Seismic Analysis of a Masonry Reinforced Concrete Shear Wall Building with Severe Architectural Irregularity, A Colloquial Discourse

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ABSTRACT In the Middle East region and particularly in Palestine, municipal land parcels are generally scarce or the cost is enormous, therefore architects are frequently compelled to produce irregular architectural layouts dictated by the geometry of the available land parcels or by their topographic location. Furthermore, vertical irregularities are indispensible and form a ubiquitous design feature in order to meet client needs that normally revolve around the local market demand and thus able to face the severe competitive considerations in the real estate industry. Floor functionality invariably change with elevation; this appealing practice is vernacularly becoming the rule rather than the exception. Seismically resistant structures on the other hand are presently an obligatory requirement according to the local government bylaws because Palestine lies well within an active earthquake prone zone. The present study undertaking presents a structural design example that includes, inter alias, turning an edifice highly irregular in plan and elevation architecturally into a structurally regular yet convenient one by a judicious distribution of shear walls that further eliminate the need for excessive column lines. The shear walls have the added advantage of effectively supporting the cantilevering stories at higher levels. The building under consideration is designed in accordance with the 1997 Uniform Building Code regulations with the intention of providing life safety performance under a potential design earthquake. Thorough comparison of analysis results is presented to show the significant advantage of the structural system characterized by proper shear wall distribution over an alternate system with poor shear wall distribution; the comparison included but is not limited to modal shapes and frequencies, story displacements. Story shear and bending moment distribution along the building height are strictly dependent on the volume of shear walls present.

Key words: Irregular Structure; Response Spectrum Analysis; Equivalent Lateral Load Method; Base Shear; Mode Shapes.

I. OBJECTIVE:

Design of reinforced concrete structures capable of resisting seismically induced forces is presently a mandatory structural engineering challenge. This is particularly emphasized because vernacular structures in the Middle East region are still masonry by enlarge. The term Masonry Structures commonly refers to stone clad edifices; more often than not such walls are not reinforced. The Middle East region Palestine included is considered an active earthquake prone zone. Structures over 20 stories in height are hitherto quite common in the Palestinian general landscape. The present structural analysis study is based on the 1997 Uniform Building Code [UBC97] which is in wide circulation although serious efforts are presently underway to encourage the structural design community in the Palestinian Territories to shift towards the International Building Code. The present undertaking addresses such challenges and offers prudent guidelines for designers when dealing with moderate rise masonry structures yet possibly enjoying severe architectural irregularities, be it vertical, horizontal or both. Moreover, what seems to be highly irregular in plan and elevation may not be as such from a seismic structural engineering perspective if irregularities are tackled effectively. This would be the result of a comprehensive yet judicious induction of an effective shear wall distribution scheme around the periphery of the structure. It is generally understood that asymmetry in architectural plans lead to considerable increases in stress which may potentially result in significant damage in particular locations within the structure. The emerging irregular structural condition demands substantially more complex analysis procedures which mundane structural engineering strive to avoid. The modeling exercise for reducing the planar irregularity forms one primary objective of the present study.

II. THE BUILDING ARCHITECTURAL TOPOLOGY:

The masonry building under consideration is located in the Palestinian city of Ramallah. The building is comprised of 17 storey levels i.e. 4G+13; having a height of about 52 meters with a total floor area of 6500 square meters. Four levels are below the natural ground level; they provide passenger car parking spaces. The six floors above grade are intended for shops and retail spaces while the uppermost five floors are meant to provide office space facilities and residential apartments. One additional penthouse level is planned at the roof level. Finally, a staircase roof exit is located at the seventeenth level. Two elevators serve the entire building albeit one staircase and one elevator shaft only serve the underground parking levels. A feature that inherently creates a vertical irregular distribution of mass. Therefore the building seems to suffer from inadvertent architectural irregularity in both the horizontal and in the vertical directions as well.

Furthermore, non aligned vertical shear walls of 20 centimeters thickness form an integral part of the structural system. They are intended to provide lateral stiffness and thus augment the need for excessive column lines. This par excellence irregularity is by enlarge due to the projected multifunction nature of the building and the general shape and location of the land parcel; the floor plans demonstrate rather long spans while the elevations portray modern architecture in some areas while keeping traditional facades in different zones. The peculiar geometry of the construction land parcel impacted considerably the architectural floor plans. Large size vitreous curtain walls are complimented with the traditionally massive masonry wall elevations. The staircases and the elevator shafts do not create continuous wall stacks within the facility because the stairs are designed to serve different zone levels within the building. Moreover, in order to gain added space yet conform to city planning regulations considerable cantilevering is visible at upper story levels. Planted shear walls within the structure are not all lined up vertically in order to respect inner architectural partitioning considerations thus present a non uniform distribution of mass and stiffness within the building. The shear walls are selected to serve strict structural objectives through creating a highly desired closed box action capable of supporting the rather long span slabs. A typical architectural floor plan and one isometric view are shown in Figures 1 and 2. Of particular concern is the height of shear wall buildings which according to the UBC is set to about 50 meters; a feature that demands thorough analysis and design.

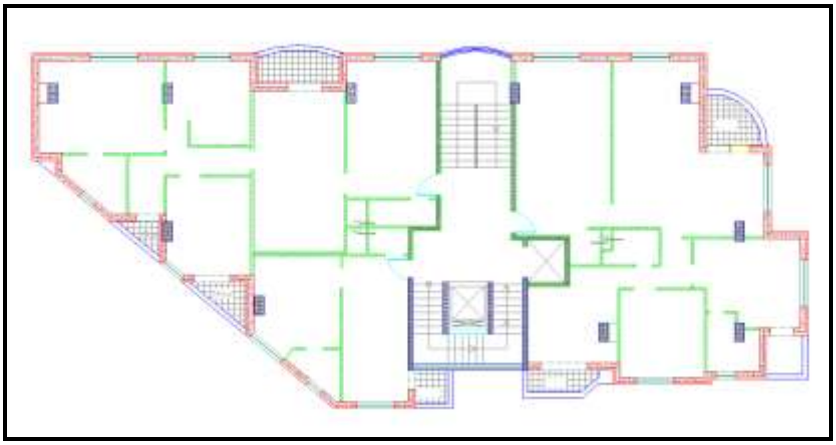


Figure 1. A Typical Floor Plan

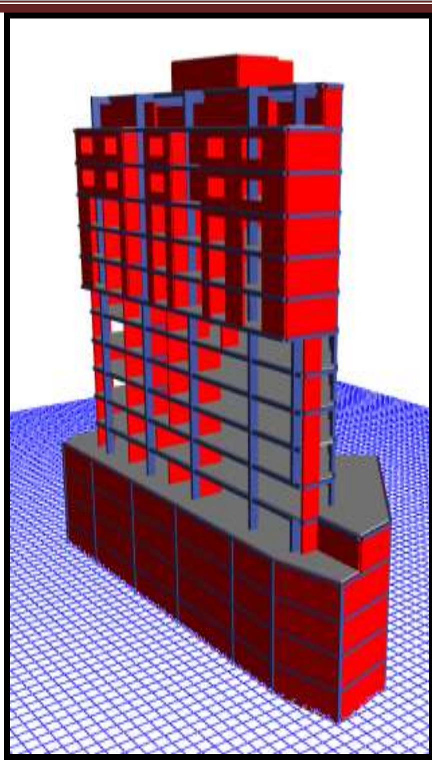
Figure 2. Isometric Views of the Building

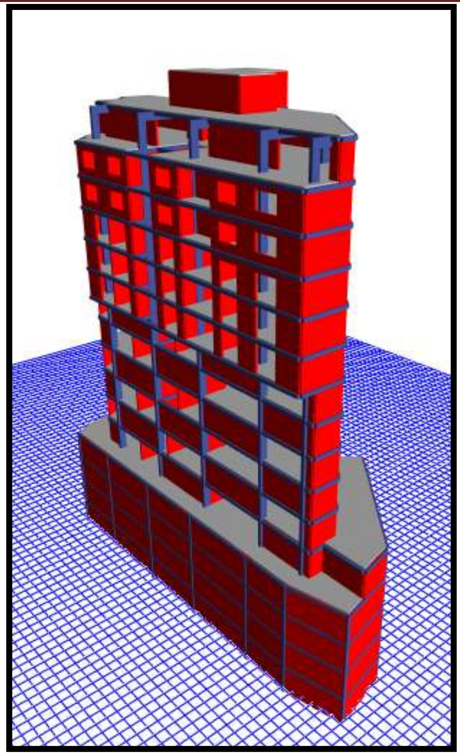
I. NUMERICAL MODELING AND ANALYSIS METHODOLOGY:

From a structural design perspective the building is comprised of a reinforced concrete moment resisting frame coupled with non aligned interior shear walls and stone clad external shear walls in compliance with the esthetics requirements set by local town planning and construction codes. The shear wall elements within the edifice together with the associated roof flat slabs create a closed box action that provide for better lateral stiffness provision and for reducing deflection whenever long spans are architecturally called for. Cantilevering facades in upper floors are managed by the inclusion of shear walls of various lengths at column centerlines. Shear walls in upper stories have a width of 20 centimeters while external shear walls are also 20 cm wide but are stone clad. In the basement floors the periphery wall is 30 cm thick with embedded concrete columns to compliment the overall framing system. The typical story height is 3 meters; the flat slabs in the basement levels are of 30 cm thickness with drop panels while in upper floors they are two-way ribbed slabs having 32 cm total thickness with properly placed hidden beams. All slabs are defined as rigid diaphragms. The cited construction materials are concrete of f'_c = 28 MPa and reinforcement bars of F_y = 410 MPa. All columns are rectangular in section and range in size from 40x90 cm in the basement floors to 30x60 cm in uppermost floors. Code specified modification factors are included in the definition of all column, wall and slab sections in accordance with the requirement 1630.1.2 of the UBC97; the effects of cracked sections are therefore included in all elements as follows:

- Beams: 0.35 I_g
- Columns: 0.7 I_g
- Walls: 0.35 I_g
- Slabs: 0.25 I_g

The spatial models shown in Figure 3 are constructed by the universally acclaimed Finite Element Analysis software ETABS 2015. Figure 3 (a) shows the numerical model of the building with poor shear wall distribution while Figure 3 (b) shows a model for the same building but with an effective shear wall distribution. The loadings applied in both cases include the standard code specified live loads, snow load and the lateral earth pressure loads against the walls of the underground story levels. The seismic data include a seismic zone 2A having a Peak Ground Acceleration of 0.15g, a soil profile type S_B, an Importance Factor of 1 and an Occupancy Category 4. The mass source is defined as 100% of the dead load as well as the superimposed dead load in addition to 30% of the applied live load. Ground supports are all fixed. Foundation behavior or their impact is beyond the intended present discourse. Testing the numerical models for equilibrium and compatibility is a granted obligation.





(a) **(b)**

Figure 3. A Rendered View of the Numerical Models

III. SEISMIC ANALYSIS PROCEDURE:

For the analysis of simple, low rise and regular structures up to 50 meter in height it is acceptable and allowed by UBC97 to employ the Equivalent Static Lateral Load Method of analysis. The method begins by estimating the base shear and then distributing it along the stories in a manner that simulates the first mode of vibration. This method works well as long as no significant contribution comes from lateral torsion modes. In different structures the Equivalent Lateral Load Method [ESLM] becomes ineffective and perhaps leads to erroneous results. It is popularly approved that response due to torsion irregularity should be considered in both directions. However. The ESLM remains a mandatory step in any seismic analysis undertaking in order to adequately estimate the base shear; however, should the procedure be followed by a Response Spectrum Analysis method continues to be the prerogative of the designer based on the general specifics of the structure under consideration. A keystone for the decision is, inter alias, the presence of torsion irregularity. Furthermore, the Response Spectrum Method is essentially a static method of analysis yet it begins after a thorough modal decomposition. The method calculates the maximum contribution values of forces and displacements generated by each mode of vibration separately, then sums the modal contributions by a mathematically appropriate technique; the Complete Quadratic Combination [CQC] is one such admissible technique and perhaps the most viable. The method is complex but it considers statistical coupling between closely spaced natural frequencies caused by modal damping. The number of modes of inclusion necessary for the undertaking is specified by UBC97; it is such that 90% of the total mass is captured for regular structures; for irregular structures 100% mass contribution is necessary. However, each modal mass should form more than 5% of the total mass. The structure is judged torsion prone when the above criterion is not satisfied. Structural damping is inherently considered through the adaptation of a suitable Response Spectrum curve. Directional seismic contributions are traditionally combined by the Square Root Sum of the Squares method.

Moreover, in addition to the standard structural design loads, seismic loads are applied in the two main orthogonal directions in accordance with the UBC97 Equivalent Lateral Load Method procedure. R which represents the inherent strength and the global ductility capacity of the lateral force resisting system is presently set to 5.5. The Response Spectrum analysis that follows is based on an adopted Response Spectrum curve recommended by the UBC97 yet tailored to suit the specific site conditions. Ten Eigen-Vectors are requested because they prove capable of capturing almost the entire mass of the structure. Scaling of results is properly applied in order to equate the base shear resulting from both methods.

IV. ANALYSIS RESULTS

Analysis and subsequently the reinforced concrete section design of the present building is carried out using ETABS 2015. This is accomplished after the standard, dead, live, snow and the earth pressure lateral loads are applied and the suitable load combinations are defined. However since design is not the prime focus of the present discourse the analysis results are presented in the form of tables and figures as they are produced by ETABS2015. Table 1 presents the results of the modal decomposition procedure. It shows the periods of vibration and the mass participations factors for each mode for the model having the well distributed shear walls versus the results of the model of the irregular structure. It is clear that the first mode of the structure with the judiciously arranged shear walls covers better than 50% of the total mass whereas the model of the poorly arranged shear walls show modest first mode contribution. This is an added indication that the ELLM is inadequate when dealing with irregular structures; the Response Spectrum method of analysis is hence the preferred route of analysis. Moreover, it is clear from the table above is the decrease in the first period of vibration from 1.03 seconds to 0.76 seconds i.e. about 25%; an indication of the associated increase in the overall structural stiffness although the volume of shear walls and the mass of the structure is diminished.

Torsion irregularity is examined by dividing the maximum displacement at each story level by the average displacement at the same level. Irregularity is marked when the resulting ratio exceeds 1.2. For the case at hand the ratio is shown in Table 2 for both systems. It is clear that when the shear walls are properly distributed the ratio is well below the 1.2 mark. This is not the case when the shear wall distribution is inadequate. The UBC97 in Table 16M mentions that whenever $\frac{\delta}{\delta_{max}} > 1.2$ then structural irregularity exists at that level which prompts the need for an amplification factor to be induced at that level in order to increase accidental torsion.

		Well Distributed Shear walls					Poorly Distributed Shear Walls				
Case	**Mode**	**Period**	**UX**	**UY**	**Sum UX**	**Sum UY**	**Period**	**UX**	**UY**	**Sum UX**	**Sum UY**
Modal	1.00	0.76	0.04	0.5	0.04	0.51	1.03	0.18	0.26	0.18	0.26
Modal	2.00	0.49	0.48	0.0	0.52	0.55	0.80	0.16	0.28	0.34	0.54
Modal	3.00	0.32	0.01	0.0	0.52	0.55	0.48	0.16	0.00	0.50	0.54
Modal	4.00	0.17	0.03	0.2	0.56	0.78	0.21	0.10	0.05	0.60	0.59
Modal	5.00	0.13	0.17	0.0	0.72	0.83	0.17	0.02	0.20	0.62	0.79
Modal	6.00	0.10	0.02	0.0	0.74	0.83	0.11	0.10	0.01	0.72	0.80
Modal	7.00	0.09	0.03	0.0	0.77	0.91	0.10	0.01	0.02	0.73	0.82
Modal	8.00	0.07	0.04	0.0	0.81	0.93	0.09	0.01	0.10	0.74	0.92
Modal	9.00	0.06	0.08	0.0	0.89	0.93	0.07	0.05	0.00	0.79	0.92
Modal	10.0	0.06	0.01	0.0	0.91	0.93	0.07	0.08	0.00	0.87	0.92

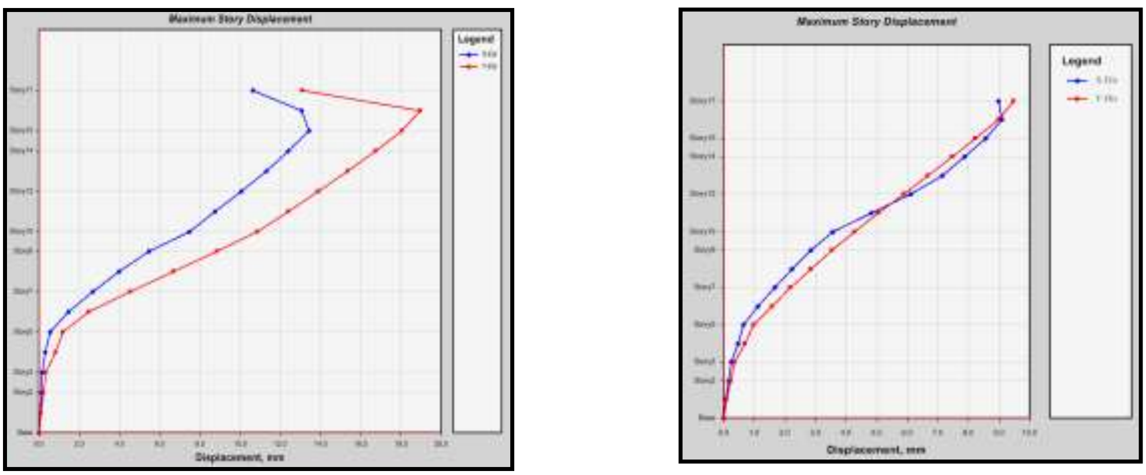
Table 1 - Vibration Periods and Modal Mass Contribution

	With Torsion Irregularity			Without Torsion		
Story	**Ellm x**	**Ellm y**	**Respsc**	**Ellm x**	**Ellm y**	**Respec**
Story17	1.17912	1.05168	1.04884	1.01224	1.00104	1.00706
Story16	1.25212	1.19794	1.26693	1.03018	1.00125	1.02484
Story15	1.31565	1.12104	1.12937	1.03912	1.00100	1.02067
Story14	1.35899	1.21658	1.29211	1.04236	1.00311	1.07187
Story13	1.35880	1.22787	1.30277	1.04004	1.00221	1.06954
Story12	1.36585	1.23500	1.31296	1.03441	1.00777	1.06518
Story11	1.37377	1.25066	1.32637	1.01707	1.00829	1.02585
Story10000	1.39129	1.26097	1.34071	1.00138	1.01980	1.03126
Story9	1.30553	1.24258	1.33749	1.00352	1.02345	1.03296
Story8	1.31253	1.20697	1.32047	1.00491	1.04265	1.05550
Story7	1.29666	1.14444	1.28142	1.00912	1.05314	1.06678
Story6	1.25671	1.01815	1.19516	1.01784	1.09124	1.10666
Story5	1.14904	1.24569	1.19008	1.01232	1.16339	1.16112
Story4	1.02303	1.02021	1.03608	1.02805	1.02607	1.00943
Story3	1.02075	1.01313	1.03782	1.02833	1.01852	1.00875
Story2	1.02319	1.00965	1.04523	1.03426	1.01498	1.0127
Story1	1.03124	1.00593	1.05826	1.04389	1.01157	1.01896
Base	0	0	0	0	0	0

Table 2. Geometric Torsion Indicator

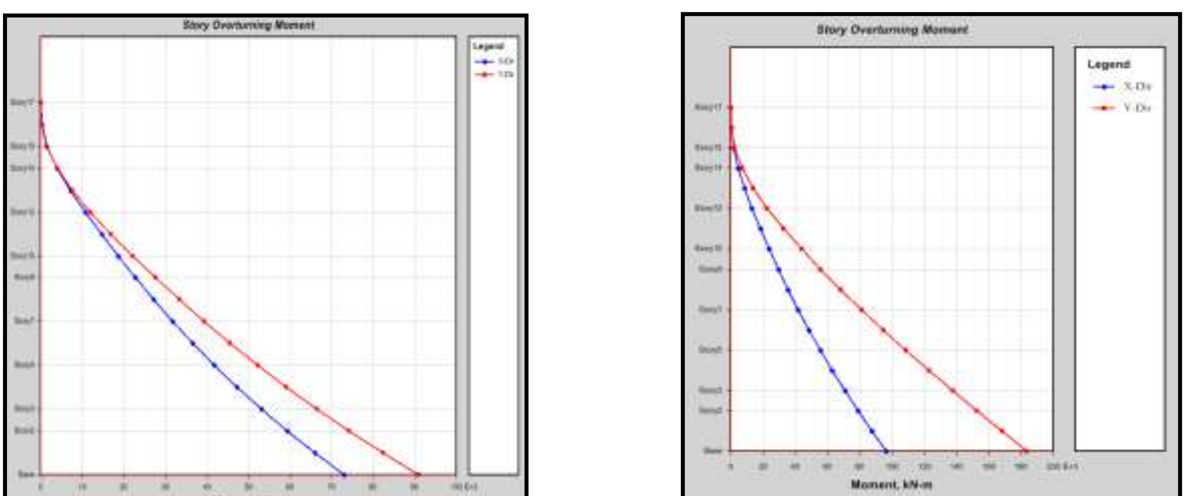
Story shear, story drift and the maximum lateral displacement of the structure are pivotal structural design parameters. A comparison between the maximum story displacement of both structural systems addressed in this presentation it is clear, as manifested by Figure 4, that the story displacements in both directions of the system with the adequately distributed shear walls are about equal in magnitude hence this system has the edge over the one with poor shear wall distribution. It is to be noted that all presented results are due to the Response Spectrum loading case of analysis since it is the prime target of the present discourse and the prudent one to follow under such conditions.

Figure 5 (a) shows the variation of the bending moment along the height of the structure with poor shear wall distribution scheme while Figure 6 (b) shows the same but for the structure with an effective shear wall distribution scheme; the variation of the bending moment is the resulting from the scaled Response Spectrum analysis in both directions. Judging from the graphs it is clear that the structure with poor distribution of shear walls underestimates the bending moments along the structure and particularly at the base in both directions. This is due to smaller volume of shear walls. The same argument applies for the story shear values shown in Figure 6.



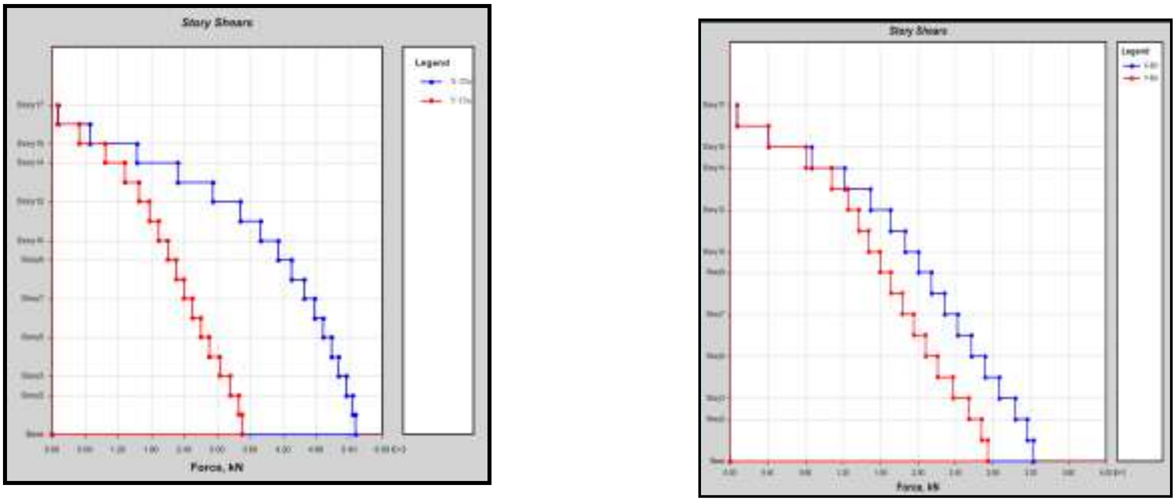
(a) (b)

Figure 4. Story Displacement for Both Systems



(a) (b)

Figure 5. The Story Bending Moment Variation for Both Systems



(a) (b)

Figure 6. Story Shear for Both Structural Systems

V. CONCLUSION:

A seemingly irregular architecturally 4G+13 story structure is analyzed considering seismic action in accordance with the UBC 97 and using two different approaches. The Equivalent Lateral Load Method in the two main directions as well as the Response Spectrum Method are used. The results of the later were scaled whereby the base shear resulting from both methods properly match; this is a code requirement. The building system is modeled in two distinct manners, one with judicious shear wall distribution around the periphery of the building while the same exercise is repeated for the same structure albeit with a rather poor shear wall distribution. The results of both models are scrutinize and compared. The intention is to show that shear wall distribution maybe effective in reducing the irregularity imposed by architectural considerations.

Structures that seem irregular in plan are in fact irregular also from a structural vantage point. However, with judicious distribution of shear walls around the floor plan that it is possible to minimize or even eliminate the effect of torsion. It is to be emphasized that unreinforced infill masonry walls, favorable in the local construction industry, do not satisfy shear wall definition or purpose. Furthermore, from the analysis results it is clear that the effort invested in identifying proper shear wall locations within the structure is a rewarding exercise in terms of the end structural performance. Proper placement of shear walls play a significant role in supporting cantilevering slabs by creating an effective yet desired box action. The presented results are limited to the Response Spectrum Method as it forms the prime focus of the present undertaking. Story displacements and story drifts are all invariably less in magnitude; this leads to better section design and a more cost effective and ultimately a safe structure. Moreover, the comparison of the end results of the Response Spectrum analysis with those of the ELLM of analysis in absolute terms is at times superfluous because the result of the base shear in the later is considered a bench mark for the scaling of the Response Spectrum results which is a pivotal intermediate step in the Response Spectrum analysis procedure; therefore carrying out an ELLM computer run is more often than not an indispensible analysis exercise.

Furthermore, it is clear that the results of analysis of the system with well distributed shear walls the output of the Response Spectrum method does not differ appreciably from that the ELLM. The comparison was made for shear, moment and lateral displacements. This further underlines the advantages of regular structures.

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