REINFORCED CONCRETE SHEARWALLS SUBJECTED TO SHOCK LOADING

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ABSTRACT

Multistoried RC framed buildings form a bulk of housing and commercial stock in most of the developed and developing countries and have to resist lateral forces such as earthquakes forces, wind forces and blast forces efficiently without undergoing complete collapse. Reinforced concrete shear walls are specially designed structural walls incorporated in buildings to resist lateral forces that are produced in the plane of the wall due to wind, earthquake and other force. The behavior and performance of RC shearwall framed buildings subjected to lateral loads such as earthquakes cannot be completely captured by analytical study, therefore one has to resort to experimentation on RC structural models to study the behavior of such RC structures. A shaking table facilitates carrying out such earthquake simulation. However they are prohibitively expensive. Therefore, an alternative approach was the use of a shock (impulse) table. With the use of the shock table progressive failure mechanism of structural building models can be captured. In the present work one geometrically scaled RC shearwall frame building model 1.86m in height and containing 3 floors(3 slabs), each floor height measuring to about 0.62m was constructed over a shock table which is a simple platform and this platform was subjected to successive shocks using a pendulum impact device . The testing was conducted to evaluate and study the performance and behaviour of reinforced concrete shearwall and the progressive failure mechanism of RC shearwall frame building model under shock loads(base impacts) .The Shear wall was L – shaped in plan and was constructed monolithic with the RC frame. The RC frame consisted of 5 beams, a slab and 3 columns per floor Accelerometers were mounted on the model and on the rear end of the shock table to capture the accelerations of the model and the shock table respectively when the shock load was applied . Free vibration tests were carried out on the model to assess its natural frequencies and thereafter the model was subjected to shock loads(base impacts) with the help of the pendulum impact device upto 210 impacts. Observations of the progressive damage in the form of cracks thus developed on the model were marked on the shearwall ,columns, beam column joints , beam and shearwall connection joints and the shearwall and floor slab connections at regular intervals of time when the shock load was progressively applied .The cracking and failure patterns of various RC structural elements such as the shearwall , beam , slab , column and foundation of the RC shearwall frame model were captured during the entire testing phase. These observations showed that the existence of the shearwall made the model stiff and stable as the shearwall attracted more damage when compared to other structural elements such as the beams, slabs and columns without allowing for collapse of the model after 210 impacts were given to the model. Since the shear wall was L – shaped in plan and located at one corner of the model frame caused the model to behave in torsion. This gives the indication that buildings with shearwalls placed unsymmetric in plan undergo torsion when subjected to lateral load .The overall performance of the shearwall in the RC frame model increased the stiffness and the lateral load capacity of the whole structure. A finite element analysis of the RC shearwall frame model was also performed as a analytic investigation to study the free vibration response and the stress distribution on the shear wall due to the applied shock load.

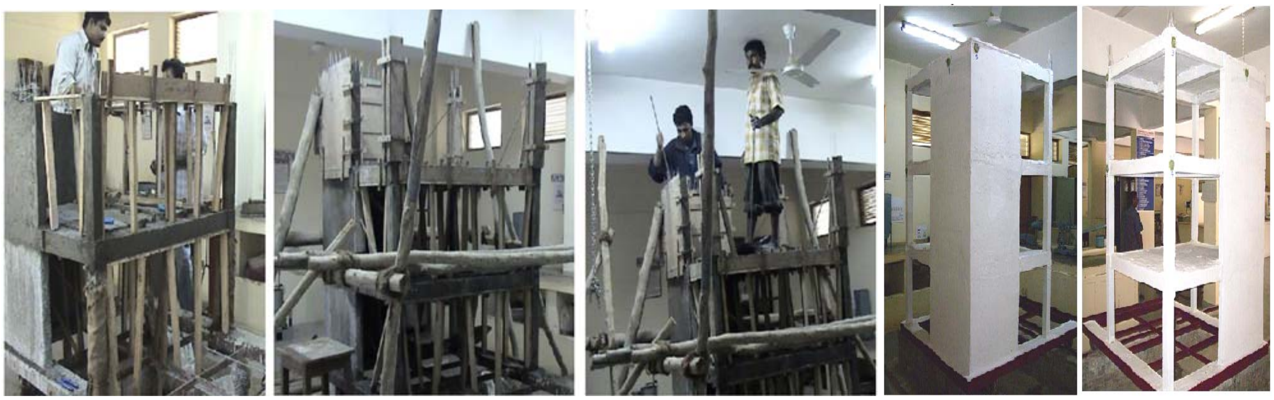
INTRODUCTION

Reinforced concrete shear walls are specially designed structural walls[7,8,9] incorporated in buildings to resist lateral forces that are produced in the plane of the wall due to wind, earthquake and other forces. These RC shearwalls are usually provided in tall buildings and have been found of immense use to avoid total collapse of buildings under lateral forces such as seismic, wind and blast forces. Shearwalls are usually provided between columns, in stairwells, lift wells and utility shafts. The functions of a shearwall are to provide strength and stiffness to resist lateral forces. However the most important property of shear walls for seismic design, as different from design for wind, is that it should have good ductility under reversible and repeated over loads. The behavior and performance of RC framed buildings subjected to lateral loads such as earthquakes cannot be completely captured by analytical study, therefore experiments have to be performed on RC structural models to study the behavior of such RC structures. A shaking table facilitates carrying out such earthquake simulation. However they are prohibitively expensive. Therefore, an alternative approach was the use of a shock (impulse) table [10,11]. With the use of the shock table progressive failure mechanism of structural building models can be captured. In the present work one geometrically scaled RC shearwall frame building model 1.86m in height and containing 3 floors(3 slabs), each floor height measuring to about 0.62m was constructed over a shock table which is a simple platform and this platform is subjected to successive shocks using a pendulum impact device. The testing was conducted to evaluate and study the performance and behavior of reinforced concrete shear wall and the progressive failure mechanism of RC shear wall frame building model under shock loads. Accelerometers were used as for picking up vibrations during the test. First the free vibration test was carried out on the model to access its natural frequencies [12] and thereafter the model was subjected to shock loads with the help of the pendulum impact device. The model was white washed before applying shock load and observations of the progressive damage in the form of cracks thus developed were marked on the shearwall ,the beam column joints , beam and shearwall connection joints and the shearwall and floor slab connections at regular intervals of time when the shock load was progressively applied .The cracking and failure patterns of various RC structural elements such as the shearwall , beam , slab , column and foundation of the RC shearwall frame model were captured during the entire testing phase. A finite element analysis of the RC shearwall frame model was performed as an analytic investigation to study the free vibration response and the stress distribution on the shear wall due to the applied shock load.

EXPERIMENTAL INVESTIGATION

Description Of The Model And Experimental Setup

The model is a RCC scaled model with a scale 1: 4.838 .The geometrical scaling [2,3] of the model is done, where as the scaling of the material strength thus used in the model has not been done. The RC shearwall frame building model is 1.86m in height with 3 floors, each floor height measuring to about 0.62m was constructed over a shock table [10,11]. The shock table is basically a rectangular ISMC 150x75x6mm channel frame which is stiffened by ISA 40x40x4 mm angles. The shock table has a plan dimension of 1.83m x 1.37m and is mounted on guide rails with help of 4 wheels fixed at the bottom 4 corners of the shock table frame. The Shear wall was L – shaped in plan with a thickness of 52mm and was constructed monolithic with the RC frame and extended upto the full height of the model, that is , 1.86m. The RC frame consisted of 5 beams per floor with dimensions 52mm in width and 83mm in depth, a slab (2 slab panels) per floor with a thickness of 26mm and 3 square columns per floor with plan dimensions of 62mmx62mm.The foundation for the model was reinforced concrete mat with a depth of 75mm which was laid in the channel section of the shock table.GI wires was used as reinforcement for all the structural elements in the model. The diameters of the GI wires used ranged from 1.4mm for longitudinal ties and stirrups for the columns and beams , 1.65mm for the longitudinal and transverse reinforcement for the shearwall, 2 mm for the foundation mat(top and bottom) , 3mm for the beam at the bottom face and 2mm at the top face of the beam , 3mm as main reinforcement for columns and 2mm for slabs in both directions. The reinforcements of the ground floor shearwall and columns were embedded and binded with binding wire to the bottom and top reinforcement mat of the foundation before concreting. The reinforcement design and detailing was followed according to IS IS456 (2000) [4] and IS 13920(1993) [6] respectively. A concrete mix with characteristic compressive strength of 60N/mm^2 was used for the shear wall and columns. Concrete mix with characteristic compressive strength of 20N/mm^2 was used for the beams, slabs and foundation. Ordinary Portland cement of grade 53, fine aggregates graded as zone III , with a fineness modulus of 2.32 and coarse aggregates passing 10mm IS sieve was used for both the above concrete mixes. Metakaolin was used as 10% by weight of cement as cement replacement for the concrete mix with compressive strength of 60N/mm^2.Accelerometers were mounted on the model to pick up vibrations during the testing. The accelerometers used was model 799LF, low frequency filtered accelerometer, Wilcoxon Research, Inc., Maryland USA. The scale factor for the accelerometer used is 500mV = 1g, where g = 9.81m/s^2.The accelerometers were mounted onto the model with help of accelerometer holders which were stuck on various points of the model with the help of metal paste. Accelerometers were mounted on the model and on the rear end of the shock table to capture the accelerations of the model and the shock table respectively when the shock load was applied. The accelerometers were connected to a data acquisition device (daq book) with the help of signal cables , junction box and BNC cables. The data acquisition device(daq book) was connected to a computer with the help of a data transfer cable. The vibration data was acquired in the computer through the software Dasy Lab and was used for further processing and analysis. Non destructive testing (NDT) using ultrasonic pulse velocity device Pundit and rebound hammer was used to find out the young’s modulus and strength of concrete in the shearwall , beams , columns and slabs of the model at all the floors after construction and curing for 28 days before the commencement of the testing when the model was still undamaged. This data of the concrete young's modulus thus got from the NDT was used as input for the finite element model. The non destructive testing(NDT) was followed according to IS 13311 (Part 1 and 2) [5]. Fig. 1 shows the construction of the model and the completed model after white washing and Fig. 2 shows the shock table before the model was built and the ultra sonic pulse test (NDT) performed on the fully constructed and white washed model before testing. Fig. 3 shows the experimental setup for the the free and forced vibration tests.



(a) Model at construction stage (b) Model after construction

Fig. 1 Construction of the model and the completed model after white washing

(a) Shock Table (b) Ultrasonic pulse test on fully constructed model

Fig. 2 Shock table before the model was built and the ultra sonic pulse test (NDT) performed on the fully constructed and white washed model

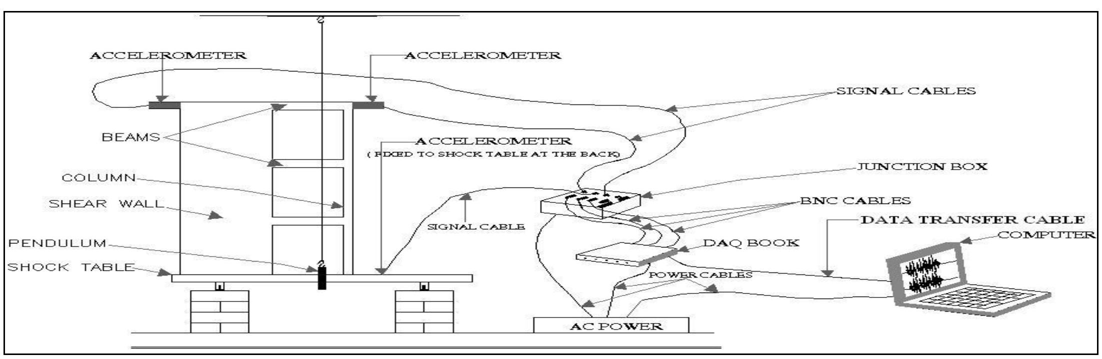


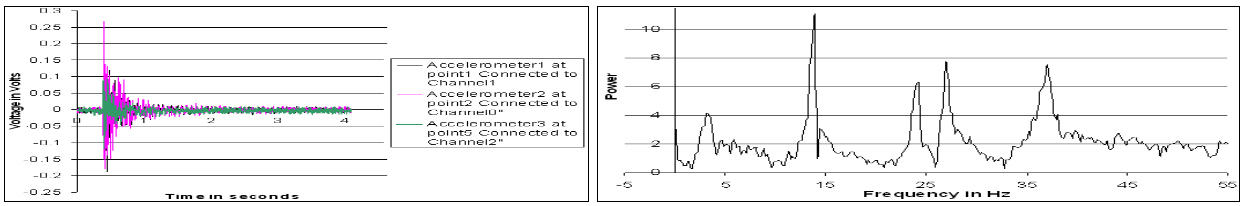
Fig. 3 Experimental setup for the free and forced vibration tests

Free Vibration Test

The model was set into vibrations by tapping. The response was recorded at different locations on the structure. Accelerometers were used to measure these response quantities. The response was obtained in terms of change in voltage, that is, analog signals. Several lower modes are also excited simultaneously. A fast fourier transform of the recorded signal helped in converting the real time history into frequency domain. Using this, the fundamental frequency and other frequencies of the model was obtained. The fast fourier transform of the raw data was done using MS Excel. The end result of the fast fourier transform from MS Excel [1] was Power and Frequency. Therefore graphs of Frequency (on X-axis) versus Power (on Y-axis) was plotted to get the fundamental natural frequency of the model and higher frequencies. The total number of raw data was 4096 and the sampling rate of the data in the data acquisition system was equal to 1000 Hz .The fourier transform was done with a sampling rate of the raw data equal to 0.244140625. All the 3 accelerometers were mounted at 5 different points on the model during the free vibration test. The model was tapped thrice during the test. Six frequencies were recorded for each tap and foreach position of the accelerometers. The average of the 6 natural frequencies of the experimental model for first tap, second tap and third tap for all the 5 positions of the accelerometers are shown in table 1.Fig. 4 shows, during the free vibration test a typical graph of voltage versus time of the raw data captured by the 3 accelerometers in position 1 and the graph plotted for power versus frequency which is the end result of the fourier analysis of the same raw data.

Table 1 : Natural frequencies of the experimental model

Natural Frequency	Peak 1 (Hz)	Peak 2 (Hz)	Peak 3 (Hz)	Peak4(Hz)	Peak5 (Hz)	Peak6 (Hz)
	13. 71	23. 56	26. 73	36. 77	41. 80	50. 08



(a) Voltage versus time for raw data (b) Power versus frequency : fourier analysis of the raw data

Fig. 4 A typical graph of voltage versus time of the raw data captured by the 3 accelerometers in position 1 and the graph plotted for power versus frequency which is the end result of the fourier analysis of the raw data.

Forced Vibration Test Of The Model: Base Impact Test

Two accelerometers were mounted on the model at 2 different locations and one accelerometer was mounted on the rear end of the shock table . The shock table housing the experimental model was subjected to a series of base shocks using a pendulum of mass 75Kg which was suspended from the laboratory roof by the help of a steel chain. The measurement of the chord length (CL) for the release of the pendulum for the base impact as well as the horizontal distance (d) and the vertical height (h) which were measured along with the chord length of release of the pendulum used to subject the pendulum for the base impact has been shown in the Fig. 5. During the impacts when the shock table would move backwards due to the applied impact from the released pendulum, the shock table with the model on it would again be brought back to the initial position after each impact so that it just touches the pendulum suspended in the vertical position. The maximum chord length (CL) dimension the pendulum could be lifted for giving the base impact to the model was1.6m. For the chord length(CL) of 1.6m t he vertical height(h) is0.455m and the horizontal distance(d) is1.54m .

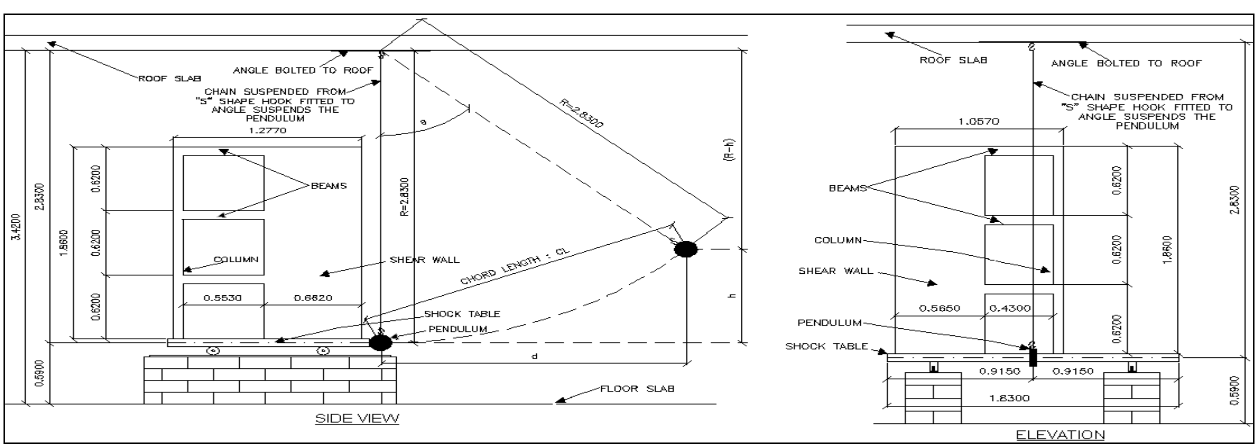


Fig. 5 Forced vibration test : Experimental model subjected to base impact . All dimensions in meters

The velocity of each base impact, kinetic energy of each base impact and the cumulative kinetic energy of successive base impacts were calculated and observation of crack development and deformations for each base impact. About 210 base impacts were experienced by the experimental model, and there was no sign of collapse. There were numerous wide cracks developed on the shear wall when compared to the beams, columns, beam column joints and slabs showing that the shearwall attracted more force and damage as it was more stiff when compared to the other structural members in the experimental model. The junction between the slab and the shearwall had developed cracks at all floors and the column at the corner diagonally opposite to the shearwall had developed more cracks due to torsion. An acceleration time history of the shock table and at one of the points (point1: at a beam column joint at 3rd floor) on the experimental model which were captured by accelerometers during different base impacts is shown in Fig. 6.

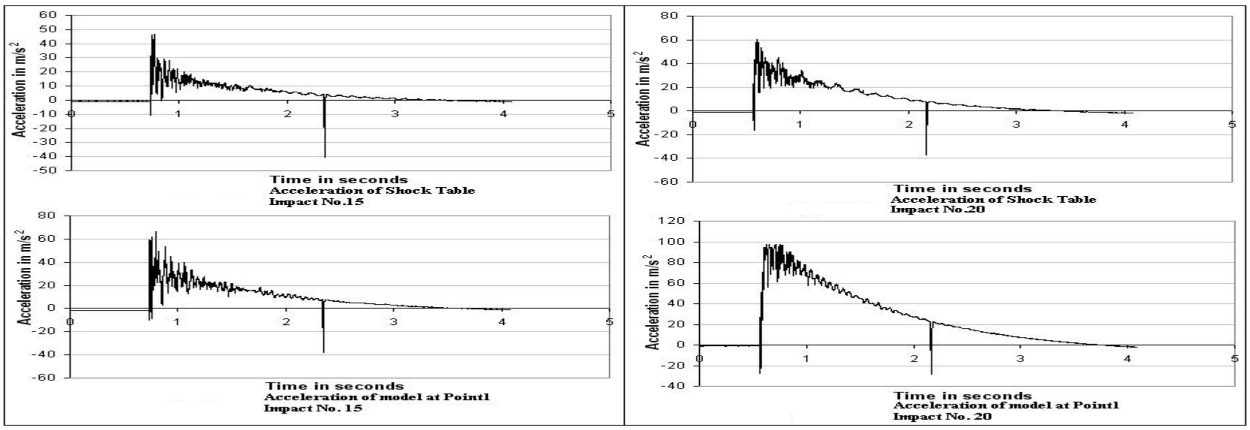


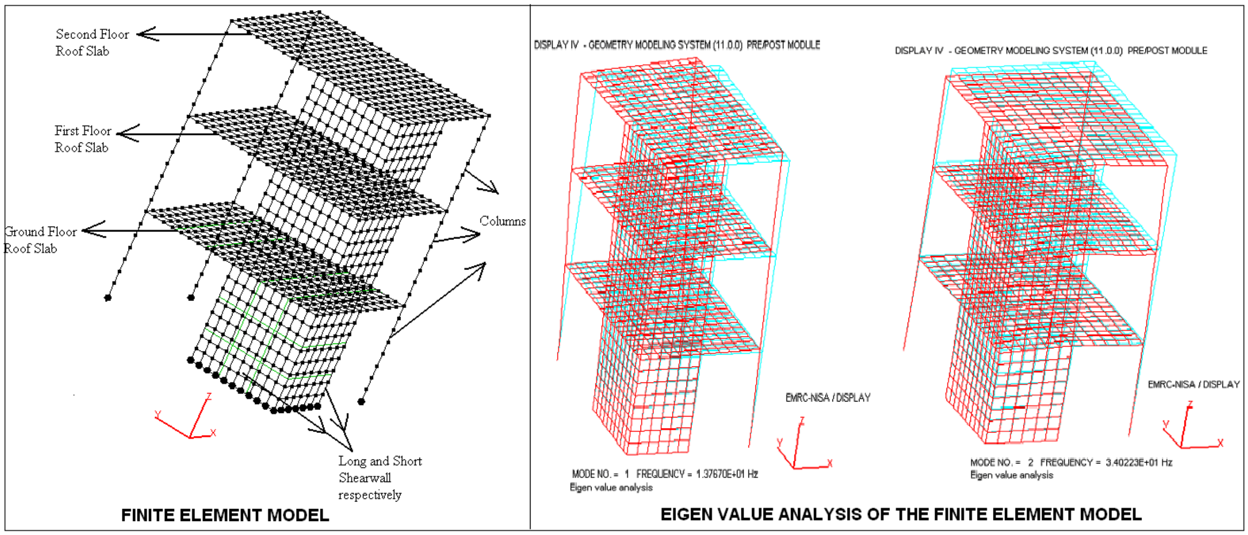
Fig. 6 Acceleration time history of the shock table and at one of the points(1)on the experimental model for different base impacts

ANALYTICAL INVESTIGATION

A finite element model was developed having same shape, dimensions and material properties as that of the experimental model using the preprocessor Diplay IV of the finite element package NISA11. The shearwalls and slabs in the finite element model were modeled using quadrilateral shell elements .The beams and columns in the analytical model were modeled as beam elements. Support conditions at the base of the shearwall and the columns has been given as fixed .The material properties assigned to the finite element model , especially the values of the young's modulus (E) assigned to the shearwall , columns , beams and slabs in the finite element model were the values thus got from the ultrasonic pulse velocity(NDT) test from the experimental model before performing the forced vibration (base impact) test. Three types of analysis have been carried out using the finite element package: Eigen value analysis, Quasi-static analysis and Linear Transient Dynamic Analysis.

Eigen Value Analysis

The eigen value analysis of the finite element model was performed and the first six natural frequencies and mode shapes of the analytical model were selected. Out of the 6 natural frequencies thus got the first natural frequency which was the fundamental frequency of the finite element model was 13.76 Hz and the FE model was in torsion mode about Z axis (vertical) in the first mode. This result matched nearly close to or exactly with the first natural frequency (13. 71Hz) of the experimental model and the mode also, as the experimental model experienced torsion during the base impacts which was observed during the test as the experimental model was seen to slightly twist about the vertical and there were spiral shaped cracks developed on the corner column which was diagonally opposite to the shearwall. Fig. 7 shows the finite element model, the first and second mode shapes of the eigen value analysis of the finite element model respectively.



(a) Finite element model (b) First and second mode shapes of the eigen value analysis

Fig. 7 Finite element model and the first and second mode shapes of the eigen value analysis of the finite element model

Quasi Static Analysis

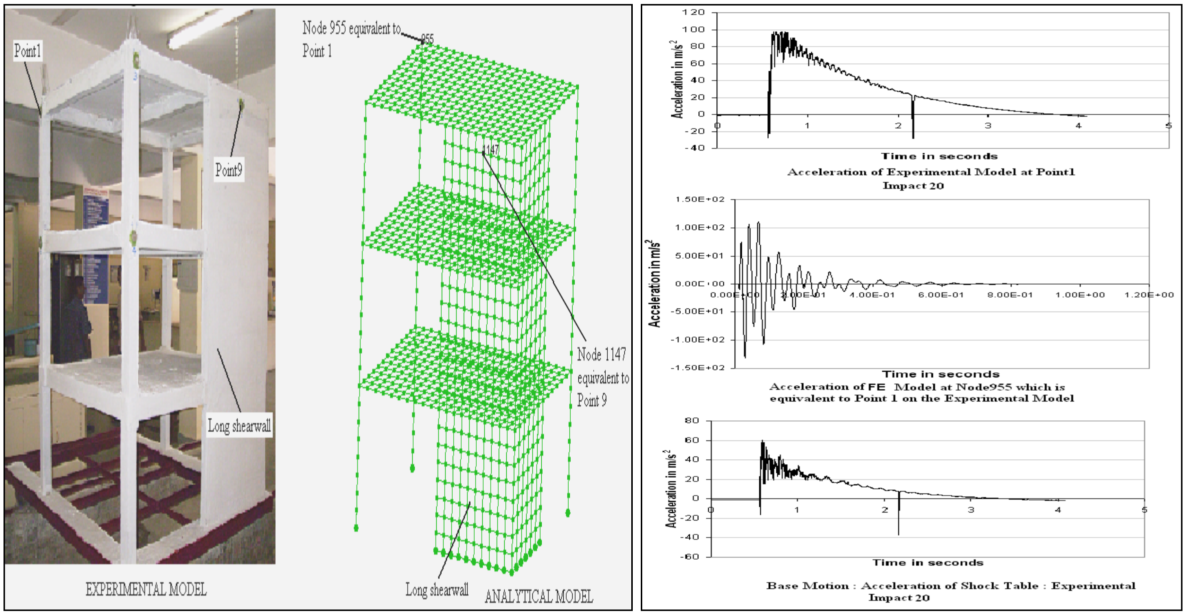
This is a quick and conservative method of estimating stresses at the maximum stressed zones in any structure. In the present investigation a lateral acceleration of 0.5g (4.905m/s^2) has been considered along Y-direction only(along the direction of the movement of the shock table). One more reason that the quasistatic analysis was done on the model is to identify the nodes in the model which were located in the maximum stress zones , so that , these nodes were selected in the Linear Transient Dynamic Analysis(TDA) to get the maximum stress time history of the model at these particular nodes.

Linear Transient Dynamic Analysis(TDA)

However the quasi static analysis doesn't take into account the dynamic behavior of the finite element model. The dynamic response of the finite element model has been obtained by caring out a linear transient dynamic analysis. It may be emphasized here that this analysis is a linear analysis in dynamics that takes into account the randomness associated with the shock load (impact load) and the dynamics of the problem .

The input "peak ground acceleration" for the finite element model in the linear transient dynamic analysis (TDA) along the Y-direction was the base acceleration data of the shock table for each base impact that was got from the accelerometer which was mounted on the rear end of the shock table during the base impact test thus obtained from the experimental investigation performed on the experimental model. The results of the linear transient dynamic analysis were obtained from selected nodes in the finite element (FE) model. The selected nodes in the FE model corresponded to the same geometric location on the experimental model where the accelerometers were mounted to capture the data during the base impacts, this has been shown in Fig. 8a.The accelerations obtained from the linear transient dynamic analysis (TDA) of the finite element model was in close comparison with the experimental values during the base impact test which is shown in Fig. 8b.

In the finite element model the location and shape of the tensile stress contours in the stress contour plots, which was obtained from linear transient dynamic analysis matched closely with the location of the cracks and cracking pattern developed on the shearwall and slabs, this has been shown Fig. 9 and Fig. 10 respectively.



(a)The TDA results were got from the nodes on the FE model which corresponded to the same location of the accelerometers on the experimental model

(b) Acceleration time histories obtained from the selected nodes on the FE model which is shown in 8a

Fig. 8 Comparison of accelerations got from the nodes of the FE model with that of the experimental model

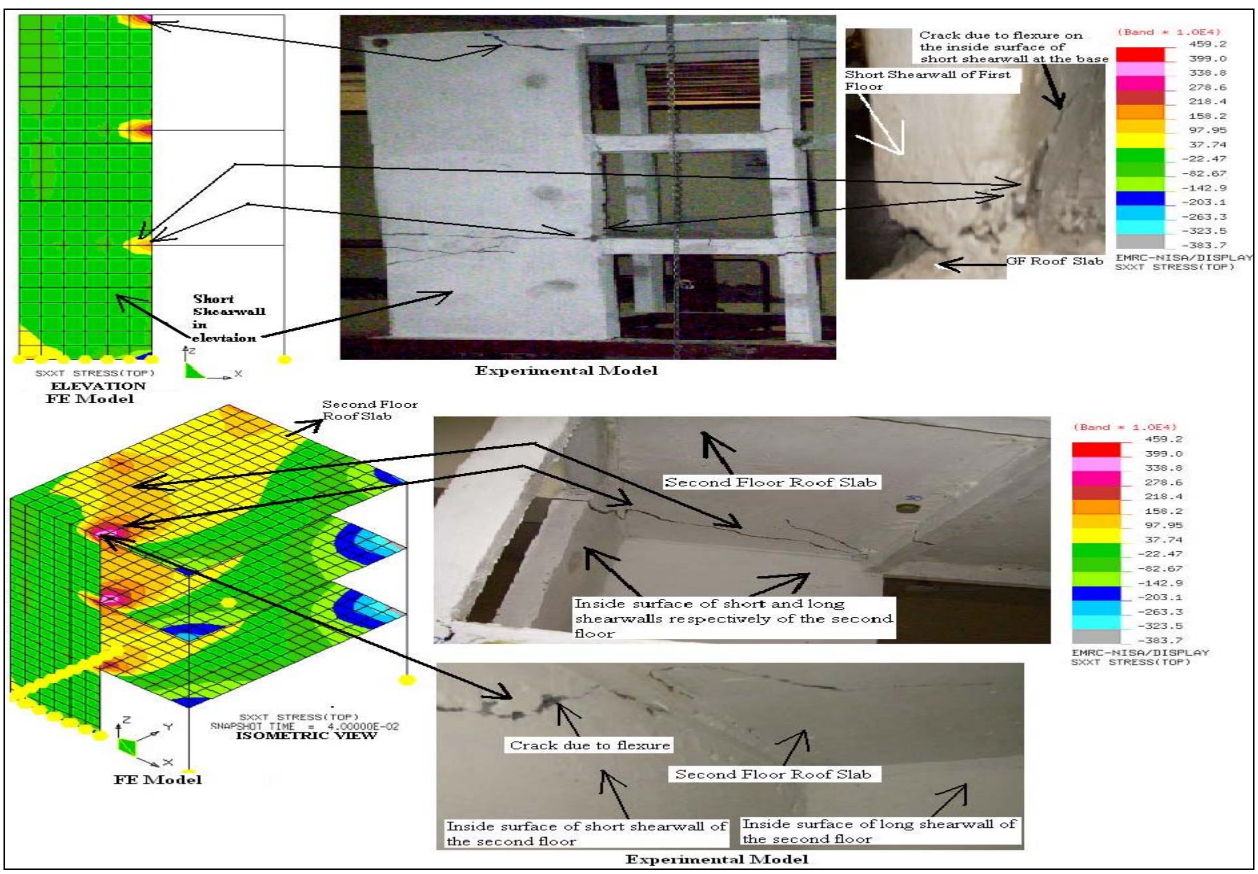


Fig. 9 Correlation of the stresses developed on the FE model from TDA with cracking pattern on the experimental model

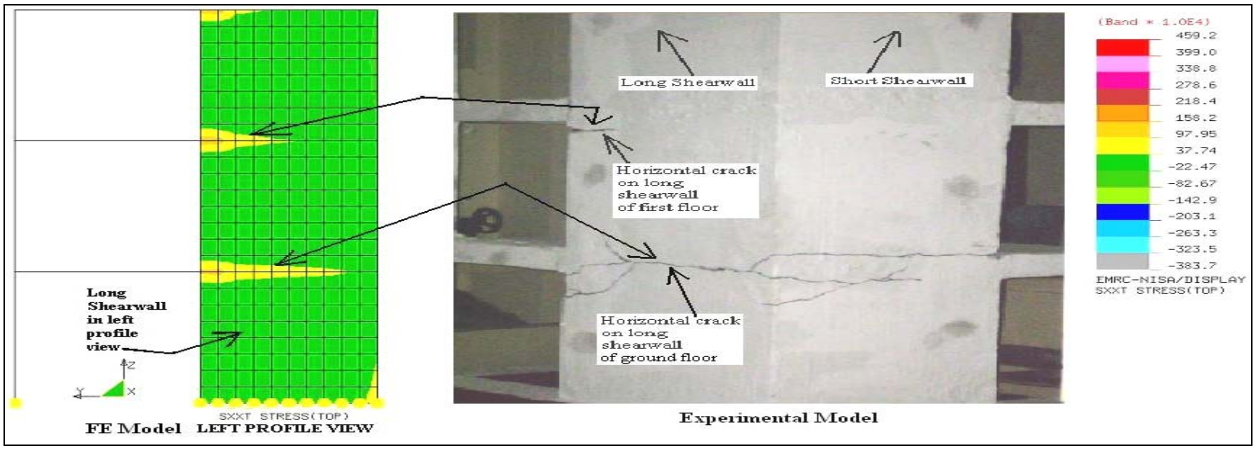


Fig. 10 Correlation of the stresses developed on the FE model from TDA with cracking pattern on the experimental model

CONCLUSION

Experimental observations showed that the existence of the shearwall made the model stiff and stable as the shearwall attracted more damage when compared to other structural elements such as the beams, slabs and columns without allowing for collapse of the model after being subjected to 210 base impacts. The shear wall which was L – shaped in plan and located at one corner of the model frame (unsymmetrically placed in plan) caused the model to behave in torsion. This gives the indication that buildings with shear walls placed unsymmetrical in plan undergo torsion when subjected to lateral load .The finite element model was able to exactly predict the first natural frequency of the experimental model in the eigen value analysis. The accelerations obtained from the linear transient dynamic analysis(TDA) of the finite element model was in close correlation with the accelerations of the experimental model (as seen in Fig. 8b). The location and shape of the tensile stress contours obtained from the linear transient dynamic analysis of the finite element model was in close correlation with the location of the cracks and cracking pattern developed on the shearwall and slabs of the experimental model .The finite element model was able to capture the behavior of the experimental model to the nearest values. The existence of the shearwall in the experimental model increased the stiffness, stability and the lateral load capacity of the whole structure.

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