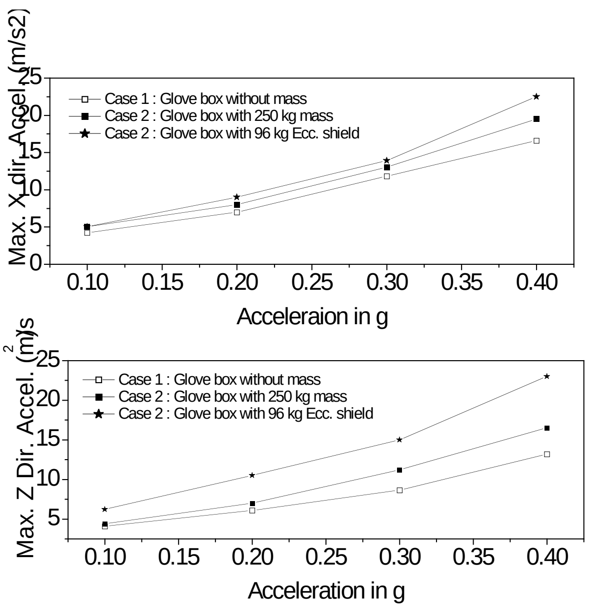

Figure 5 Comparison of max. acceleration at the top of the glove box for all the 3 cases.

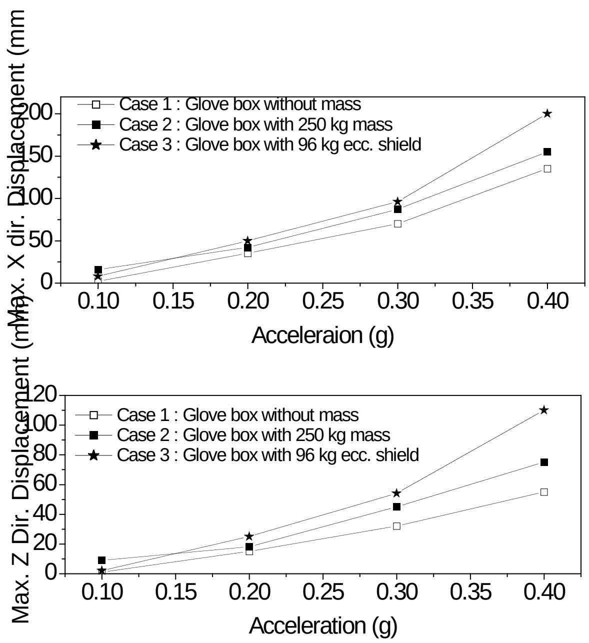

Figure 6 Comparison of displacement of the glove box for all the 3 cases.

4 OBSERVATIONS AND TEST RESULTS

In all the test conditions it was observed that the glove box shifted from its original position after each test. The graphs of peak acceleration in X and Z direction at the top of the box v/s the peak base acceleration for all the 3 cases of single glove box is shown in Fig. 5. The graphs showing the permanent displacements observed for single glove box at the end of time histories for all the three cases are shown in Fig. 6. It is observed that the displacement at the end of each test as shown in Fig. 6 was negligible at 0.1g peak base acceleration and was considerable at 0.2g. peak base acceleration. It is seen from the graphs that the displacement and peak acceleration of the glove box with eccentric shield is the maximum while that of empty glove box is minimum of all the three cases. Single glove box with an eccentric mass is most unstable at 0.4g and has a tendency to overturn. At 0.4 g base acceleration, the peak acceleration of top of this glove box reaches the value of 23 m/s^2 with the displacement of 200 mm. However leak-tightness of glove box was maintained upto 0.4g for all the three cases. Fig. 7 shows the comparison of the FFT spectra of the acceleration time history obtained at the top of the empty glove box with fixed and free piping connection at 0.3g base acceleration The FFT spectra of fixed condition of pipe is wider and have more high frequency components than the free condition. It is however seen that the peak acceleration for the glove box is almost same for both conditions. This is due to the rotation of regulating valve connecting the pipe about vertical axis. Due to this rotation, it is also observed in the tests that the glove box rotated about the fixed support and displacements of the glove box were 10 % less than free case. Leak- tightness was maintained upto 0.4g for both the conditions of pipe support.

For the two type IV glove boxes connected by transfer tunnel as shown in Fig. 2, upto 0.2 g three directional motion, leak-tightness and structural integrity was maintained. At 0.3 g the transfer port got tilted and some free objects kept inside the glove box slided. The transfer port was repositioned for exciting the train of boxes for 0.4g. At 0.4g the transfer port came out and fell down on the floor and free objects inside the box moved to large extent.

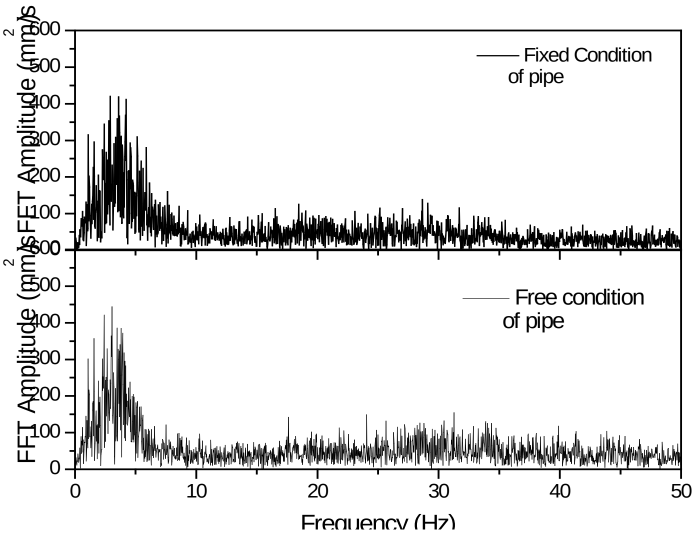

Figure 7 Comparison of FFT spectra of acceleration time history for fixed and free piping conditions in tests.

5 FINITE ELEMENT ANALYSIS OF GLOVEBOX

The type IV 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 noded shell elements and supporting structure is modeled as beam element with 6 degrees of freedom at each node. 1 inch ventilation pipes connected to the glove box are also modeled as beam element.

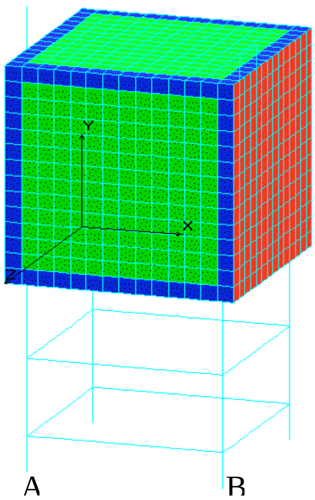

Figure 8 FE model of the glove box

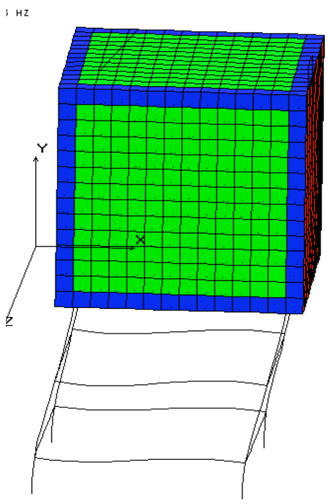

Figure 9 Fundamental mode shape of the glove box

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. Gap friction element is used to model the friction between floor and supporting four legs of the glove box. The FE model of the glove box is shown in Fig. 8. Following assumptions are made for the dynamic analysis of the glove box. Only friction between the legs and floor, modeled as gap friction element behaves nonlinearly and the glove box and the supporting carriage behaves linearly throughout the analysis. 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 [5] for welded steel structures.

The free vibration analysis of FE model is carried out considering fixed leg support and the fundamental frequency of 8.6 Hz is obtained having the mode shape shown in Fig. 9. The frequency obtained from tests is 7.2 Hz which is slightly lesser than the analysis frequency**.** This is due to the fact that in tests frequency is obtained at sine sweep excitation of 0.05g peak acceleration at which the model sticks to the floor and exact fixed support is not simulated as in the analysis**.**

6. GOVERNING EQUATIONS OF MOTION

The glove box with supporting carriage under earthquake acceleration in three orthogonal directions sliding on PVC floor in two horizontal directions has equations of motion given by

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}+[D]\{F\}=-[M][r]\{\ddot{u}_g\} \qquad (1)$$

$$\{F\}=\begin{Bmatrix}F_x\\F_z\end{Bmatrix} \qquad (2)$$

Where [M], [C] and [K] are the mass, damping and stiffness matrix respectively of the glove box system. $\{\ddot{u}\},\{\dot{u}\},\{u\}$ are the acceleration, velocity and displacement vectors in all three orthogonal directions x, y(vertical) and z., [D] is the location matrix of frictional forces at the leg supports of the glove box, {F} is the vector containing the frictional forces given by Eq. 2 in two orthogonal directions, {r} is the influence coefficient matrix and $\{\ddot{u}_g\}$ is the ground acceleration in x, y and z directions.

The limiting value of frictional force $F_s(t)$ at the sliding support is time dependent as the normal reaction at the support will be varying with time and is expressed as

$$F_s(t)=\mu F_y(t) \qquad (3)$$

Where $F_y(t)$ is the time dependent normal reaction which depend on the vertical ground acceleration $\{\ddot{y}_g(t)\}$ and μ is the coefficient of friction. The system will start sliding when the resultant of the frictional forces in x and z directions (F_x, F_z) exceeds the limiting frictional force given in Eq. (3). However if the resultant of the frictional forces is less than the limiting force the system will stick to the surface. The above equations are solved and the effect of bi-directional interaction of frictional forces is taken into account in the analysis of the glove box and its carriage structure. Consideration of this effect in the analysis is also investigated by the authors [6,7] where in they have showed that sliding base displacement is higher than the case in which the interaction effects of frictional forces in two orthogonal directions are ignored. The interaction effects of frictional forces will be ignored when the structural system will be modeled as a 2-D system. The analysis in the present work is performed using 3D FE model (Fig. 8) and the governing equations of motion are solved using Newmark -β time integration technique assuming linear variation of acceleration over small time interval of 0.005 seconds.

7. DISCUSSION OF RESULTS

Analysis of the glove box without mass is carried out for three directional excitations using test base time histories for peak acceleration 0.1g to 0.4g in step of 0.1g. The displacement v/s time obtained from the analysis for 0.1g and 0.4g peak base acceleration in x and z directions are shown in Fig. 10. It is observed from the analysis that the permanent displacement in x and z for 0.1g peak base excitation is 3 mm and 2 mm respectively. The permanent displacement for 0.4g base excitation is 120 mm and 40 mm respectively.

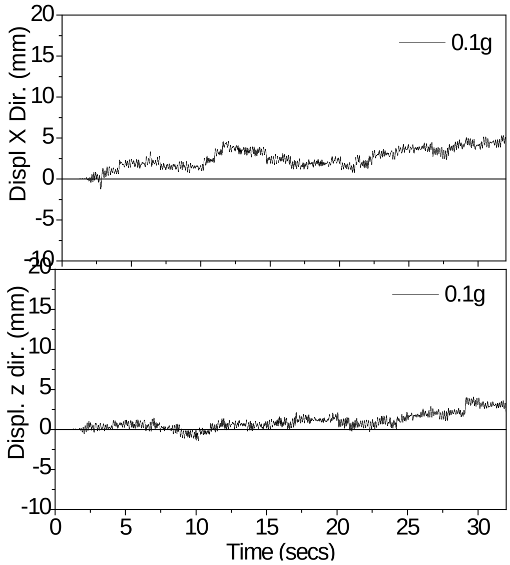

Figure 10 a Displacement v/s time of the glove box for 0.1g peak base acceleration in X and Z directions

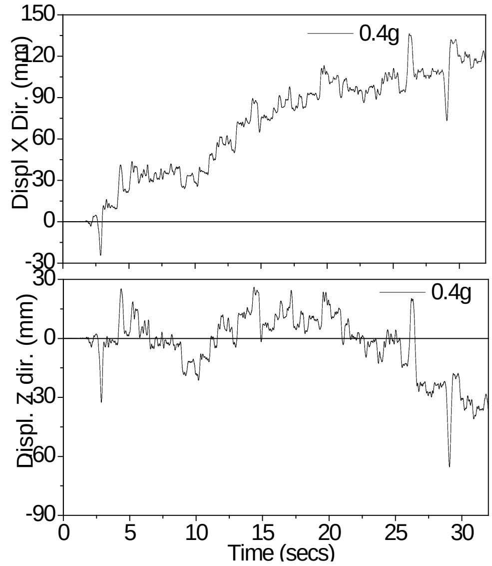

Figure 10 b Displacement v/s time of the glove box for 0.4g peak base acceleration in X and Z directions

This displacement is slightly (10–12 %) lower in comparison with the test results shown in Fig. 6. The displacement v/s time diagram for 0.1g excitation shows high frequency components due to sticking of the legs to the floor at low excitation. FFT spectra of analytical and test acceleration time history obtained at the top of the glove box at 0.1g base excitation is compared in Fig. 11. It is observed from the Figure that the peaks of the FFT spectra of analysis and test are in good agreement. The frequency content of test and analysis time histories are also in good agreement. Fig. 12 shows the frictional force displacement hysterisis loop at one of the support in X direction at 0.4g peak acceleration for which the displacement v/s time diagram is shown in Fig. 10 b. It is observed from the hysterisis loop that the frictional force at each leg support of 392 kg glove box is about 150 N and there is variation in the limiting frictional force with time. This is the result of the change in the normal reaction at the supports because of the vertical acceleration of the excitation. The effect of time dependency of the limiting frictional force was studied by Bakre et. al [8] and have stated that this effect must be considered for accurate analysis of the structural system with friction support.

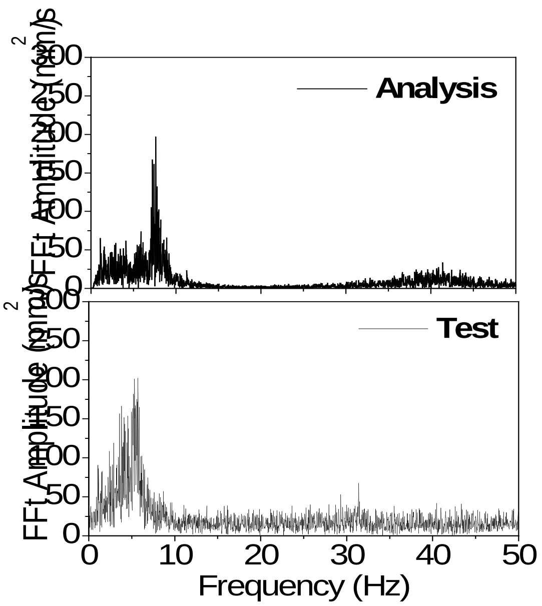

Figure 11 Comparison of FFT spectra of analytical and test acceleration time history obtained at top of the glove box at 0.1g peak base excitation

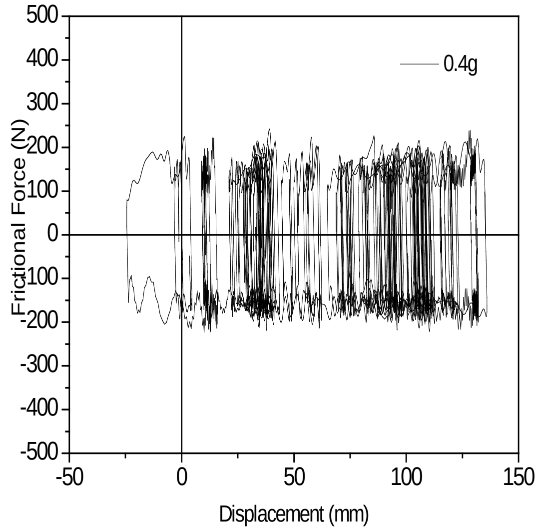

Figure 12 Frictional F–δ hysteresis loop at ıe of the support in X dir. for 0.4g excitation.

It is observed that the maximum stress in the vertical members of the carriage supporting the glove box is 71 N/mm^2 which is well within the allowable limits. It is also seen that there is large energy dissipation in the hysterisis loop due to which there will be increase in damping of the system. The damping ratio depends on the ratio of hysterisis energy to the total strain energy [9] and it decreases with increasing

excitation level [10]. This fact is observed from the Fig. 6 wherein the increase in acceleration and displacement from 0.3g to 0.4g excitation is higher than the increase from 0.2g to 0.3g. The damping due to energy dissipation is higher at 0.3g excitation than that at 0.4g excitation. This is due to the fact that though hysteresis energy increases with amplitude of displacement, the strain energy increases with square of the amplitude as excitation increases resulting in lesser damping at higher excitation.

8 CHECK FOR OVERTURNING OF GLOVE BOXES

Overturning of glove boxes due to three directional excitation, is also an important concern to asses the seismic stability of glove boxes. Hence the overturning moments are calculated for all the three cases viz. single glove box without mass, with 250 kg mass and with eccentric radiation shield of 96 kg. The moments are calculated about legs AB of the box shown in Fig. 8 considering peak base acceleration acting in the direction which causes the overturning of the box. The net overturning moment is obtained by subtracting the dead weight moment from the moment due to earthquake forces. The graph showing the net overturning moment v/s peak base acceleration is shown in Fig. 13 for all the three cases. This net overturning moment however does not persist with time. It is observed that amongst the three cases the box with eccentric radiation shield is most vulnerable to overturning. If the vertical acceleration due at earthquake acts in downward direction at 0.4g peak base acceleration, the box without mass and with 250 kg mass (case I and II) will have no overturning but the box with radiation shield will have a net overturning moment of 500 N-m. It is also observed from the test that the box with radiation shield was quite unstable and was about to overturn at the peak base acceleration of 0.4g. Hence such boxes located on higher floors where the peak floor acceleration is about 0.4g should be anchored to the floor.

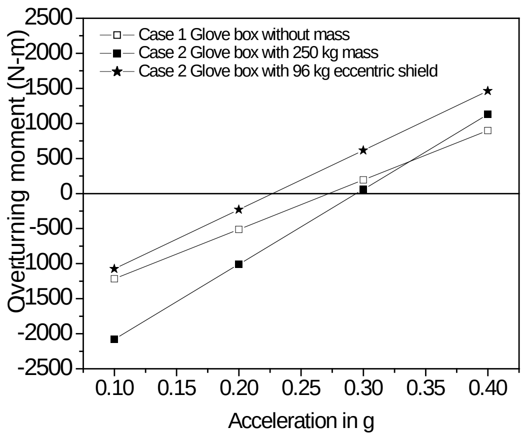

Figure 13 Overturning moments v/s base aceeleration for the glove box

9 CONCLUSIONS

The stability of single glove boxes without mass, with 250 kg mass and with 96 kg eccentric shield along with two glove boxes connected by transfer tunnel was checked by shake table tests. The glove boxes slided without over toppling for 0.2g to 0.4g peak base acceleration. During and after the tests the leak tightness of the glove box was maintained upto 0.4g peak base acceleration for the case of single glove box. However, leak tight ness was not maintained above 0.2g peak base acceleration in case of two glove boxes connected by transfer tunnel. Single glove box with an eccentric mass is unstable at 0.4g base acceleration and has a tendency to overturn. At this base excitation it has large horizontal displacements of more than 200 mm and acceleration of 23 m/s^2 . Thus the glove boxes located at ground floor level are safe for design earthquake loads of 0.2g peak base acceleration. However, if the glove boxes are located at higher floors where the design base acceleration will be higher than 0.2g, the glove boxes will need to be properly anchored.

Nonlinear dynamic analysis is carried out for the single glove box without mass for 3 direction excitation considering bidirectional interaction of frictional forces. The variation of the limiting frictional force due to vertical excitation was also considered in the analysis. The analysis and experimentally obtained displacements and accelerations of the glove boxes were found to be in agreement. Friction at the structural supports is known to reduce the seismic response of the structures by its energy dissipation**.** Maximum stresses in the structural supports of the glove boxes were found to be 71 N/mm^2 and were within allowable limits.

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