CHAPTER 5

EXPERIMENTAL INVESTIGATION

5.1 GENERAL

The analytical study for the particular structures presented in chapter 4, showed that RTF and water tank are effective in reducing the response of the structure subjected to seismic excitation. In a logical next step, a shake table experimental study with a small-scale model with the intention of verifying the effectiveness of the proposed models as a vibration absorber in a real structure was carried out. Owing to the limited capacity of the testing equipment and a desire to investigate the performance of the models when the structure is subjected to seismic excitation, small scale models were used for the study. This chapter presents a detailed report of scaling of the model, and the experimental investigation carried out on a frame with and without the proposed vibration absorber system in a shake table subjected to sinusoidal excitations.

5.2 SCALING OF PROTOTYPE

Shaking table tests has proved to be a powerful method for assessing the seismic capacity of buildings. However the size and bearing capacity of shake tables are limited and full scale models may not prove economical. Hence the usual practice is to use scaled models. The design of scaling model adopts model materials, similitude law and estimation of relative test errors.
In physical experiments, it is difficult to simulate precisely the boundary conditions of a prototype by using a small-scale model, due to the errors induced from test specimens. Also, mechanical properties and experimental conditions could be different from each other. Nevertheless, a small scale model should satisfy the similitude relationship of a prototype and reflect significant properties on test results. Consequently satisfying the similitude law, small-scale model tests could be reliable to predict the seismic performance of prototypes.

5.2.1 General Similitude Law

Similitude law is generally applied to define a specimen for scaled model tests. A proper similitude law should be selected for satisfying a specific test objective or method. Typically in time-dependent loading problems, three independent scale factors, which represent three fundamental dimensions, namely, mass, length and time, need to be selected for designing the scaled models. Thus selecting three dimensions, other scale factors can be derived from the principles of dimensional analysis. Scale factors may be determined from consideration of the capacity of testing facilities in the scaled model tests. When the same materials on both a prototype and a scaled model are used, a scale factor for stress becomes unity. Thus, various derivatives can be obtained based on the selected dimensions. Considering an adequate added mass, three conventional similitude laws with the same material could be normally derived as shown in Table 5.1, in which a scale factor for length is S as a basic dimension.

5.2.1.1 Mass-based law

When the effect on gravity loads plays an important role, it is convenient to select a scale factor for mass as S3. In this law, mass distribution of prototypes is accurately simulated in scaled models and there is no need to
consider an added mass. However, a scale factor for time is defined as S. Such a compression of time would have complicated the test conditions. In particular, using a conventional dynamic testing method like shaking table tests, the limitation on shaking speed could be occurred. But pseudodynamic tests being carried out in a static manner may be satisfied with the mass-based similitude law.

5.2.1.2 Time-based law

If gravity loads can be negligible on evaluating the seismic performance of the scaled models, a scale factor for time can be chosen as a basic dimension. The work by Kumar (1997), this law has been justified by stating that since the frequency effects are preserved, qualitative information can be obtained regarding the seismic performance of the structure subjected to the given earthquake. However, in the inelastic range, it should be realized that structural response could not be obtained exactly, since the forces are no longer proportional to the displacement. The time-base similitude law has been mainly applied to the pseudodynamic tests by previous researchers. In case of the shaking table tests, an added mass is needed because a scale factor for mass is S.

5.2.1.3 Acceleration-based law

Although acceleration inputs as an artificial loading could be controlled, the acceleration of gravity is not controlled artificially. Thus, a scale factor for acceleration should be unity to simulate both gravity and inertia forces at the same time. In the acceleration- base similitude law, added mass and compressed time are needed for performing the real-time dynamic tests because scale factors for mass and time correspond to $S^2$ and $S^{\frac{1}{2}}$, respectively.
respectively. However, it is an ideal method for the pseudodynamic tests that deals with mass and time numerically assumed in a computer.

In the present work modeling of steel frame for a reinforced concrete prototype structure was done using acceleration based law. All the quantities except the mass was scaled down.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Dimension</th>
<th>Scale Factor</th>
<th>Acc. Based law</th>
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<tbody>
<tr>
<td></td>
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<td>Mass based law</td>
<td>Time based law</td>
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<td>Length</td>
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<td>S^3</td>
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<td>MT^{-2}</td>
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<td>Damping</td>
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<td>Frequency</td>
<td>T^{-1}</td>
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5.2.2 Prototype and Model

In the present work the prototype model considered was a single bay 3 storey framed reinforced concrete structure. The specifications of the prototype are given below:

Number of bays in x direction : 1
Number of bays in y direction : 1
Number of floors : 3
Spacing of columns in x and y direction : 3m c/c
Floor height : 3m
Beams and columns : 274 x 274mm
Slab : 120 mm thick
Natural Frequency : 4.08 Hz
Mass : 21614 kg

The scaling ratio for the model was taken as 1:6 due to the limitations of shake table facility available. Acceleration based law was adopted for scaling. The model material was taken as steel. All the parameters except the mass was scaled as per the law. No additional mass was added for the experiment. The specifications of the model are given below:

Number of bays in x direction : 1
Number of bays in y direction : 1
Number of floors : 0.5
Spacing in x and y direction : 0.5m c/c
Floor height : 0.5 m
Beams and columns : ISA 25 x 25 x 3 mm
Slab : 5 mm thick
Natural Frequency : 10Hz
Mass : 43 kg

5.3 STUDIES TO COMPARE FREQUENCIES

5.3.1 Analytical Studies

For analytical investigations of the model, the routines of ANSYS were used to design the model. Beams and columns were developed using
Beam 188 element and the slab using Shell 63 element. Figure 5.1 shows the model developed in ANSYS. To evaluate the frequencies of the system reduced method of modal analysis was used. The first three natural frequencies of the model were 9.998 Hz, 29.40 Hz and 47.62 Hz, respectively.

5.3.2 Experimental Investigation

Experimental investigations were carried out at A-Star laboratory, Structural Engineering Research Center (SERC) Tharamani, Chennai. To carry out the experimental investigations, the welded steel frame model was fabricated. Beams and column were made of ISA 25 x 25 x 3mm and the slabs were made of 5 mm thick plate. Spacing between the column was kept as 0.5m c/c and floor height was kept as 0.5m. Figure 5.2 shows the fabricated model.

Figure 5.1 ANSYS model of Scaled Model
The column legs were welded to 100 mm x 100mm x 10mm plates, which in turn was bolted to 16mm base plate. To find out the natural frequencies, an accelerometer was placed at the center of the top floor beam. This accelerometer was connected to the charge amplifier, which in turn was connected to Fast Fourier Transform (FFT) Analyzer shown in Figure 5.3. The schematic representation of the experimental setup is shown in Figure 5.4. A brief description of the equipment used is given below.

**Fast Fourier Transform Analyzer: (Make : A and W 3524)**

The Fast Fourier Transform (FFT) Analyzer is a signal analysing equipment in the field of vibration measurements. It is a user friendly device which is able to display and print spectrum and responses. FFT Analyzers take ‘time varying input signal’ and compute its frequency spectrum. Fourier's theorem states that any waveform in the time domain can be represented by the weighted sum of sines and cosines. The FFT Analyzer samples the input
signal, computes the magnitude of its sine and cosine components and displays the spectrum of these measured frequency components. A FFT Analyzer measures all frequency components at the same time. To measure the signal with higher resolution, the time record is increased. Figure 5.3 shows the FFT analyzer used.

**Accelerometer: (Make: Bruel and Kjaer 4370)**

An accelerometer is a device for measuring the acceleration and gravity induced reaction forces it experiences. They are used to sense inclination, vibration, and shock. The sensitivity of the accelerometer used was 9.96 picocoloumb/ms² and it weighed 54g.

**Charge Amplifier (Make: Bruel and Kjaer 2635)**

Charge amplifier is a circuit that does not amplify the electric charge present at its input, but actually obtain a voltage proportional to charge and yield a low output impedance. Hence it is a charge-to-voltage converter. The signals in terms of response from the structure sensed by the accelerometers are very minute. These small signals are amplified and fed into the FFT Analyzer.

![Figure 5.3 FFT analyzer with charge amplifier](image-url)
Initially, the model was gently tapped with a tamping rod at the top floor. The natural frequencies of the system were directly read from the FFT analyzer. The first three natural frequencies of the system were 11 Hz, 36.25 Hz, 61.875 Hz. The damping in the model was evaluated from the decay pattern of response time history record and it was noted as 1.03%. Hence the damping of the prototype, calculated as per acceleration based law is 3.95%.

5.4 RESPONSE TO SEISMIC ANALYSIS

In order to compare the behaviour of prototype and model, time history analysis was carried out on both the models in ANSYS using four earthquake data, namely, i) El Centro(E): The N-S component recorded at the Imperial Valley Irrigation District substation in El Centro, California, during the Imperial Valley California earthquake of May 18, 1940 with PGA of 0.35g. ii) Hachinohe(H): The N-S component recorded at Hachinohe City during Takochi-oki earthquake of May 16, 1968 with PGA 0.229g. iii) Kobe(K): The N-S component recorded at the Kobe Japanese Meteorological Agency (JMA) station during Hyogo-ken- Nanbu earthquake of January 17, 1995, with PGA 0.59g. iv) Northridge(N): The N-S component recorded at Sylmar County Hospital Parking lot in Sylmar, California, during Northridge, California earthquake of January 17, 1994 with PGA 0.843g.
the Elcentro data. The time interval for the model was reduced by $S^{1/2}$ (where $S$ is scale factor) and acceleration was taken as unity as per acceleration based law.

![Comparison of deflection pattern for Elcentro Data](image1.png)

**Figure 5.5** Comparison of deflection pattern for Elcentro Data

![Comparison of deflection pattern for Hachinohe Data](image2.png)

**Figure 5.6** Comparison of deflection pattern for Hachinohe Data
The damping in the model was found as 1.03%, hence prototype damping was taken as 3.95% ($S^{3/4}$). The peak response and deflection pattern was compared. The comparison of deflection pattern is given in Figure 5.5 to
Figure 5.8, and the maximum variation in peak response was obtained as 16%.

5.5 RESPONSE TO HARMONIC EXCITATION

The behaviour of the model without TMD was compared analytically and experimentally by subjecting the model to harmonic excitation. To carry out experimental investigation, the model was mounted on a slip table of dimensions 1m x 1m. The test setup involves the following: A computer with necessary software for vibration control is connected through a Local Area Network (LAN) to a Digital Vibration Controller. The output from this controller forms the input for the Power Amplifier which discharges the required power to the Ling slip table. Another setup line starts from the slip table and ends at the FFT Analyzer. Two channels arise from the slip table - Channel 1 from any of the floors slabs levels and Channel 2 from the base of the slip table. These channels pass through the Charge Amplifier and transfer the responses to the FFT Analyzer.

The response in this case is always relative and hence dimensionless.

Response = Response [Channel 1] / Response [Channel 2] = Top acceleration / Bottom acceleration

The model was subjected to a base acceleration of 0.07g and the peak response of the frame was found out. Figure 5.9 shows the response of the system. The response ratio was found as 117.633. The bottom acceleration was found as 0.34m/s². Hence the maximum acceleration response at the top floor was 39.995m/s².
5.5.1 Performance of RTF as TMD

As per the optimization procedure described in section 5.1.2, the optimized mass ratio and frequency ratio were 1.5% and 0.965 respectively, for the TMD. The RTF was designed for these optimize values. The RTF was designed with a single circular column and a steel plate to form the roof. The length of the column leg was 400 mm and diameter was kept as 10mm, the roof of the frame was made of 100 mm x 100 mm x 10mm steel plate. Figure 5.10a shows the RTF fabricated. The RTF was attached to the roof of the model at the center. Sweep swine test was carried out again subjecting the frame to an acceleration of 0.07g and the response of the structure was found. When RTF was mounted on the frame, the response ratio was 1.694 (Figure 5.11) in the first mode. Hence 69 times reduction in peak response was noted due to the addition of RTF.
5.5.2 Performance of Water tank as TMD

The Water Tank was made as a 100 x 100 x 50 mm box structure using a 1.2mm thick sheet. A single central column of length 400mm was welded to the bottom of the tank. The level of the water in the tank and the length of the leg of the column were adjusted to match the optimized parametric value. The tank with approximately half filled water matched with the optimized frequency ratio and the length of the leg was 400mm. Figure 5.10 b shows the fabricated water tank. The tank was mounted on the steel frame and sweep swine test was repeated. The response ratio was 10.7587 (Figure 5.12) when water tank with ½ water level was mounted on the frame, thereby reducing the response by 11 times. It was also observed that further increase in water level had very little impact in the response.

![Figure 5.10 Fabricated TMD](image)
5.6 COMPARISON WITH ANALYTICAL INVESTIGATION

For analytical investigations of the model, the routines of ANSYS were used to design the model. Beams and columns were developed using Beam 188 element and the slab using Shell 63 element. To evaluate the frequencies of the system reduced method of modal analysis was used. Harmonic analysis was carried on the model with an acceleration of 0.07g and
the peak response was found. Then the model was loaded with RTF and water tank at the roof at its center. Figure 5.13a and Figure 5.13b presents the model with RTF and water tank respectively. The modeled RTF and water tank had the same dimensions as that of the fabricated systems. Harmonic analysis was performed again to estimate the reduction in peak response due to the addition of RTF and water tank.

Figure 5.14 shows that the response reduction with RTF is 61% and with water tank as TMD it is 10%. There is good correlation between the analytical and experimental results.

(a) With RTF  
(b) With Water Tank

Figure 5.13  ANSYS model with TMD

![Graph showing response comparison](image)

Figure 5.14  Comparison of Response
5.7 SUMMARY

To validate the optimization procedure and the effectiveness of implementing RTF and water tank as TMD was experimentally investigated. Sweep sine tests were conducted on the model without TMD, with RTF as TMD and with water tank as TMD and the peak response of the system was measured in terms of relative acceleration. Results show that with RTF, up to 60% reduction can be achieved whereas with water tank the response reduction is around 10%.