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MODEL EXPERIMENTAL STUDY ON THE BEHAVIOUR OF TALL STAGGERED WALL STRUCTURES

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ABSTRACT

This study investigates the behaviour of tall staggered wall buildings in which the external load bearing walls of the structure is achieved by staggered wall arrangement along the height of the structure.

Complete Perspex tall staggered wall structure model is fabricated and the complex model is subjected to static and shaking table vibration tests. Simplifications in the analytical approach are implemented and the final idealized model of the staggered wall structures to predict the behaviour of staggered wall building is analysed. The simplified approach predicted good agreement of deflections with static tests and the shaking table natural frequency results have shown some discrepancies within the normal bond of the experiments.

Keywords: Model testing; tall building; staggered shear-wall; shake table test; static test.

1. INTRODUCTION

Changes in structural design philosophies for tall buildings from moment resisting frames and flexible frames with heavy infills to stiffer lightweight structures has resulted in increased use of various forms of structural walls [1]. A combination of shear wall and frame structures has proven to provide a major if not all the required strength for lateral loading of tall building. The perimeter frame and the central wall act as a composite structure as the lateral force is mostly carried by the frame in the upper portion of the building and by the core in the lower portion [2].

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One innovative structural system developed to meet the building massing requirements take the form of perimeter staggered shear-walls combined to a central core. These elements will provide the major required strength for lateral loading resulting from gravity, wind and earthquake effects. The horizontal load is transferred to staggered walls below through diaphragm action of floor slabs [3]. The staggered walls are designed as storey-high deep beams [4].

Tests of scaled models conducted in laboratories ([5-9]) along with analytical techniques ([10-12]) and numerical methods ([13-14]) can reveal important information of how a structure performs under complex hazardous environments such as earthquake.

In view of the introduction this new type of external bearing for high rise buildings, achieved by staggered wall arrangement along the height of the structure, experimental work on a three dimensional Perspex model to provide the necessary information on the elastic behaviour of such structures has been carried out.

The tests have been carried out on static rig to study the response of the structure to horizontal loads and on a shake table to evaluate the dynamic characteristics in fundamental modes.

The aim of this study is to investigate the behaviour of a tall staggered wall building and a comparison of results with a simplified analytic approach based on the combination of the frame analogy and the simplicity of the continuous connection approach ([10-15]) is presented.

Static and dynamic tests on such complex model structure have not been previously done and this work is a contribution that will serve to more advanced studies.

2. THE TEST MODEL STRUCTURE

Model analysis and testing represents an approach in which relatively few simplifying assumptions need be made [16].

A symmetrical Perspex model structure of staggered wall building is built. The structure consists of perimeter diagonals and a central core. The diagonals are created by casting a staggered pattern of walls on consecutive levels The broad faces of the model have a pair of single diagonal bracings creating a coupled braced frame, while the narrow faces have double intersecting diagonal bracings Fig. 1 (a), (b), (c). The final 38 storey model structure is an example of a staggered wall structure suitable for tall buildings.

2.1 Model material

The material for the model should have a modulus of elasticity low enough in comparison with the maximum permissible stress, for the required degree of accuracy of measurement of both deflection and strain to be achieved and so that straining of the material beyond its elastic limit does not occur. Of the plastic available in sheet form, acrylic is probably the most suitable in that it is easy to machine and joint with appropriate solvents.

Hence plastic material of low modulus of elasticity such as Perspex has been chosen for the construction of the model. The effect of humidity on such material are negligible and if precautions related to temperature controlled conditions are observed, acceptable results can be obtained.

The followings are mechanical properties values of the perspex material:
Young modulus E= 2900 N/mm^2; density ρ= 1.18 gr/cm^3; Poisson's ratio ν=0.36

2.2 Model construction

The thirty eight storey model of 60 mm height and 2280 mm overall height was constructed from sheet Perspex to the plan dimension of Fig. 1. It can be seen that the load resisting system consists of core 'C', one pair of staggered shear walls 'A' and two pairs of staggered shear walls 'B' of Fig. 1 (a); (b).

All floor slabs, the core structure and external staggered shear walls are nominally 3 mm thick.

The component parts of the model were cut roughly and machined to the required dimensions. Where openings in the perspex sheets were to be provided, these were cut using 5 mm diameter slotting cutter giving a 2.5 mm radius fillet at each corner.

The complex shapes of the staggered walls ′A′ and ′B′ were cut using a 10 mm diameter cutter. The model was founded on a 20 mm thick slab of perspex. The vertical units of the model were cemented into 15 mm deep slots in the base using ″Tensol″ cement N°12 (dichloro methane mixture). Holes were cut in the floor slabs to accommodate the core which was first cemented separately using ″Tensol″ cement N°12 and put into position on the base.

The model is relatively high, its construction conforming to the first configuration with no external bearing B, was done in different stages. First a number of slabs were slipped down from the top of the model to the required level and kept into position from each other by distance pieces. The whole assembly was welded together, using (silicone compound) for core-slabs connections and ″Tensol″ cement N°12 for external bearings A-slabs connections. The same process was repeated and the model representing configuration type 1 was built, and then tested.

The external load bearings B were added and cemented to the first type of model using ″Tensol″ cement N°12. The complete model in its last configuration was then tested.

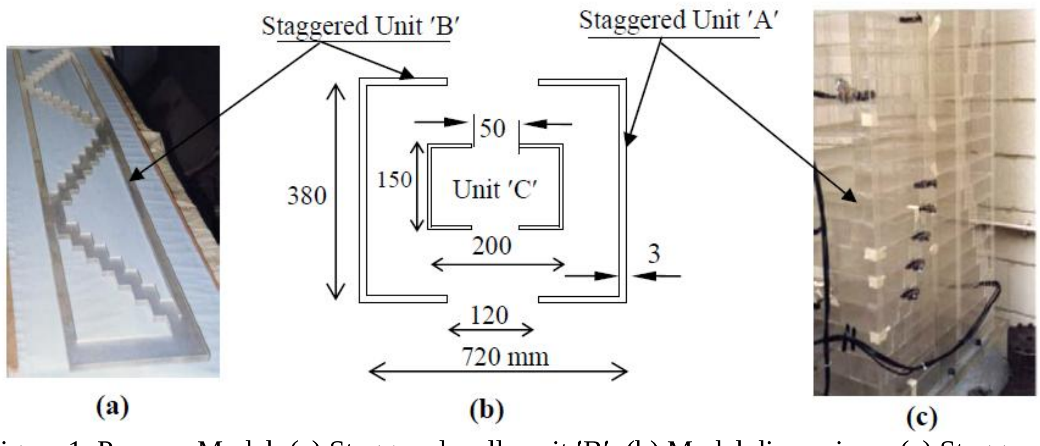

Figure 1. Perspex Model: (a) Staggered walls unit ′B′; (b) Model dimensions; (c) Staggered walls assembly

3. TESTING EQUIPMENT

3.1 Static test

The static testing rig comprises three U units of 305 mm x102 mm x 42.18 kg universal channels welded to three 1524 mm x 762 mm x 25 mm thick steel plates each of which was bored with a 200 mm square grid of 12 mm diameter holes to allow the passage of holding down bolts.

The perspex base was fastened directly to the horizontal steel plate by means 10 mm bolts.

The model was loaded at every forth level by means of lead shot bags applied to hangers suspended by nylon threads looped around the floor slabs and passed over free running pulleys. These pulleys were fixed to a vertical steel angle Fig. 2(a).

The loads were applied in increments of 100 grams up to 1000 grams. At each increment deflections are measured by means of dial gauges, of accuracy 0.01 mm, supported by magnetic stands attached to the vertical steel plates. Strains were measured by means of electrical resistance strain gauges (Shoa 5 mm, 120 Ohms). Strain gauges and terminal strips were attached to the perspex and dummy gauges were connected to a separate piece of perspex to compensate for small temperature changes, Fig. 2(b). All strain gauges were insulated using a drying polymethane coating and wired to a switch box which is in turn connected to a strain indicator which recorded the strains directly in micro-strains. For further protection against temperature variations the monitoring system, that is the switch box and the strain indicator, was covered with a polythene sheet.

3.2 Dynamic test

Shake tables are frequently used to study structural behaviour under earthquake ([17-18]).

A series of vibration tests were used to determine experimentally the dynamic characteristics of the model structure such as natural frequencies, mode shapes and damping in the structure.

The model was bolted securely to a hydraulically floated shake table which could be given sinusoidal input in the range 0.5 to 2000 Hz at a maximum power input of 2 x 250 watts, Fig. 3 (a).

Accelerometers were used to monitor the response of the model. The amplified readings were taken from an accurately calibrated, high gain, two channel storage oscilloscope, Fig. 3 (b).

The first four measured natural periods of vibration of the model were determined and values of damping were obtained from the forced vibration.

(a) (b)

Figure 2. Static test rig (a) Perspex Model; (b) Strain bridge, switching box and a separate piece of perspex with dummy gauges

(a) (b)

Figure 3. Vibration test rig (a) Model on shake table; (b) Power amplifiers, accelerometer amplifiers

4. EXPERIMENTAL INVESTIGATION

4.1 Static tests: procedures and results

The loadings were applied in increments at the centre of the model to produce bending, and in such magnitudes that any creep effects in the perspex were insignificant.

To determine the most suitable positions for strain gauges it was necessary to consider the possible structural action of the model. Fortunately the cross section is symmetrical about two axes and it was therefore decided to confine the first set of strain gauges to one face of the external load bearing structure ′A′.

To ensure that the stresses would be less affected by any localised foundation effects, the strains were measured above the third floor.

Deflections and strains were noted at each increment and load-deflection and load-strain curves were plotted.

The pulley system was subsequently moved to one corner of the model where the dial gauges were positioned and another test run was carried out for combined bending and torsion effects.

All the tests were carried out quickly and to a strict time schedule to minimise errors due to creep of the perspex.

A range of test results corresponding to pure bending with a load applied near the centre of rotation, and bending with torsional loading applied at the extreme edge of the slabs are presented, Figs. 4 and 5.

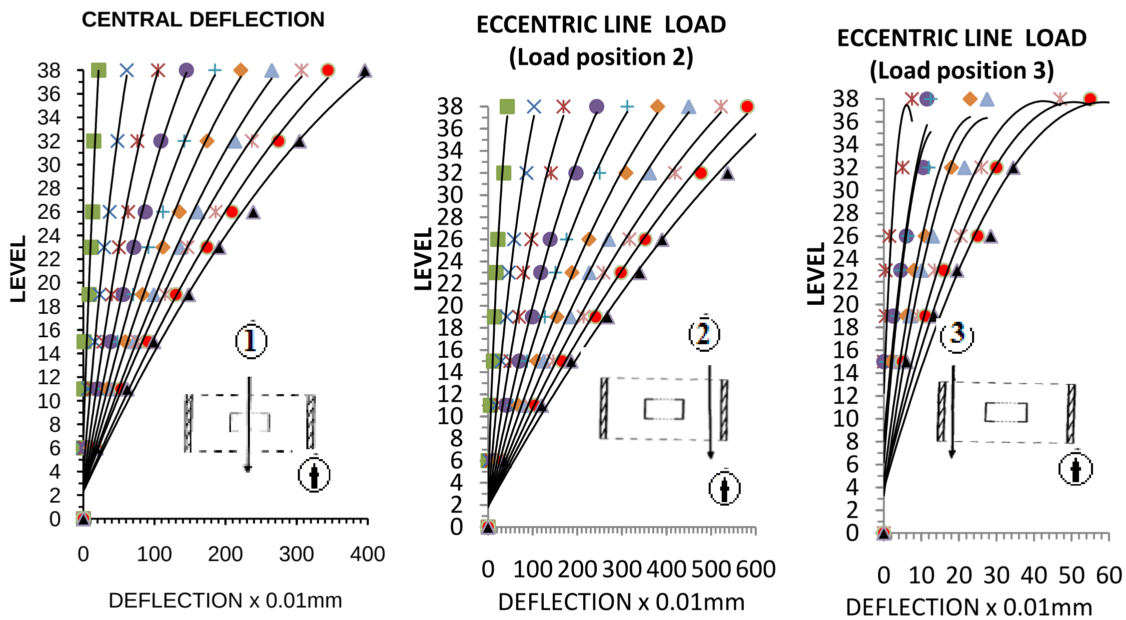

Figure 4. Deflection profile of the model [Model Phase I]

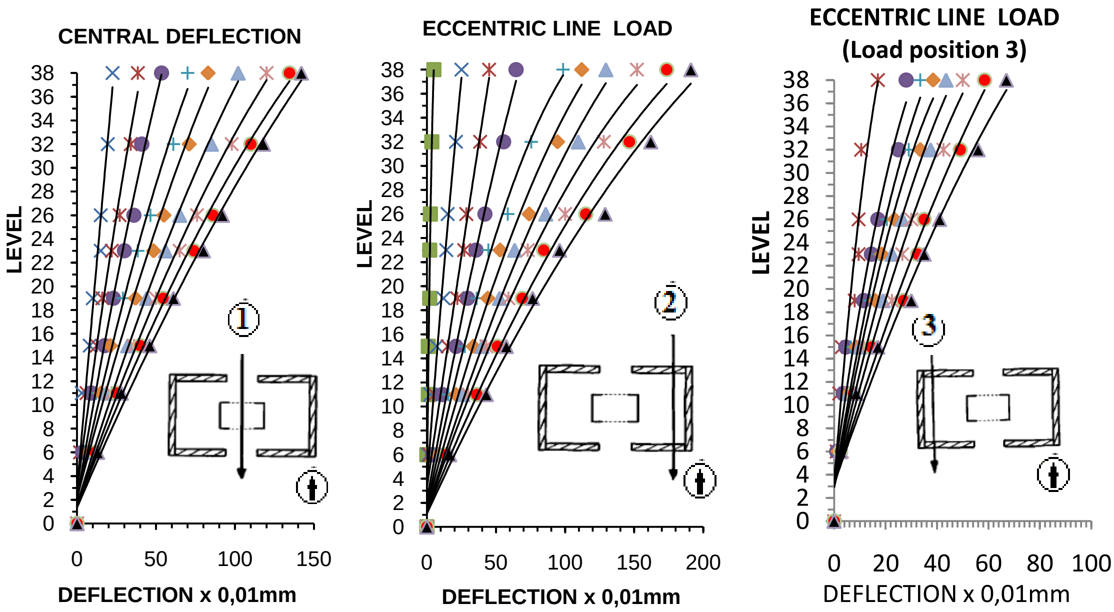

Figure 5. Deflection profile of the model [Model Phase II]

4.2 Dynamic tests: procedures and results

After the first series of static tests was complete, the model was moved to the shake table to which the base was securely bolted, Fig. 3(a). The model was vibrated through the range 1 to 400 Hz several times. Employing an accelerometer mounted at the top of the model, where the movements are greatest, the natural frequencies of vibration of the model structure were determined. The accelerometers were connected to the oscilloscope, and relative magnitudes were easily found [19]. Around each natural frequency, readings over the frequency band were taken and values of response against frequency were plotted to determine values of the critical damping, using the half power point method [20].

Mode shapes for the first four natural frequencies were obtained by keeping the frequency constant and recording the amplitude at each level by suitably positioning the accelerometers.

These tests were carried out with centrally placed accelerometers and a second test series followed, with accelerometers placed at the edge of the model.

The static and dynamic tests were therefore concluded for the first phase model structure and the external load bearing assemblies ′B′ were added and tests repeated for the phase two model.

Usually, only the first few modes of vibration contain enough vibrational energy. Fig. 6 shows the first four lateral mode of vibration of the idealized staggered wall structure.

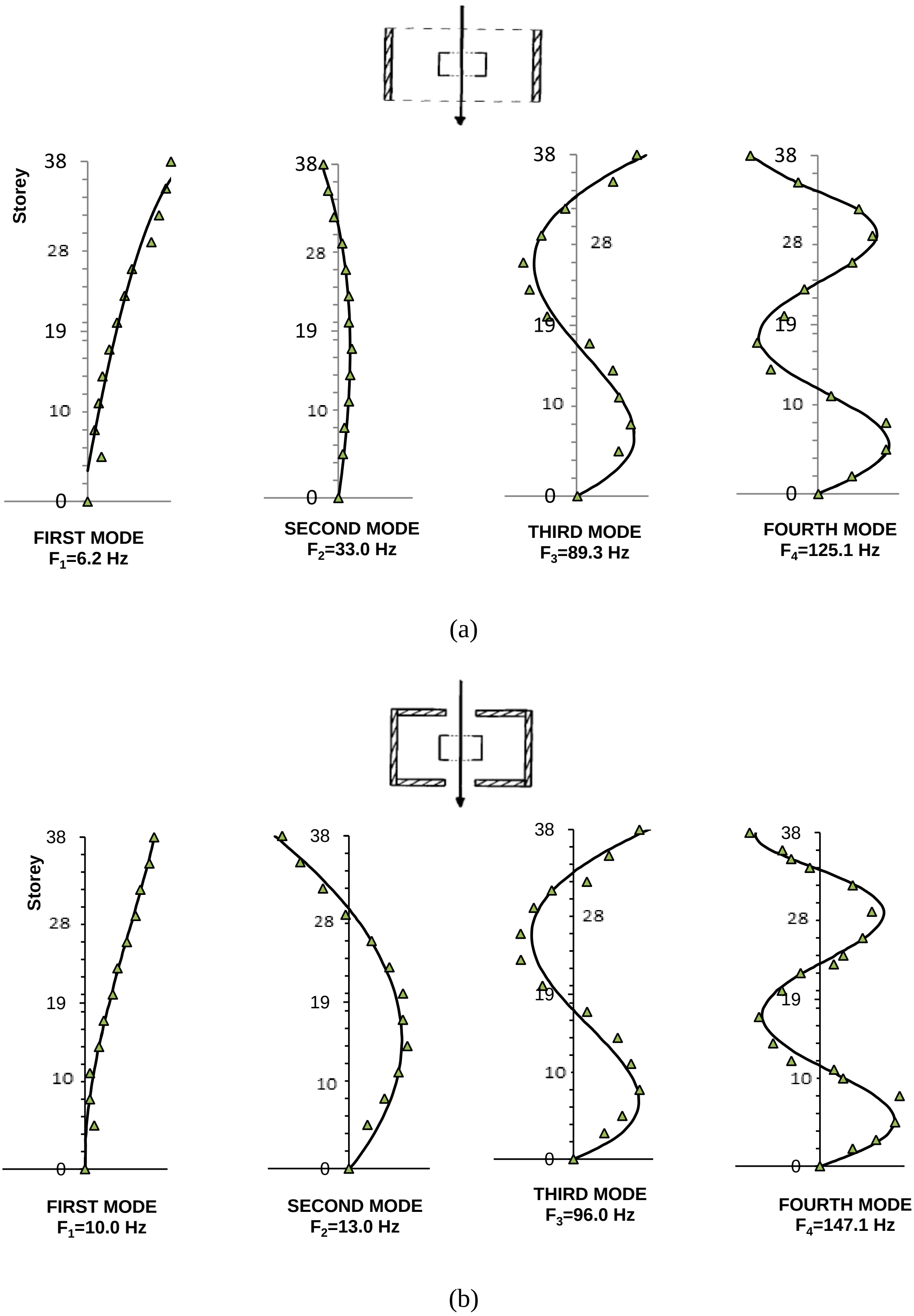

Figure 6. Mode shapes (a) Model structure ′A′; (b) Model structure ′B′

Around each natural frequency, readings over the frequency band were taken and values of response against frequency were plotted Fig. 6 to determine values of the critical damping, using half power method.

Table 1 shows values of the percentage of critical dumping for the three remaining modes.

Table 1: Critical dumping of the model structure with staggered wall ‘A’, (b) With staggered walls units ′B′ added

Mode	Experimental critical dumping	
	Model structure-‘A’	Model structure-‘B’
2	0.065	0.035
3	0.042	0.042
4	0.035	0.038

The percentage of critical dumping in the model varied with the frequency of vibration and average values of 4.9% and 4.1 % of critical dumping was obtained for model structure with staggered walls unit ′A′ and with staggered walls′B′ added, respectively .

5. SIMPLIFIED ANALYSIS METHOD

Although the formulation of a three dimensional analysis of almost any tall building structure is possible, simplifications of the problem were implemented for our analytical approach.

In this approach, the three dimensional model structures are subdivided into its major bracing systems, Fig. 7.

The overall action and analysis procedures for the basic structure are dealt with in the following manner:

The floor slabs are connected solely by floor slabs; the analysis has been performed with beam equivalent stiffness [3], and the staggered wall systems are idealized as frame systems [15].

A more simplified structure, Fig. 4, having the same overall shape and dimensions as the complex one was then adopted.

Most of the work was based on the concept of the continuous connection method [10] and the direct finite element analysis using beam element which is one of the most practical alternatives from the computing point of view [21].

5.1 Assumptions

The floors are considered to be rigid in their own plane.

The geometry of plan, storey height, member properties, elastic modulus and Poisson’s ratio are all assumed to be constant through the height of the structure.

For the torsional analysis of the couple core, the continuous connection technique is used. Vlasov’s thin-walled beam theory applies.

Lumped mass are considered at reference levels for the solution of eigenvalue problem.

5.2 Simplification of the structure

The simplified structure is obtained by reducing the number of horizontal floor slabs Fig. 7. If the effective length of the member is increased by the removal of lateral supports, the moment of inertia of the member should be increased such that [15]:

$$I_S = I_C.(N_C/N_S)^2 \quad (1)$$

Where s represents the simplified structure, c the complex one and N the number of members. The cross-sectional area of the member is assumed unaltered.

If identical structural members are equally spaced, their number can be reduced, by increasing the moment of inertia of each removing member to:

$$I_S = I_C.N_C/N_S \quad (2)$$

And increasing their cross sectional areas to:

$$A_S = A_C.N_C/N_S \quad (3)$$

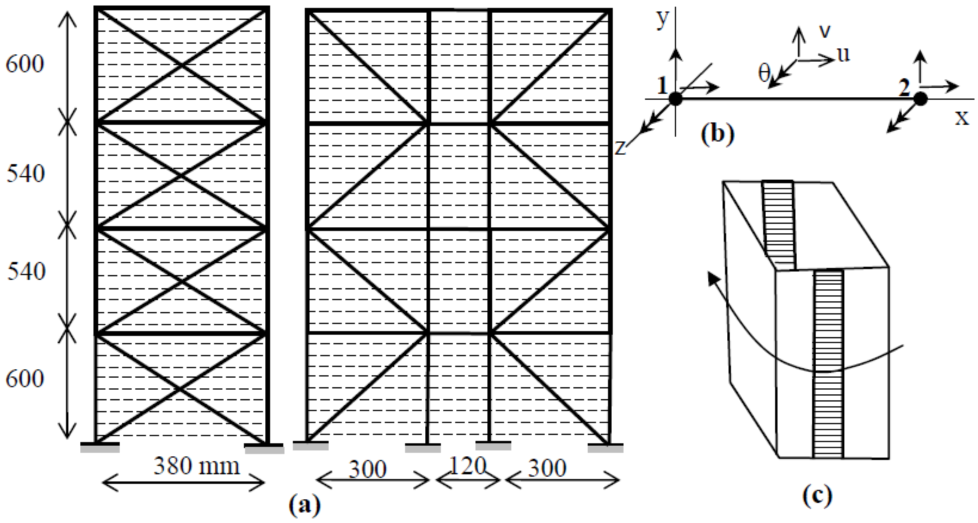

Figure 7. Idealised structures (a) Lateral bracing A and B; (b) Beam element; (c) Core C

5.3 Analysis of the complete structure

The load deflection relationship may be expressed in matrix form [10] as,

$$\underline{Y}_k = \underline{F}_k.\ \underline{P}_k \quad (4)$$

$\underline{Y}_k$ et $\underline{P}_k$ are column vectors of deflections y_{ik} and total applied load p_{ik} at the set chosen reference level x_i, and $\underline{F}_k$ is a square flexibility matrix of influence coefficients f_{ijk} obtained using the direct finite element approach and the cantilever bending theory for the staggered wall units and the cantilever channels respectively.

Relationships of the form of the above equation may be set up for each wall assembly.

For the core system unit ′C′, the torque rotation relationship is expressed in the form,

$$\underline{\theta}=\underline{K}_k\,.\underline{T}_k \tag{5}$$

$\underline{\theta}$ and $\underline{T}_k$ are column vectors of rotations θ_i and total twisting moments T_i at the same set of reference levels, and $\underline{K}_k$ is a square matrix of influence coefficients k_{ijk}.

The displacement of any element at level x_i at a distance z_k from the centre of rotation consists of a deflection $y_i + \theta_i . z_k$ and a rotation θ_i .Equation (4) becomes,

$$\underline{Y}_k = \underline{y} + \underline{\theta}\,.\underline{z}_k = \underline{F}_k .\, \underline{P}_k \tag{6}$$

where $\underline{y}$ and $\underline{\theta}$ are column vectors of the deflection of the datum position and the rotation at each reference level.

The forces must be resisted by the wall system assemblies, so that, for horizontal and rotational equilibrium,

$$\begin{gathered}\underline{P}_i = \sum P_{ik} \\ \underline{T}_i = \sum P_{ik}\,.\,z_k + \sum T_{ik}\end{gathered} \tag{7}$$

P_{ik} and T_{ik} are the horizontal load and twisting moment carried by wall assemblies. For the complete structure, the equilibrium equations become,

$$\begin{gathered}\underline{P} = \Sigma \underline{P}_k\,; \\ \underline{T} = \Sigma \underline{P}_k z_k + \Sigma \underline{T}_k;\end{gathered} \tag{8}$$

$\underline{P}$ and $\underline{T}$ are the column vectors of the total applied load and twisting moment at each level.

Substitution of equations (6), (5) into (8) yields,

$$\begin{gathered}\underline{P} = \Sigma \underline{F}_k^{-1}.\, (\underline{y} + \underline{\theta}.z_k) \\ \underline{T} = \Sigma \underline{F}_k^{-1}.\, (\underline{y} + \underline{\theta}.z_k).z_k + \Sigma \underline{K}_k^{-1}.\underline{\theta}\end{gathered} \tag{9}$$

The solution of Equations (9) is,

$$\begin{gathered}\underline{y} = [\underline{G}_1 - \underline{G}_2.\, \underline{G}_3^{-1}.\, \underline{G}_2]^{-1}.\, [\, \underline{P} - \underline{G}_2.\, \underline{G}_3^{-1}.\underline{T}\,] \\ \underline{\theta} = [\, \underline{G}_3 - \underline{G}_2.\, \underline{G}_1^{-1}.\underline{G}_2]^{-1}.[\underline{T} - \underline{G}_2.\underline{G}_1^{-1}.\underline{P}\,]\end{gathered} \tag{10}$$

Where

$\underline{G}_1 = \Sigma \underline{F}_k^{-1}$
$\underline{G}_2 = \Sigma \underline{F}_k^{-1}.\, z_k$
$\underline{G}_3 = \Sigma(\underline{F}_k^{-1}.z_k^2 + \underline{K}_k^{-1})$

Once the deflections and rotations have been determined, the loads and the twisting moments of the different wall systems may be evaluated from equations (4) and (5).

Fortran programs that includes the effect of each the idealised bracing systems A, B and the double channels core′C′, Fig. 7, has been written using NAG library routines [21], to calculate the flexural stiffness matrices and deflections as part of the static analysis and to find the natural frequencies and associated mode shapes as part of the standard eigenvalue solution.

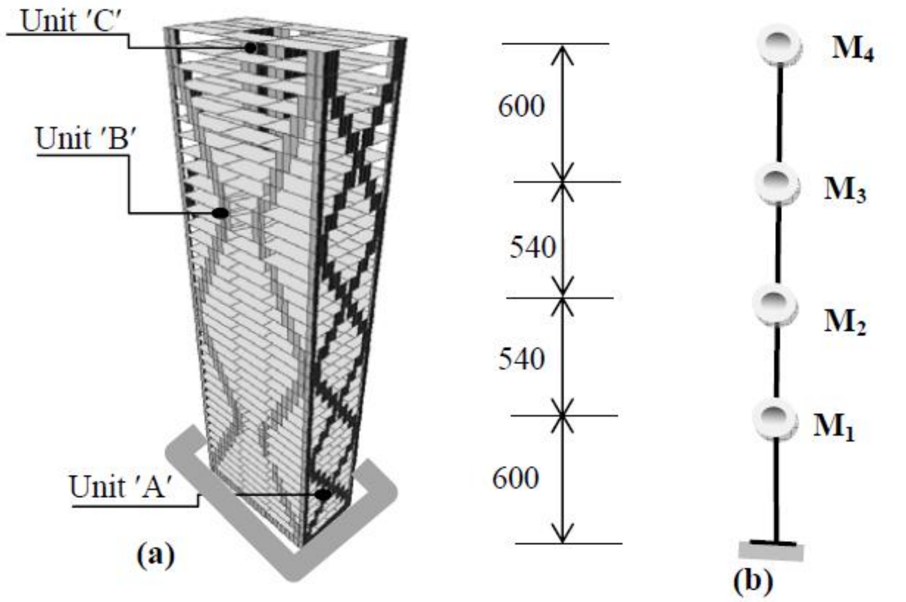

Figure 8. (a) Perspex Model (Perspective elevation); (b) idealised structure (lumped mass)

The lumped masses are considered at reference levels Fig. 8 (b) throughout the analysis approach.

6. COMPARISON AND DISCUSSION

Lateral deflections for a series of static tests on the structure model with lateral bracings “A” and with the bracing system “B” added to get the complete structure are shown together with the theoretical results Fig. 9. Comparison of deflection profiles of the phase 1 and phase 2 model structures for a centrally applied load of 10N at each reference level is shown.

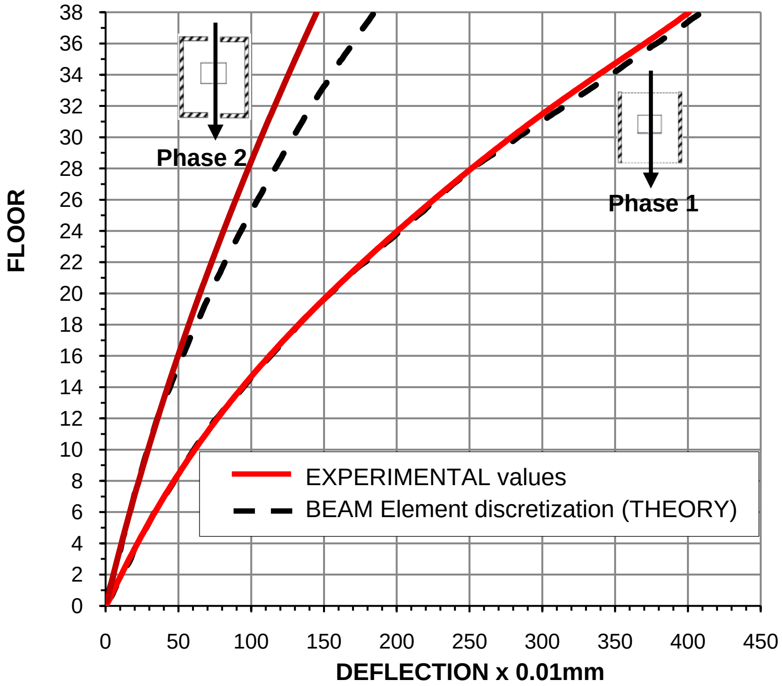

Figure 9. Deflection profile of model phase I & II (Comparison Theory/Experiment)

Dynamic test results for natural frequencies are shown for configurations in Table 2 and Table 3 respectively together with the theoretically determined values.

Table 2: Comparison of natural frequencies of the model structure with staggered walls unit ′A′

Mode	Experiment		Simplified method	
	Period(ms)	Frequency(Hz)	Period(ms)	Frequency(Hz)
1	161.3	6.2	178.6	5.6
2	30.3	33.0	32.81	30.5
3	11.2	89.3	13.12	76.2
4	7.4	135.1	7.65	131.0

Table 3: Comparison of natural frequencies of the model structure with staggered walls units ′B′ added

Mode	Experiment		Simplified method	
	Period(ms)	Frequency(Hz)	Period(ms)	Frequency(Hz)
1	100.0	10.0	122.0	8.18
2	23.25	43.0	25.6	39.1
3	10.42	96.0	11.2	89.4
4	6.8	147.1	6.9	145.5

Results for the analytical approach based on the simplified method presented in this study are within 10% of those from experiments for model structure with staggered wall ′A′ and 18% with staggered walls units ′B′ added to complete the model structure.

Table 2 shows higher frequency values from shake table tests and this true for small scale models [7].

Mode shapes for the first four natural frequencies were obtained by keeping the frequency constant recording the amplitude by suitably positioning the accelerometers.

7. CONCLUSIONS

Small scale modelling in engineering research and experiment is attractive for the understanding of the behaviour of staggered wall complex spatial structures.

When idealizing a complex structure such as the one under investigation, the first inclination will be to discretize the problem into blocks. Therefore two separate configurations have been considered in testing and analysing the model structure.

Experimentally determined lateral deflections, natural periods with critical damping and mode shapes have been presented for the model structure. The complex model was fabricated to be representative of a typical staggered wall building.

Although the simplified approach predicts fairly accurate results for theoretical deflections, for dynamic tests the results are within the normal bounds for such investigations. One reason for discrepancies may be in the estimation of the effective width of slabs.

Shake table tests usually give higher frequencies in small scale models, however the results can still reveal the dynamic characteristics of a structure.

In this study, the analytical model has been made as uncomplicated as possible for this experimental investigation.

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