

"Drop or Hidden Beams vs. Flat Slabs, which Way is Forward", A Performance Based Colloquial Narration

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Abstract - Reinforced Concrete structures form the backbone of mundane construction in Palestine. The standard roofing systems adopted are generally comprised of either solid slabs on drop beams, ribbed slabs on shallow beams, or of flat plates with or without drop panels. The latter system is gaining popularity due to the added potential of saving on floor heights. Furthermore, seismic analysis and design is an increasingly imposed requirement by local governments due to the proximity of the region to the Dead Sea fault which is capable of producing moderate to large magnitude earth tremors. Therefore, the country, lies well within an active earthquake prone zone. The present numerical investigation targets the different flooring systems for the purpose of conducting a performance based comparative study. The horrendous cost of repair, the extended disruption time of use and the possible loss of life demand rigorous scrutiny of the present construction practices. The selected structural topology for the present study undertaking is representative of the structural forms adopted by local architects for multi-family dwellings; this includes a medium-rise building structures, with regular and horizontally irregular floor plans, most common in Palestine. The structures are modeled to represent the three ubiquitous roofing forms. The present narration forms a comprehensive discourse that includes yet not limited to post yield behavior. The results compared are, inter alias, the standard dynamic parameters such as the time-period, the story drift, the lateral displacement and the base shear magnitudes as well as the respective Performance Points. The seismic analysis is conducted based on the quasi static Response Spectrum Method; the nonlinear analysis is conducted according to the first generation of Pushover Analysis, namely Capacity Spectrum Method of ATC 40 and the improved guidelines of Fema 440. The present study elaborates on the adequacy of the present roofing trends; evaluates their potential seismic susceptibility and offers prudent design recommendations.

Keywords - Response Spectrum Analysis; Shallow Beams; Base Shear; Pushover Analysis; Performance Point.

I. INTRODUCTION

Designing a seismically resistant structure is presently mandatory in the State of Palestine according to local government bylaws because the region lies well within an active earthquake prone zone, proximal to the Dead Sea fault. Seismic resistance is imperative for avoiding unwarranted repair cost, minimize disruption time and for protecting against loss of life. The ubiquitous construction practice generally specifies flooring systems comprised of either solid slabs on drop beams, ribbed slabs on shallow beams or flat plates. The most recent trend that is gaining popularity however, is the flat plate roofing system with or without drop panels. In order to analytically investigate the impact of the different roofing systems on the structural behaviour due to potential seismic events, a number of moment-resisting framed structural models, yet of the same roof area are scrutinized. The topology of the selected structures and the floor height is representative of most local buildings. The analysis results include, but are not limited, to the fundamental periods, the natural frequencies, drift and storey displacements.

The present narration is based on seismic analysis by the standard linear elastic methods, i.e. the Response Spectrum Method. The non-linear Pushover Analysis of ATC 40 investigates the trend of progressive failure that may occur and identifies potential weak zones likely to reach critical states during seismic events. Pushover Analysis, a form of Performance Based Design, provides information on the collapse mechanism if when it happens. The present exercise is conducted using the Finite Element Method based software ETABS 2019.

II. NUMERICAL MODELING

Six symmetrical models of medium-rise bare frame structures are investigated. Three of them are comprised of a G+5 Storey levels having five bays in each direction with a uniform grid of 5-meter spacing while the rest are for an irregular floor plan, yet of the same floor area, and having the same number of storeys. The height of all floors is 3.2 meters. Figure 1 and Figure 2 show the plans and the 3D views of the constructed numerical models. Columns and beams are modelled using two node linear frame elements. The drop beams have a 60x30 cm section; hidden beams are of 25x60 cm section while the solid slab thickness is 13 cm; in the flat slab system the thickness is set at 25 cm. Slabs are assigned a semi rigid property. The columns have a square section of 40 cm width. The Response Spectrum curve selected is a smooth one with soil profile D and a damping ration of 5%. The loads and the architectural modules are in accordance with standard vernacular building predilection. Effective stiffness is defined in following Fema 356 guidelines; [Beams $0.5 E_c I_g$; Columns $0.7 E_c I_g$; Walls $0.7 E_c I_g$; Slabs $0.25 E_g I_g$]. Table 1 shows pertinent structural and material data. A total fixity is assigned for all ground supports. The following study, linear and performance based, focuses on the following three different numerical models. They are:

- Model 1 - A Bare Frame with solid slabs on drop beams
- Model 2 - A Bare Frame with ribbed slabs on shallow beams
- Model 3 - A Bare Frame with flat plate slabs without drop panels

The above three Models are replicated for a horizontally irregular structure. The following are pertinent data:

- Live Load = 2 KN/m²
- Superimposed Dead Load = 4 KN/m²
- Importance Factor = 1 [ASCE Table 1.5-2]
- Risk Category II; Soil Profile C; Seismic Design category D
- Ordinary Moment Resisting Frame, R = 3.0
- Over Strength Factor, $\Omega_o = 3$
- Deflection Amplification Factor, $C_d = 2.5$
- Structural Damping: 5%

Table 1: Model Description, Material and Earthquake Data

Storey Height	3.2 m
Beam Size -drop-	60 x 30
Beam Size -hidden-	25 x 60
Column Size	40 x 40
Slab Thickness	varies per model
Concrete Grade M35 (f'_c)	28 MPa
Reinforcement Bars (F_y)	410 MPa
S_s	0.70
S_1	0.16
Response Reduction Factor	3.0
Modulus of Elasticity/Concrete	30×10^6 MPa

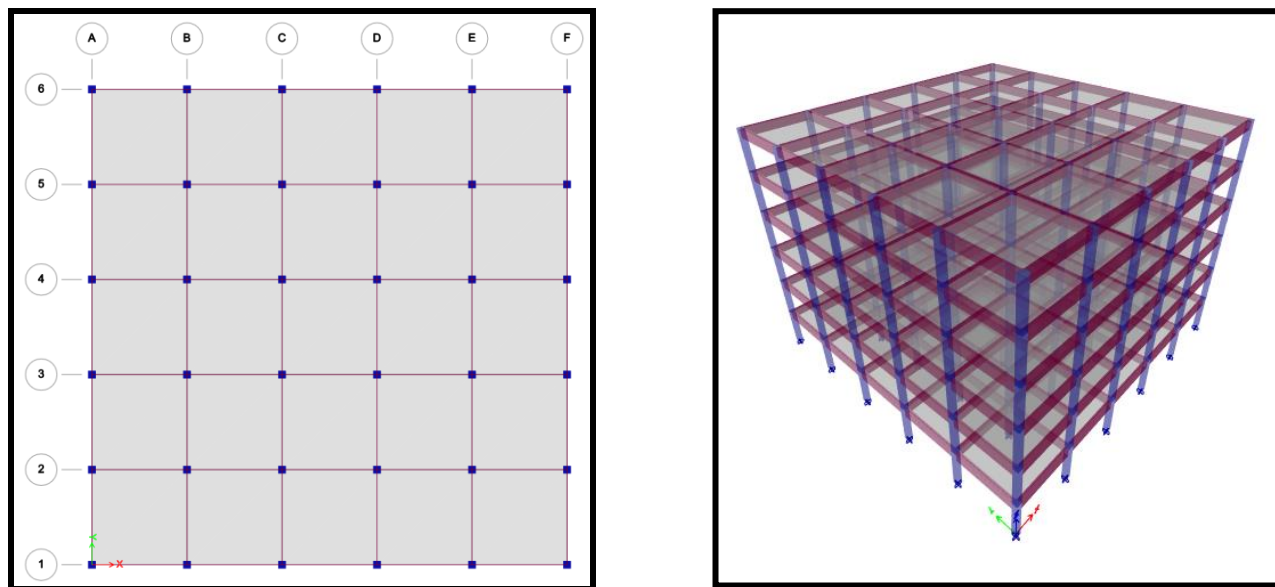


Figure 1: Plan and a 3D View of the Investigated Regular Structure

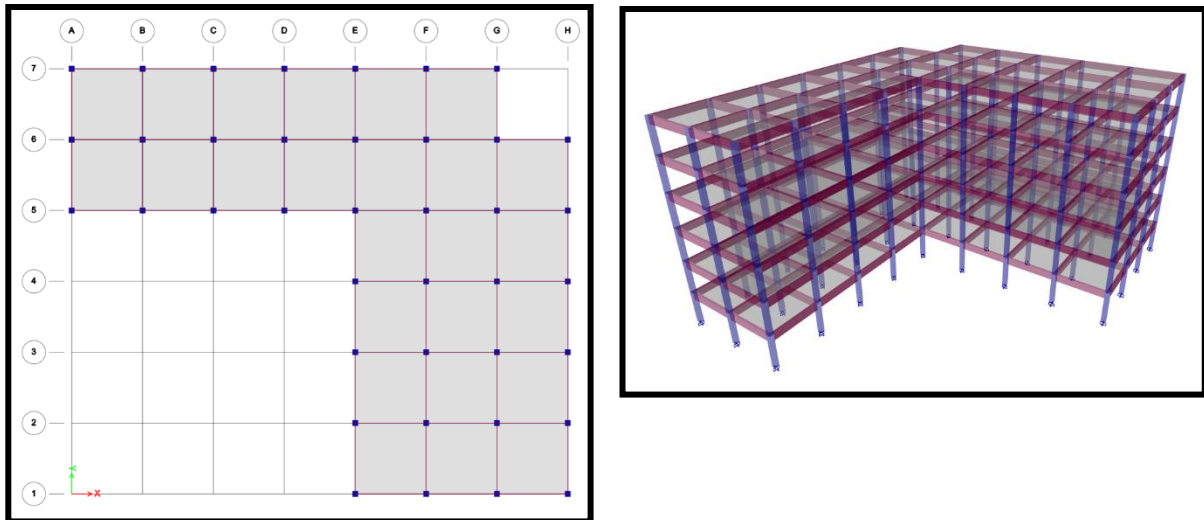


Figure 2: Plan and a 3D View of the Investigated Horizontally Irregular Structure

III . THE LINEAR ANALYSIS PROCEDURE

The Standard Response Spectrum procedure includes modal decomposition, i.e. extracting an appropriate number of mode shapes, setting a mass source, defining a suitable Response Spectrum function, selecting a correct scaling factor and finally carrying out modal superposition. Twelve mode shapes are selected for the present discourse, ample to capture 90% contribution of the total mass. The CQC method is set for modal combination while a SRSS is set for directional combination. The seismic mass source is defined as 25% of the applied live loads added to the entire self-weight of the structure together with the superimposed dead load. The analysis is initially performed by the Equivalent Lateral Load Method. This is mandatory for better quantifying the appropriate scaling factors in the two principal directions. Following ASCE 16.3.4 a 5% accidental eccentricity is called for.

IV . RESULTS OF THE LINEAR ANALYSIS

Table 2 exhibits the Fundamental Period and the Base Shear for the regular and the horizontally irregular structural models. It is apparent that, for the present study cases, no appreciable difference is noticed in the fundamental period between the regular and the irregular structures hence the base shear is of the same order of magnitude. However, the fundamental period is lower in the system with drop beams; this is an obvious conclusion due to the considerable added stiffness. Moreover, The lateral displacements due to Seismic Forces resulting from the Response Spectrum Analysis are shown in Figure 3 and Figure 4. They exhibit substantial difference in magnitude between the three respective models, for both the regular and the irregular types. The flat slab system exhibits quadruple values than the system with drop beams while hidden beams show values almost double in magnitude. Storey drift for the irregular models are shown in Figure 5; it follows a similar trend.

Table 2: The Fundamental Periods and Base Shear for the G+5

	Regular Models			Irregular Models		
	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
T (sec)	1.740	2.795	4.358	1.711	2.763	4.331
BS (KN)	3118	3388	3360	3165	3440	3377

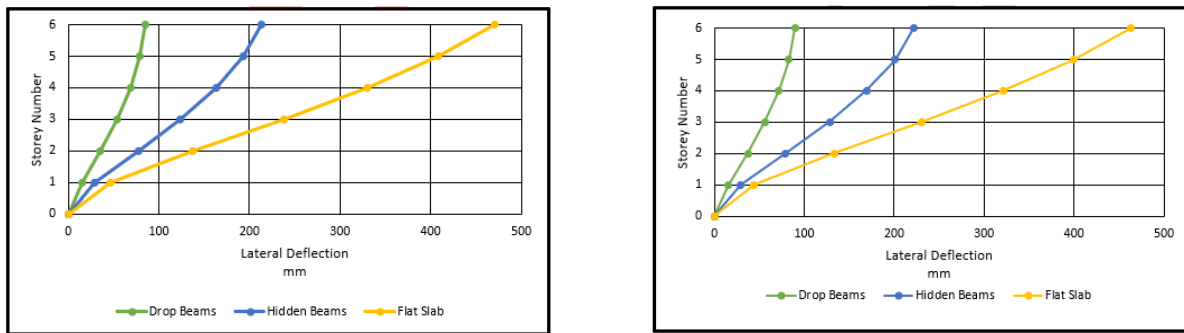


Figure 3: Lateral Displacement for the G+5 Regular Structure
 Figure 4: Lateral Displacement for the G+5 Irregular Structure

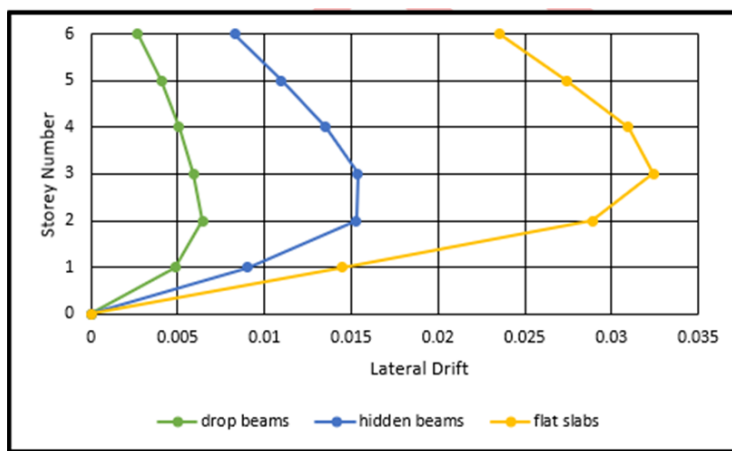


Figure 5: Lateral Storey Drift - Irregular Building -

V. THE NONLINEAR STATIC PUSHOVER ANALYSIS PROCEDURE:

Pushover Analysis is the numerical implementation of Performance Based Design philosophy which emerged towards the end of the last century in response to the desire of insurance companies and the communities of real estate investors. It is a rather new seismic engineering protocol; the presently prevailing exponential growth of the numerical computational power contributed tremendously to the evolvement of the technique. The procedure is conducted in lieu of the elaborate nonlinear Time History Analysis. The objective is to have adequate control over maintenance cost post-earthquakes; in addition to design safe structures with a rather short occupancy interruption during such events. Therefore, the present study targets the prediction, beyond yield, of the structural behaviour under strong seismic events for the three distinctly different roofing systems of both structural topologies. This is a complex undertaking primarily due to the gradual change of section properties during deformation; this prompts continuous change in seismic forces due to the progressive change that occurs in the structural period and damping.

The objective of the Performance Based Design procedure, in a nutshell, is to focus on life safety under strong action earthquakes in order to minimize repair cost and to better manage usage disruptions of buildings post-earthquake events. Nonlinear static analysis is used to predict nonlinear behaviour of structures. The present analysis method maybe force controlled or displacement controlled. The following exercise is based on the first generation of PBD; this is a displacement-controlled procedure known as the Capacity Spectrum Method. Essentially, the method reduces a multi-degree of freedom system into a single degree of freedom system having its own effective damping ratio. The following is a summary of the procedure per ATC 40.

For a well-designed structure, non-linear hinges are added to all structural elements of the finite element model. For columns and from ASCE 41-17, coupled axial flexural or PM₂M₃ frame plastic hinges are assigned at 5% and at 95% of the element length. In beams, uncoupled moment rotation frame plastic hinges are assigned at the same relative locations keeping the middle the beams elastic; i.e. plastic hinges are assigned at the edges of all elements, where cracks are generally expected to happen. The selected locations expectedly have higher reinforcement ratios and hence expected to be somewhat brittle. The nonlinear structural model is then pushed laterally by a monotonically increasing invariant force pattern until a maximum target displacement of a control node at the roof level is reached; P-Delta effects are properly considered. For the present undertaking

a lateral load pattern proportional to the first mode of vibration and the storey masses is applied. The target displacement is placed at 4% of the building height. The master node selected is close in location to the center of gravity of the top level. A plot of the base shear (y-axis) versus the roof displacement of a control point at the roof (x-axis) is hence generated. The curve represents the inelastic load carrying capacity of the structure. However, prior to pushing the structure, a Pushdown non-linear static load case is defined; this involves the entire Dead Load in addition to 30% of the applied Live Load. The Pushdown load case is force controlled while the lateral load case is displacement-controlled; the process continues until the target displacement is reached. This Pushover curve is then converted to an SaSd format or the so-called Capacity Spectrum while the demand curve expressed by the selected response spectrum is converted to ADRS [Acceleration Displacement Response Spectrum] or the Demand Spectrum, following the procedure of ATC 40, Chapter 8. This leads to the creation of two plots of unified coordinates.

The intersection of the Pushover curve with a reduced form of the demand curve i.e. modified to accommodate the emerging equivalent damping, defines the Performance Point or the maximum inelastic displacement of the control node during a potential seismic event. This is normally implemented in accordance with the Improved Linearization procedure spelled out in Fema 440, Improved Non-Linear Static procedure. Once the Performance Point is located the physical status of all nonlinear hinges is determined.

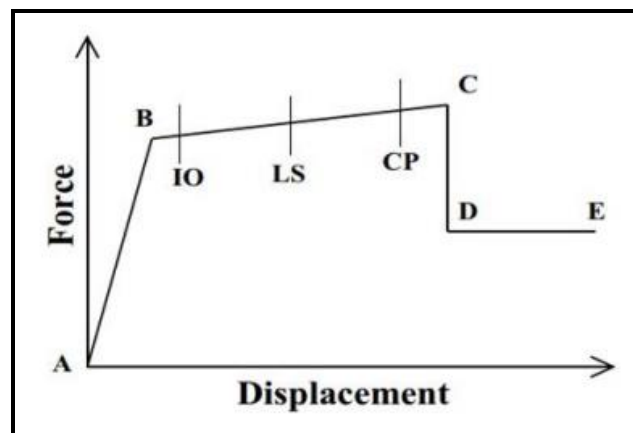


Figure 6: A Typical Hinge Load Deformation Backbone Curve

The nonlinear hinge represents the localized force-displacement relation of a member through the elastic and inelastic phases under seismic action. Five points A, B, C, D and E shown on the hinge backbone curve, Figure 6, define the force deflection behavior while the three points IO, LS, and CP define the acceptance criteria for the hinge. Point A signifies the unloaded structure; point B shows the first yield of the element; point C shows the place where significant degradation begins, i.e. its nominal strength. The drop from C to D signifies the initial drop in strength of the element. The space between D and E allows the element to sustain gravity loads. Point E is the point where the maximum deformation takes place and no longer can sustain gravity loads. IO stands for Immediate Occupancy; LS stands for Life Safety; CP stands for Collapse Prevention. When the Performance Point is near the elastic range, the structure is considered satisfactory. Conversely, when the point of intersection leaves a modest reserve of capacity then the structure is pronounced weak and would behave poorly under a strong seismic action. For the realistic prediction of the Performance Point, it is customary to subject the structure to earthquakes stronger than normally anticipated. Moreover, peer review and audit are essential for the indicated analysis protocol.

VI. RESULTS AND CONCLUSION

The purpose of the present investigation was to predict the behavior of structures having different roofing systems within the elastic range as well as at post yield. The models were replicated for an irregular L shape building having the same floor area. The floor plans are representative of local architectural forms. Linear analysis was conducted via the Response Spectrum Method while the Nonlinear Pushover Analysis procedure was followed to predict the behavior at post yield. Moreover, since the customary practice is to subject the structure to a stronger earthquake than the structure is designed for, the following results are for an earthquake with $S_1 = 1.1$ and $S_5 = 0.26$. These are close to the highest values recorded in Palestine. Table 3 shows the Performance Points of the various Models.

1. Models of solid slabs on drop beams sustain the maximum magnitude of base shear; conversely flat slab models sustain the least measure of base shear. This is manifested in both the linear and the nonlinear analysis.
2. Deflection and Inter-storey drift values resulting from the Response Spectrum analysis are substantially lower in magnitude in frames with solid slabs on drop beams roofing system than the other roofing systems. This is exhibited in Figure 3, Figure 4 and Figure 5.
3. The Performance Points resulting from Pushover Analysis in accordance with Fema 440 Equivalent Linearization show higher sustained shear values with lowest displacement values for models of solid slabs on drop beams. Flat slab

systems are on the low end of the scale, i.e. they are most vulnerable to earthquake excitation among the three investigated roof slab systems. Flat slabs exhibit modest sustained Base Shear values yet an associated maximum displacement. These are shown in Table 3 and illustrated in Figure 7 and in Figure 8.

4. Hinge formation and projection in accordance with the set acceptance criteria, Table 4, indicate clear susceptibility in the Flat Slab roofing system; in irregular systems the feature is simply amplified. The hinges in a flat slab system are all located in columns; a feature that adds to their vulnerability to earthquake excitation.
5. Further investigation of the topic is recommended with the inclusion of shear walls and vertical irregularity to the general topology of the investigated models. Identification of demand hazards and the associated demand estimation, characterization of site and source distance are essential requisites that require added attention. Furthermore, examining the effect of higher modes is counseled.

Table 3: Performance Points Regular G+5

	Regular Structure			Irregular Structure X direction (minor)			Irregular Structure Y direction (major)		
	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
	BS (KN)	9679	6346	3230	10208	6355	3213	10053	6278
Displacement (mm)	351	581	756	320	546	746	323	552	747

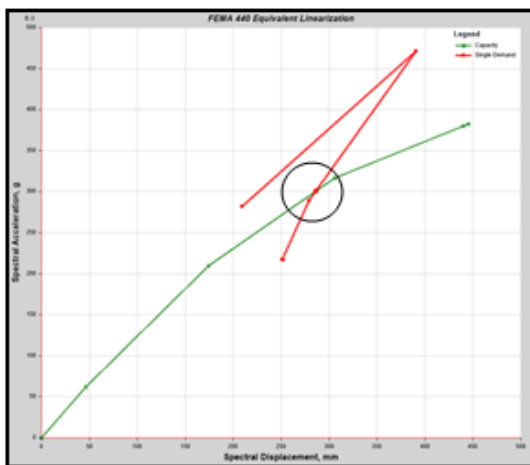


Figure 7: Performance Point of Drop Beam Model

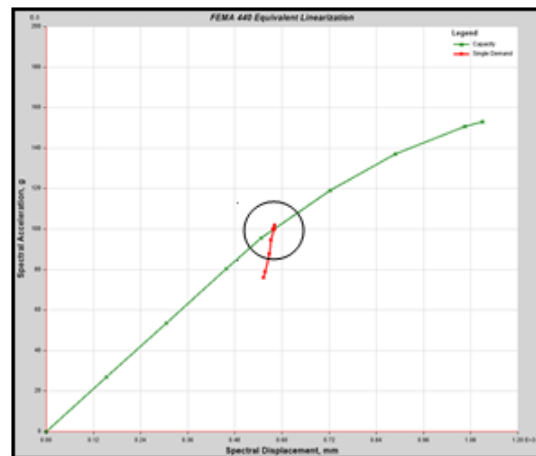


Figure 8: Performance Point of Flat Slab Model

Table 4: Hinge Deformation Progression

	Regular Structure			Irregular Structure			Irregular Structure		
				X direction			Y direction		
	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
Step #	4	4	5	3	4	7	3	4	7
IO-LS	67	45	22	69	37	29	77	33	26
LS-CP	0	0	0	0	0	0	0	0	0
>CP	5	3	14	7	5	10	14	6	13

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