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A Scaled Diagrid Building Model For Shake Table Test: A Simplistic Cost-Effective Approach

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Abstract: This study presents a cost-effective simplistic approach towards shake table experiment on a scaled DiaGrid building model. The DiaGrid mechanism consists of inclined columns in contrast to vertical columns in conventional structural mechanisms. The inclined columns convert all the external actions into axial actions (i.e. axial compression-tension), which makes the mechanism more stiff in resisting lateral forces, mainly high wind gusts and severe earthquake excitations. This study is focused to discuss a simplistic approach for constructing a scaled DiaGrid building model as well for performing a shake table test with few past severe earthquake time histories. The laws of similitudes and the availability of testing resources are the key factors limiting the model's scaling.

A Finite element software SAP2000 is used to validate the physical test results. Sticking to the simplistic approach, major parameter targeted for verifying results is 'lateral displacement'. Displacement values for all the considered earthquakes arrive close to the values obtained in FE analysis. The behavior of an actual DiaGrid structure under future earthquakes can be predicted by performing the simplistic shake table test on a small scale structure subject to probable, non-predictable, or even non-realistic ground shakings that might occur during the life span of the building.

Keywords: DiaGrid building, Shake table testing, Scaled model, Similitudes, Seismic behavior, Experimental analysis

Introduction

Tall structures are the only possible solutions for the densely packed urban regions. Engineers and architects round the globe are consistently trying to empower tall structures w.r.t. lateral forces like winds and earthquakes. Aesthetically rich tall structures significantly contribute to the city's architectural, cultural and tourism values e.g. Burj Khalifa (UAE), Taipei 101 (Taiwan), WTC (USA), Swiss Re (UK), CTF Finance Centre (China), Petronas Towers (Malaysia), Lotte Super Tower (South Korea) and many more. All these tall structures have different structural systems, looking to the type and intensity of the external forces, ground conditions, earthquake possibilities and also the architectural aesthetics.

A recent type of a structural system is the DiaGrid structural mechanism. A rapid evolution of this structural mechanism is observed mainly because of a simple triangular arrangement of the columns which not only contribute to the lateral stability of the structure but also adds an aesthetic appearance and attraction. Few known DiaGrid structures are shown in Fig. 1.

(a) (b) (c) (d) (e) (f)

Fig. 1: Few famous DiaGrid structures
(a) Shukhov Tower-Moscow (b) Bank of China Tower-China (c) Swiss Re Tower-UK (d) Hearst Tower-USA (e) Lotte Super Tower-South Korea (f) The Leadenhall Building-UK

Vladimir Shukhov, a visionary Russian engineer and architect, known for his innovations in lattice structures, was first to design an overhead water tank with the DiaGrid structural mechanism in 1896 (Edemskaya & Agkathidis, 2015; Rahimian, 2016). *The main mechanics associated with the DiaGrid system refers to the triangulation formation occurring by inclined columns and beams, due to which all the major lateral forces (earthquakes, winds, etc.) as well as the gravity forces (dead loads, superimposed loads, etc.) gets transformed into axial forces as axial compressions or axial tensions (Fig. 2). Thus, under lateral forces, DiaGrid mechanism handle shear deformations through axial forces unlikely to the conventional mechanisms which handles them mainly through flexural forces.*

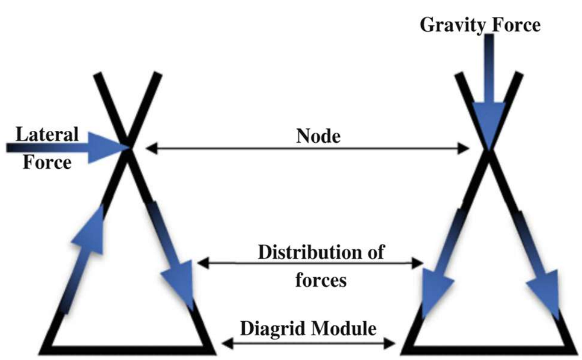


Fig. 2: Force distribution in a typical DiaGrid inclined column member

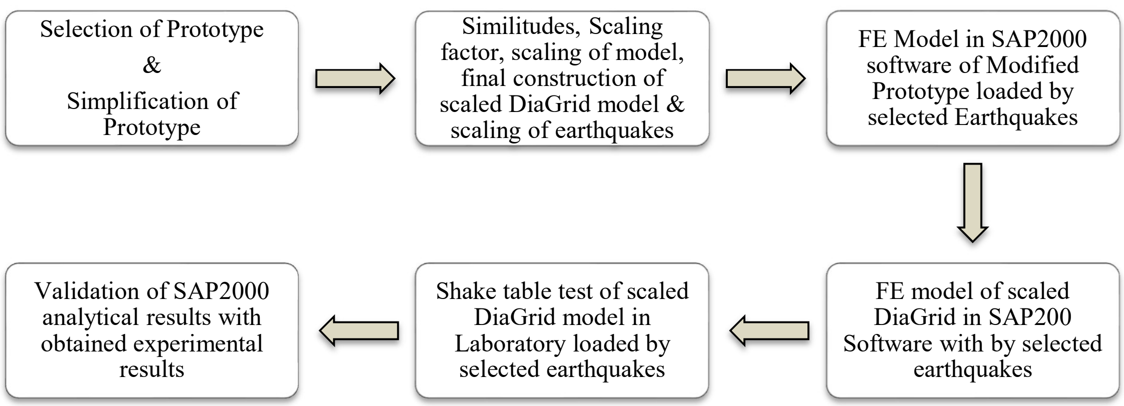
The overall strength of the DiaGrid mechanism depends upon the DiaGrid angle (θ). The *flexural rigidity* of the columns is maximum if they are oriented at $\theta = 90^0$ (vertical). The *shear rigidity* of the columns is maximum if they are oriented at $\theta = 35^0$ (inclined with horizontal at 35^0). For DiaGrid structures constructed so far, the major lateral loading considered is wind loading for which the optimal angle (θ) ranges between 60^0 to 70^0 with horizontal[3]. All the DiaGrid buildings that exists are build in regions with high wind gusts. Considering wind forces, major research on lateral stability of the DiaGrid structure is carried out so far.

It has been proven that DiaGrid performs better than other conventional moment-frame systems against wind forces, *but* the same has to be checked for earthquake forces also. Because for high seismic regions, earthquake forces become the dominant parameter for designing tall DiaGrid structures. However, none of the building design code so far is observed to have seismic performance factors for DiaGrid structures. Severe ground shakings demand very high lateral stability as well as sufficient ductility. Well, a preliminary seismic analysis has shown better performance of the DiaGrid compared to conventional moment frame structures (Naik & Desai, 2019).

For special structures to be constructed in the region of high seismicity, standard computational methods are not sufficient to evaluate lateral stability of the structure. To perfectly depict the actual-like behavior, shake tables tests are essential. Many researchers (Chunyu et al., 2012; Li et al., 2006; Shi, 2000; Watanabe & Hiroyuki, 2004; Zhou & Li, 2010) have conducted shake table tests and identified the key parameters governing the behavior of a structure under various ground motions. Almost all the types of prevailing building structures such as steel, RCC, Composite, wooden, high-rise, low-rise etc. are already tested and observed on shake tables. However, in the author's knowledge, none of the researcher have worked to experimentally observe behavior of a small scale DiaGrid structure under severe ground motions.

The aim of this study is to develop a cost-effective approach to construct a scaled DiaGrid model and conduct a shake table test, as opposed to a hi-fi shake table tests methods described in many research works (Heshmati et al., 2020; Liu et al., 2017; Moaveni et al., 2010; Saranik et al., 2012). This study explains a simplistic approach, procedure, necessary similitude relationships, construction of the scaled model, and lastly method and working of the complete shake table test for a DiaGrid building model.

The flow of the study



Prototype details and simplification

Hearst Tower, NY (Lucas, 2006; Rahimian & Eilon, 2008) is considered as the prototype. The symmetrical rectangular plan shape and relatively low height are the major reasons for selecting Hearst Tower as the reference prototype building (Fig.1-d). This building has been designed mainly considering gravity loads and wind loads. For seismic forces, the design was based on New York city building code, seismic zone-2A (Rahimian & Eilon, 2006).

For the scale down model of the Hearst Tower, few small modifications are done to achieve identical structural member sizes, plan symmetry and load distributions (Table 1). The original building in rectangular shape is simplified to a square plan shape to ease the construction and docking of the model on the shake table at the laboratory. *The main parameter of the DiaGrid mechanism- the DiaGrid angle - is not modified but adopted as same as the original i.e.* $\theta=70^0$.

All the diagonal members, beams, vertical columns of central core and the slabs are kept uniform in their respective sizes throughout the height. The original prototype consists of first 10 floors (non-DiaGrid) having an open hall space for architectural requirements (Naik & Desai, 2019). Above this hall space, there are 36 floors (as offices) with DiaGrid mechanism. But the simplified prototype considered for this study consists of only DiaGrid floors (i.e. 36 floors).

Table 1

Geometrical and Structural details of Hearst Tower, NY

Parameter	Prototype: Actual Hearst Building, NY	Simplified Prototype
Diagrid Module	Triangle with (b x h) = 12.12m x 16.54m, **θ = 70 degree**	Triangle with (b x h) = 12.375m x 16.95m, **θ = 70 degree**
Plan Dimension	48m x 37m	49.5m x 49.5m
Floor Nos.	10 (conventional floors) + **36** (DiaGrid)	**9** (each representing 4 floors) = 36
Total Height	34.14m (normal) +**148.86** (Diagrid)	152.55 (DiaGrid only)
Load per Floor area	Average (DL + LL) = 10 KN/m2	-Same-
Diagrid Member Sizes	Varying from bottom to top, W14 x 132 to W14 x 370	All diagonals of W14x 370
Peripheral Ring Beam size	W 30x 90	-Same-
Floor Beam size	W 21x 55 and W 21 x 48	-Same-
Material Used	Structural Steel A992 Grade-ASTM for DiaGrid and concrete for the core	-Same-

Similitude laws and scaling factors

Geometrical as well as kinematic or dynamic similarities are taken into account while scaling a prototype. Looking to the nature of the problem, researcher may adopt 'true', 'adequate' or 'distorted' model(Hamid Reza Tabatabaiefar & Bita Mansoury, 2015). *True* model is scaled by satisfying all the similarities. *Adequate* model is scaled aiming primary parameters of the problems allowing secondary parameters to influence to deviate the prediction. A *Distorted* model will achieve the predicted behavior with distortions in the similarities or vice versa(Moncarz & Krawinkler, 1981). Among all these three types, this study has adopted 'adequate' model for the low-cost shake table test. The similitude laws are considered with reference to a geometrical scaling factor **(λ)**. Finalising the scaling factor (λ), the following key-points are considered:

- The physical size of the shake table
- Pay-load capacity of the shake table
- Headroom availability in the laboratory
- Necessary material's availability
- Sizes of available structural members to be used for scaled model
- Member connection possibilities in the scaled model

Cauchy similitude and Froud similitude are the basic similitude relationships that, one may adopt for the testing of a scale-down model(Bairrao & Vaz, 2000). This study adopts Froud similitude laws. The inter relationships of all the geometrical and dynamic primary parameters are explained in table 2.

Table 2
Adopted similitude relationships

Length	λ	Acceleration	**1**	Mass density	**1**
Area	λ^2	Time	$\lambda^{1/2}$	Force	λ^3
Volume	λ^3	Frequency	$\lambda^{-1/2}$	Specific density (ρ)	**1**

Scaling Factor (λ)

The primary consideration for deciding the scaling factor (λ) is the size of the shake table and headroom available at the SVNIT laboratory of earthquake engineering. The simplified prototype has overall dimensions as 49.5m x 49.5m x 152.55m. The shake table size being (700mm x 1000mm) and headroom height permitted in the laboratory, the scaling factor (λ) arrives to 75. Approximating λ = 75 gives model dimensions as 660mm x 660mm x 2034mm. Well, It has to be checked for other parameters also.

The DiaGrid member size of the simplified prototype is uniformly W14 x 370 which is having a cross section area as 70322 mm^2. As the studies have shown that DiaGrid members mainly carry axial forces, thus the cross-section area dimension is targeted for deciding λ. The minimum dimension of round steel bars available in the market is 3mm, but advisable is 4mm (for welding requirements). 4mm diameter bars with a cross section area as 12.5mm^2 allows the scaling factor as 75 $\left(\lambda \approx \sqrt{70322/12.5}\right)$.

The floor load (DL +LL) on the building (Mele et al., 2012) is around 1000 kg/m^2. Considering 49.5m square floor, the total load on the typical floor is 2300000 kg. So, the total floor load from all the 36 floors is 83000000 kg. Adding self-weights of the diagonals and central core columns, the total weight of the simplified prototype is 96520000 kg*. For designing the scale model, the specific density ρ (the ratio of overall mass over overall volume) is taken as 1.

$$\rho_{simplified\ prtototype} = \rho_{model}$$

$$\Rightarrow \left(\frac{Total\ Mass}{Overall\ Volume}\right)_{simplified\ prototype} = \frac{96520000}{49.5 \cdot 49.5 \cdot 49.5} = \rho_{model} = 258.22\ kg/m^3$$

$$\Rightarrow \rho_{model} = \left(\frac{Total\ Mass}{Overall\ Volume}\right)_{model} = \frac{Total\ mass\ of\ the\ model}{0.66 \cdot 0.66 \cdot 2.034} = 258.22\ kg/m^3$$

$$\therefore\ Total\ mass\ of\ the\ model = \frac{258.22}{0.66 \cdot 0.66 \cdot 2.034} = \mathbf{230\ kg} \qquad (1)$$

Self-weight of the model plus some *additional mass* on each floor can satisfy this specific density criteria. Another important parameter to be considered is related to the dynamic similarity, i.e. natural frequency of the building. The calculated natural frequency of the simplified prototype is 0.44 Hz. Therefore, the natural frequency of the scaled model should be 3.8 Hz ($\sqrt{75} \times 0.44$). This also fits into the frequency range of the unidirectional shake table available at the SVNIT laboratory of earthquake engineering.

Looking to all the above major key parameters, the scaling factor finalised is $\boldsymbol{\lambda = 75}$.

The design and construction of 1:75 scale model

The overall size of the scaled DiaGrid model is 660mm x 660mm x 2034mm. The diagonal members- the main load carrying members of DiaGrid mechanism- are finalized as 4mm diameter mild steel bright bars. Peripheral beams connected to the DiaGrid members are finalized as 3mm steel bright bars. The mild steel plate of 2mm thickness is used as slabs. The central core with vertical columns is designed with the same 4mm diameter mild steel bright bars. The 5mm thick base plate is projected 100 mm outward from the plan dimensions of the model.

All the joints are welded joints with higher fabricating accuracy. To depict the actual DiaGrid joint (DiaGrid Node), 20 mm x 20 mm plates with 2 mm thickness are used and the DiaGrid members and ring beams are welded uniformly to this steel plate. This enables the transferring of forces as uniformly as in the actual

*Calculated by author

prototype. Moreover, during the excitations, to control the unwanted buckling in the diagonals, ring beams are introduced at half floor height to reduce the unsupported length of the diagonals.

The material used to manufacture the model is steel bright bars for 1D structural members and mild steel plates for 2D structural members. The stress-strain relationship of a 12mm bright bar is shown in Fig. 3. The tensile test results are used to define the material properties in SAP2000 software.

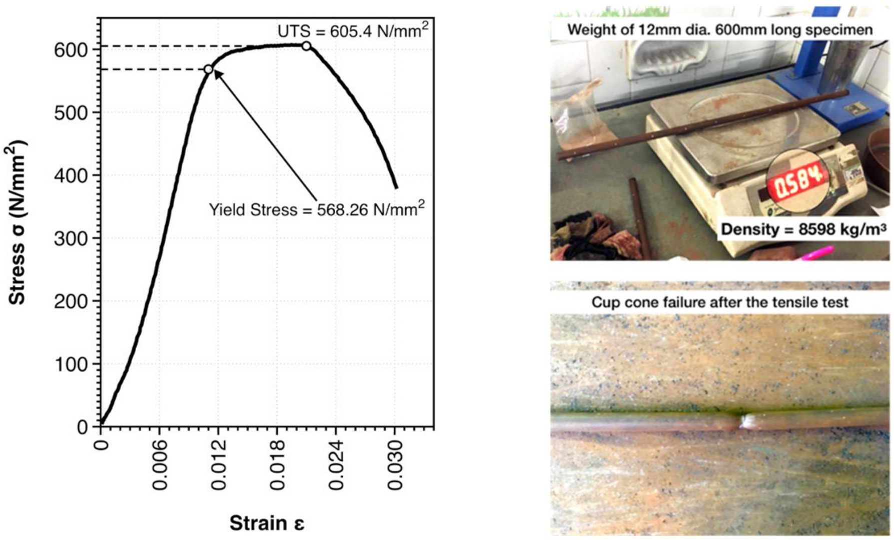


Fig. 3: Stress-Strain relation from Tensile test on a steel bright bar and other details from the test

The self-weight of the model including the base plate is around 93 kg (Fig. 4). According to dynamic similarity requirement, the mass should be **230 kg** (Eq. 1). An additional mass of 137 kg is to be installed before testing the model. Further, distributing this additional mass into 9 floors, each floor should be allotted around 15 kg of extra mass. The diagonal grid does not allow much space to apply the masses. So, 3 numbers of 5 kg each mass blocks (Fig. 4) are designed in such a manner that they can be easily placed or removed from the model when required.

Fig. 4: Weight of the model and the mass block

Special care is taken for mounting the model onto the shake table. The model should be perfectly mounted to match the exact lateral direction of the shaking movement. If there exists a little deviation in mounting, the shaking may produce torsion in the model. To achieve this, a uniform grid of bolt holes are fabricated on the base plate to match the holes on the shake table. The detailed construction drawing of the scaled DiaGrid model is shown in Fig. 5.

Scaling of earthquake time histories

A typical earthquake time history data is in the form of acceleration/ velocity/ displacement versus time. Three actual earthquake time history records, including Kobe (Japan, 1995), El Centro (USA, 1940) and Uttarkashi (India, 1991) are selected for performing the shake table test on the scaled model. The detailed description of selected earthquakes is given in table 3. One may select as many variety of earthquakes as he/she can, but to keep the study concise and simple, only three actual time histories are considered.

The scaling of the actual earthquake data is done considering the principle of dynamic similarity. The accelerations of the model and the prototype remain same, (Table 2) i.e. the scaling relation is 1.0. Therefore, the accelerations of actual earthquake and scaled earthquake need to remain same. Thus, the 'time' is scaled (Meymand, 1998).The original time step (time interval between two successive data value) of the earthquake time histories is scaled with $\sqrt{\lambda}$. Each time step is multiplied with ($\sqrt{75}$) = 0.1155. The earthquake time histories are shown in Fig. 6.

Table 3
The primary details of selected earthquakes^

Earthquake	Country & Station	Component	Peak Ground Acceleration (PGA) (cm/s²)	Mw (R)	Hypo-central distance (km)	Time Duration (s)	Original time step (Δt)	Scaled time step 0.1155*Δt
Kobe,1995	JAPAN JMA station	0	805.4	6.8	48	48	0.02	0.00231
El Centro,1940	USA, USGS station 0117	180	350	6.9	54	54	0.005	0.00058
Uttarkashi,1991	INDIA, IITR station	75	304.2	7.0	39.5	39.5	0.02	0.00231

^Source: https://www.strongmotioncenter.org

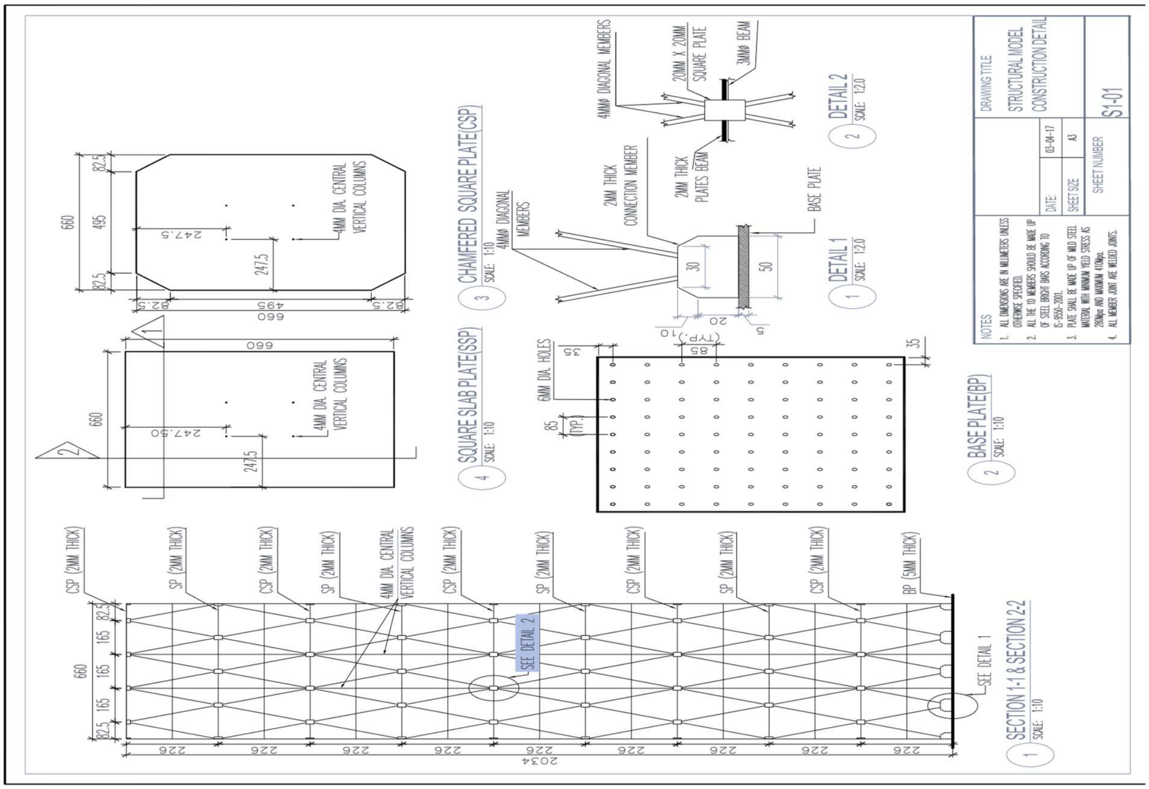


Fig. 5: Construction detailing of the model

Testing of the scaled model

The main aim of the shake table test is to evaluate seismic response and to observe behavior of a structure. The top storey displacement, inter-storey displacements, modal frequencies, damping ratio etc. can be the parameters for studying behavior of the structural model. To achieve the above aim, the scaled model is prepared according to the design and construction requirements (Fig. 5). The model is firmly fixed on the shake table. The data acquisition system is attached to record the acceleration values. The accelerometers are fixed at floor levels to capture acceleration v/s time data. The displacements v/s time data can be obtained by double integrating the captured acceleration v/s time data.

The data acquisition system here used is NI cDAQ-9174, along with the LabView software to record and process the captured data. The model consists of total 9 floor levels, but considering the availability of 'input ports' in the data acquisition system, the accelerometers are attached at 8 floors, starting from the top (Fig. 7, Fig. 8). The time history input to the shake table is prepared as follows:

Actual time history data (acceleration v/s time) → Scaled time history data (acceleration v/s scaled time) → double integration of scaled time history (displacement v/s time)

The displacement time histories are derived from the scaled time histories of selected earthquakes. Double integrating the scaled acceleration time histories in time domain gives scaled displacement time histories. These scaled displacement time histories can be given as input (Fig. 9) to the shake table controller. The test is performed to evaluate the lateral displacements under the effect of the applied earthquakes. A Fast Fourier Transform (FFT) of the recorded acceleration data is also performed to assess the natural frequency of the tested scaled model in order to confirm dynamic similarity.

A trial test is done in prior to the actual test using few known constant frequency cycles. The results are verified using SAP2000 software (similar to a sine sweep test).

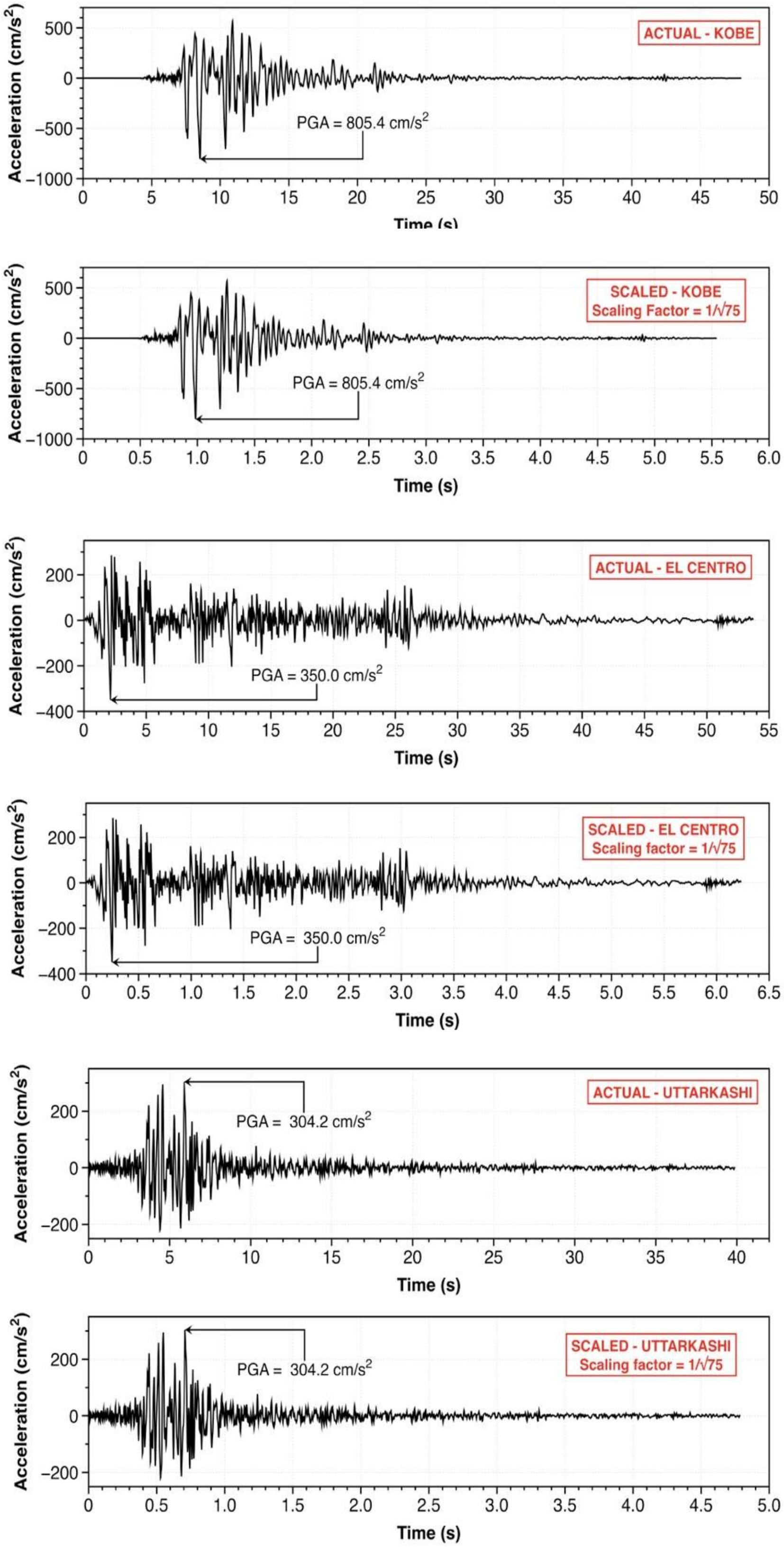


Fig. 6: Actual records and scaled records of selected earthquake

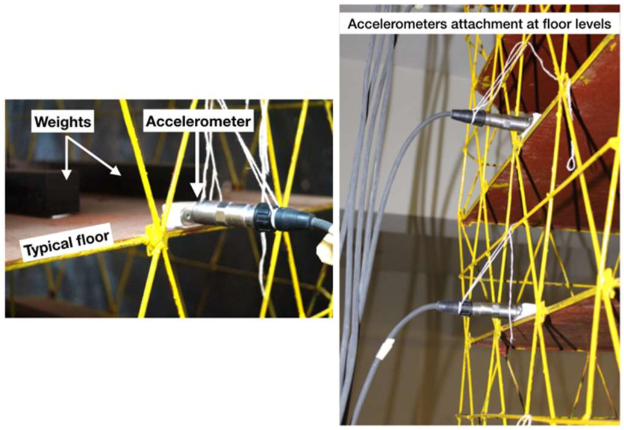


Fig. 7: Accelerometer attachments and details

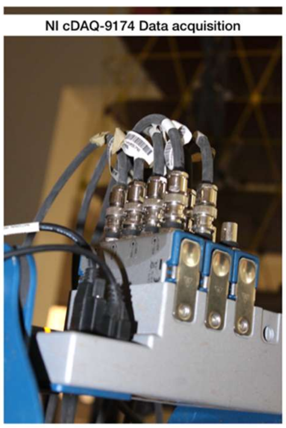


Fig. 8: Data acquisition system and attachments

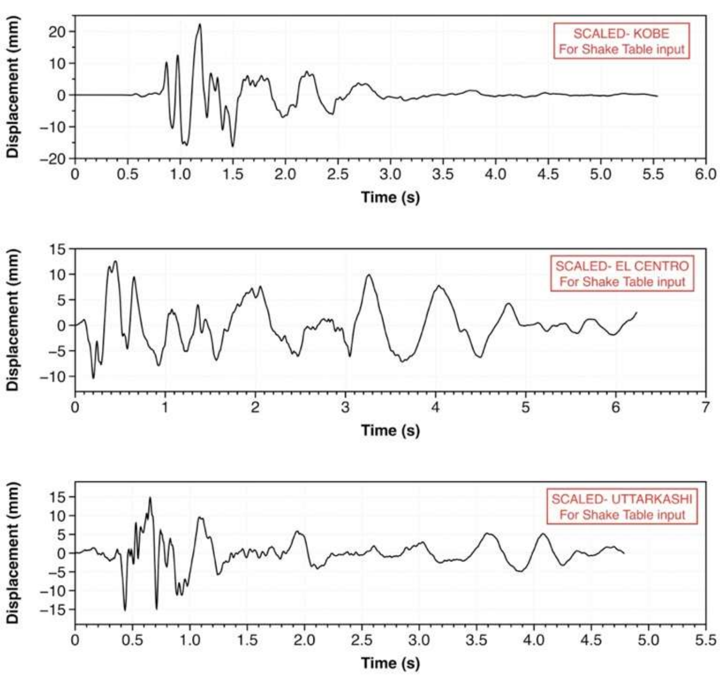


Fig. 9: Input to shake table controller- displacement v/s time

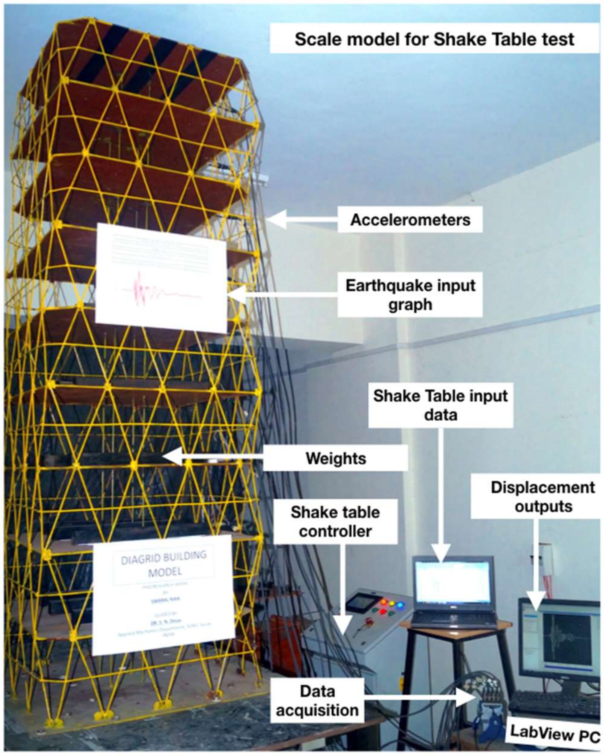


Fig. 10: Experimental setup

Results and Discussion

The recorded floor displacement v/s time graphs are in good accordance with the input displacement time history graphs for all the selected earthquakes. It is evident from Fig. 11 that the scale model has shaken exactly as it was expected to. The post shaking behavior of the model is also visible from these graphs. The recorded graph pattern and maximum lateral displacement values are later compared with the numerical analysis performed in SAP2000 software.

The maximum lateral displacements at floors are shown in Fig.12. Moreover, the modal frequency of the model is observed to verify the dynamic properties. The mass being kept same, verifying the modal frequency will give a clear idea of the stiffness of the model. As per similitude laws, the modal frequency should be 3.44 Hz. The experimental modal frequency is carried out using a mathematical process called Fast Fourier Transform (FFT) in LabView software. The FFT process transforms given values from time domain to frequency domain. After performing FFT to captured time domain data, the modal frequency resulted is 3.38 Hz. The SAP2000 also gives the 1st modal frequency as 3.32 Hz. All these values are in acceptable limit. The stiffness of actual scaled model and analytical model are in a good match.

Validation of experimental results

The obtained results & behavior of the model are verified using FE software SAP2000 (see FE model in Fig. 13). All the experimental values of storey displacement are closely matching with analytical values from SAP2000 (Fig. 14). Moreover, all the experimental values (displacement v/s time) captured for the floors (as shown in fig. 11) also matches to the values obtained from SAP2000 software (see fig. 15). It should be noted that while modelling in SAP2000, there shall be no compromise about the material properties, geometrical properties, joint connections, base constraints, constraint's locations, loadings, etc. (table 4).

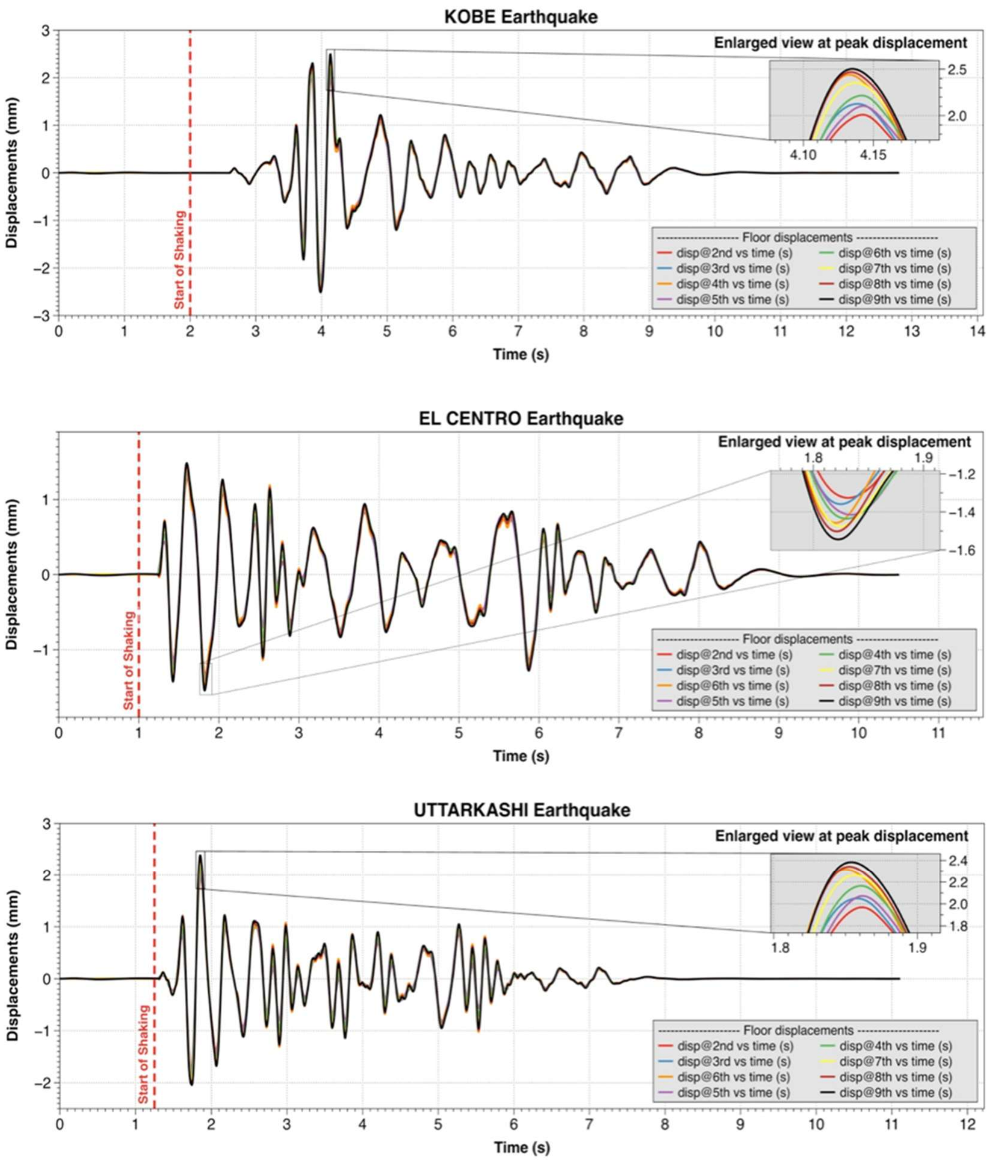


Fig. 11: Experimental records of floor displacements for selected earthquakes

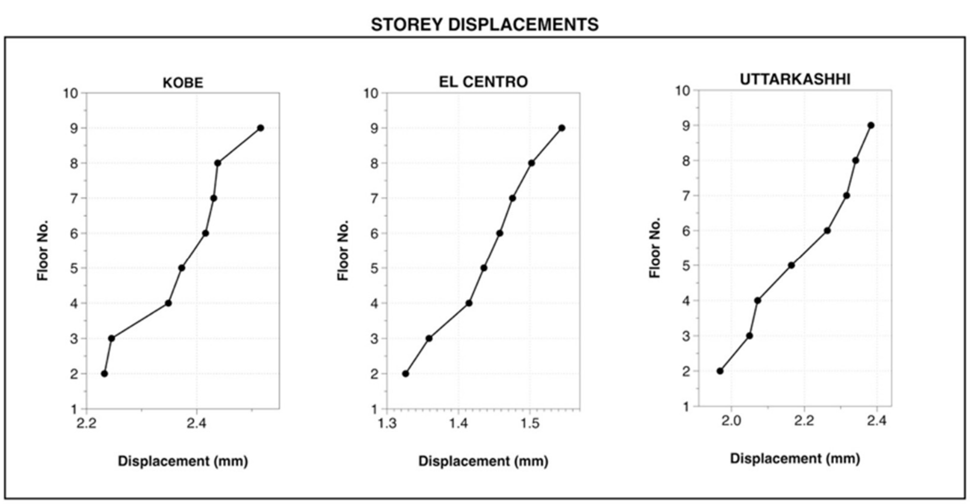


Fig. 12: Experimental records of maximum floor displacement values

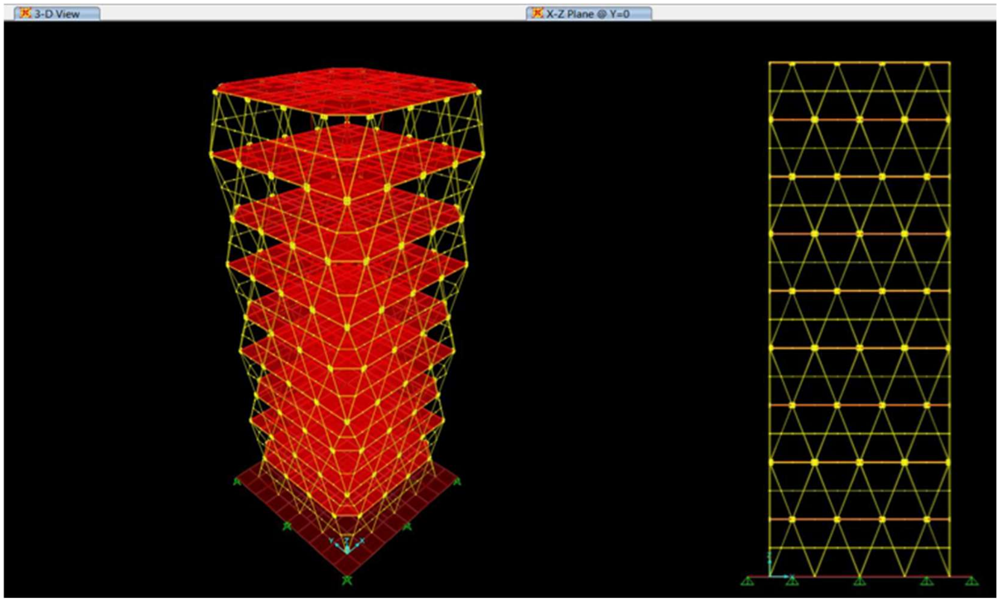


Fig. 13: SAP2000 model views

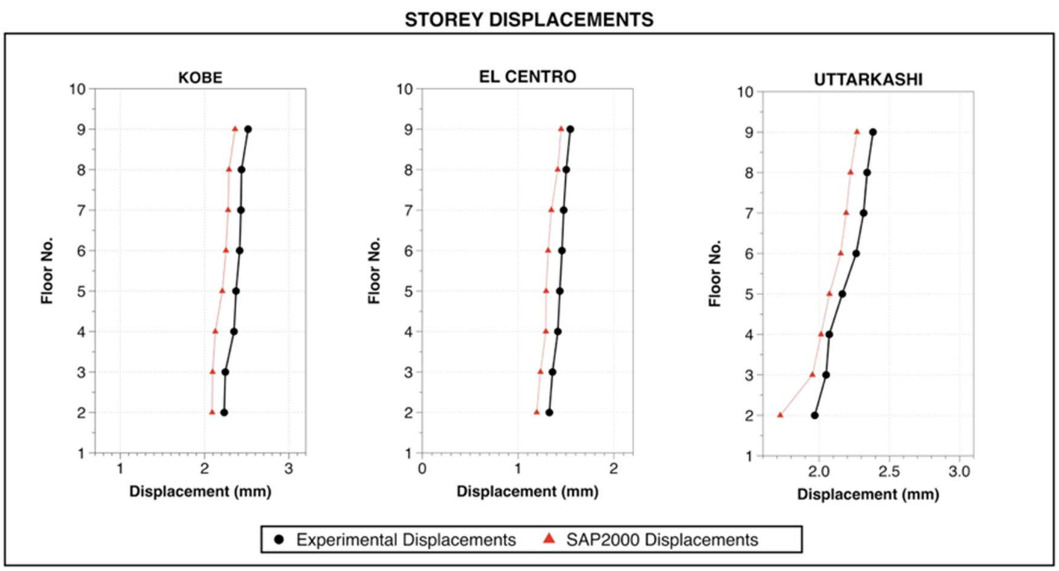
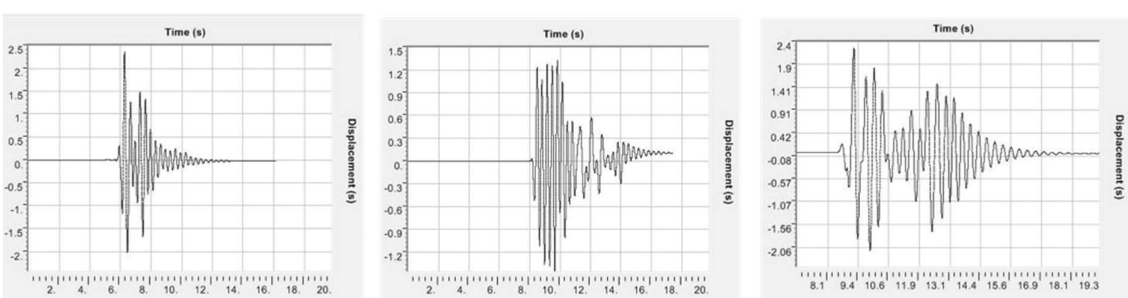


Fig. 14: Comparison of experimental results and SAP2000 results



(a) (b) (c)

Fig. 15: Displacement v/s time results from SAP2000 software for (a) Kobe earthquake (b) El Centro earthquake (c) Uttarkashi earthquake

Table 4
Major parameters incorporated in SAP2000 software

DiaGrid Diameter	Beam Diameter	Columns, Diameter	Slab plate Thickness	E (MPa)	ρ (kg/m^3)	μ	Super imposed floor load
4 mm	3 mm	4 mm	2 mm	2.0E5	8598	0.29	34 kg/m^2 ≈ 15kg/floor

Discussion

The experimental results and the analytical predictions are in good accordance with each other. All the experimental values are differing with the analytical values within 5% to 7% range. Even for these random shaking under the influence of earthquakes, the results are within acceptance range which shows that the methodology and analytical procedures considered are fairly correct. Another observation is regarding the diminishing pattern of the obtained results. Once earthquake comes to rest, from the very moment, the displacement values diminishes faster compared to the same values from the SAP2000 software. This is because the software analyses the model in ideal condition and damping after stopping of the earthquake.
The differences in the experimental values and SAP2000 values (Table 5) are mainly because of the energy absorption at bolted base connections. This cannot be exactly adopted for a rigid base connection in the software. Also, all other connections being welded, there might have been some minor defects which could not be incorporated in the software. The software considers all the joints with complete continuity and fixity. Moreover, the shake table may have produced minor deviations in displacements while shaking with the given input data.

Table 5
Experimental and analytical results comparison for top displacements

Earthquake	Experimental result	Analytical result	% difference
Kobe	2.5157	2.3614	**6.53**
El Centro	1.5446	1.4492	**3.02**
Uttarkashi	2.3832	2.2693	**4.78**

Conclusion

This study has shown detailed procedure for making a scaled DiaGrid model as well as conducting a shake table test on the same.
Experimental study includes three various earthquake time history data as input to the shake table. The behaviour of the model under the shakings is captured through lateral displacements. To verify the design of the scaled model as well as the testing procedure, the same was prepared in a FE software SAP200 for analytical evaluation. The SAP2000 FE model is assigned all the geometry, loading and material as same as for the physical scaled model of DiaGrid. Assigning the same ground shaking in the FE model and analysing for the results analytically, it closely matches to the experimental results. This proves that, the test procedures and concepts used for the study are fairly correct.
A simple DiaGrid building model subjected to ground shakings is analysed in the study. This study will open a window to many researchers and students who are working to optimize earthquake resistant tall structures. The presented methodology can be applied to various DiaGrid models for further study. Also, DiaGrid models can be compared with same size models with different conventional structural systems. As far as the author's

knowledge, no such clear simplistic approach to a shake table testing for a DiaGrid model is studied and presented. This study does not aim for a particular result or parameter to optimise DiaGrid under earthquakes, but just gives a clear insight into the simplistic approach for performing shake table tests.

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