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Seismic Analysis of Buildings Using Direct Displacement Based Design Method

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Abstract: *This research presents a comprehensive study to perform the seismic analysis of buildings using Direct Displacement Based Method (DDBM), which is a viable and logical alternative to current force-based code approaches. This method is based on a concept of designing structures to achieve a specified performance limit state defined by strain or drift limits. The main objective of the paper is to examine analytically the use of DDBM in seismic design of different types of structural systems (frame, wall, and dual wall-frame buildings) and compare it with the traditional Force Based Design Method (FBDM). Using a developed Excel spread sheets for DDBM procedure, a set of buildings with different heights (2, 4,6,8,10,12,14,16,18, and 20 stories) and different structural systems (frame buildings, wall buildings, and dual wall-frame buildings) are analyzed and the results are compared with those of (Force Based Design Method) FBDM modeled using computer programs SAP and ETABS. This comparison proved that Direct Displacement Based Method is more reliable as it is based on a secant stiffness (rather than initial stiffness) representation of structural response, using a level of damping equivalent to the combined effects of elastic and hysteretic damping. This design method is extremely simple to apply and is very successful in providing dependable and predictable seismic response.*

Keywords: *Performance-based design, displacement based design method, displacement ductility demand and capacity.*

I. Introduction

Throughout the past 100 years, the seismic structural analysis has received great attention compared with other acting loads. The evolution of this analysis passed through different phases starting by considering the response of the structure subject to seismic action is purely elastic. Some years later, experimental and empirical evidence showed that the ductility of structure plays an important role in his resistance to inducing inertia forces, many times larger than those predicted by the elastic analysis, when subject to ground shaking. Consequently, the ultimate strength considerations were introduced to assess the seismic structural performance. This evolution has lead to the realization that although the strength is enough important in reducing the deformation and strains related to seismic damage, the proper definition of structural response should be related to deformations rather than strength.

This appreciation has lead to the development of a considerable number of seismic design concepts based on deformation capacity. The Direct Displacement Based Design Method (DDBM), introduced by Priestley in 1993, is the basis of the performance–based design approach to replace codes traditional Force-Based Design Method (FBDM) approaches. DDBM has been subjected to comprehensive investigations in past recent decades. The main concept of DDBM suggests that the structure should be designed to fulfill a given strain or drift boundaries when subject to a chosen seismic action. The fundamental objective behind the research efforts in this field resides in developing simple realistic and applicable design approach satisfying the target of DDBM philosophy. The approach should deal with different structural systems and as well as different structural materials.

The main difference between FBDM and DDBM revolves in the characterization of the structure. While FBDM characterizes the structure in terms of its elastic properties (initial stiffness and elastic damping), DDBM characterizes the structure by secant stiffness at maximum displacement and viscous damping (inelastic response).

II. Fundamentals of Direct Displacement-Based Seismic Design

The fundamentals of DDBM are enough simple as have been presented in many earlier publications (Priestley 2000, Priestley, 2003). With reference to Fig.1 which considers a SDOF representation of a frame building (Fig.1(a)), the bilinear envelope of the lateral force-displacement response of this SDOF is shown in Fig.1(b).For a given level of ductility demand, a structural steel frame building with compact members will be assigned a higher level of equivalent viscous damping than a reinforced concrete bridge designed for the same level of ductility demand as shown in Fig.1(c), this is a consequence of "fatter" hysteresis loops.

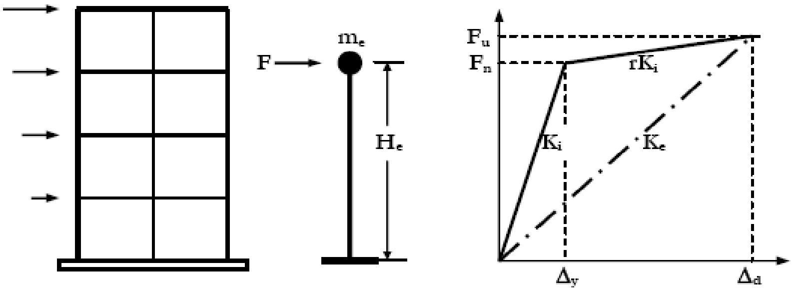
With the design displacement at maximum response determined as discussed, and the corresponding damping estimated from the expected ductility demand, the effective period $T_e$at maximum displacement responseΔ_d, measured at the effective height H_e(Fig.1 (a)) can be read from a set of displacement spectra for different levels of damping, as shown in the example of Fig.1(d). The effective stiffness K_e of the equivalent SDOF system at maximum displacement can be found by inverting the normal equation for the period of a SDOF oscillator to provide

$$K_e = 4\pi^2 m_e / T_e^2 \quad (1)$$

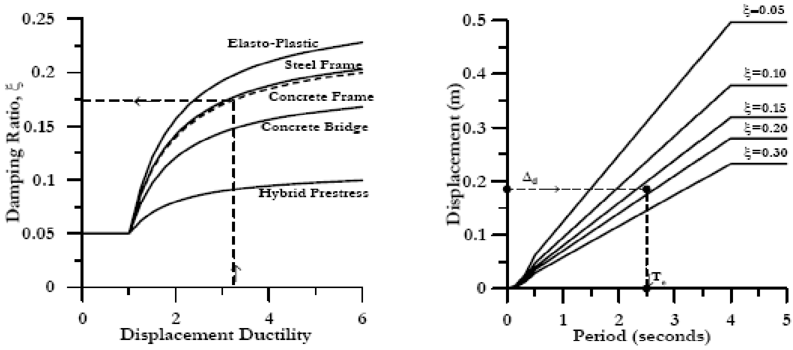
Where m_e is the effective mass of the structure participating in the fundamental mode of vibration.From Fig.1 (b), the design lateral force, which is also the design base shear force, is thus

$$F = V_{Base} = K_e \Delta_d \quad (2)$$

The design concept is thus very simple. Any complexitythat may existrelates to determination of the characteristics of the equivalent SDOF structure, the determination of the design displacement, and development of design displacement spectra.



(a) SDOF Simulation (b) Effective Stiffness K_e



(c) Equivalent damping vs. ductility (d) Design Displacement Spectra

Fig. 1 Fundamentals of DDBM "Displacement-Based Seismic Design of Structures" Priestly 2007

2.1 Design Displacement

The characteristic design displacement of the substitute structure depends on the limit state displacement or drift of the most critical member of the real structure, and an assumed displacement shape for the structure. This displacement shape is that which corresponds to the inelastic first-mode at the design level of seismic excitation. Thus the changes to the elastic first-mode shape resulting from local changes to member stiffness caused by inelastic action in plastic hinges are taken into account at the beginning of the design. Representing the displacement by the inelastic rather than the elastic first-mode shape is consistent with characterizing the structure by its secant stiffness to maximum response. In fact, the inelastic and elastic first-mode shapes are often very similar.

The design displacement of the equivalent SDOF structure (the generalized displacement coordinate) is thus given by

$$\Delta_d = \sum_{i=1}^{n}(m_i \Delta_i^2) \,/\, \sum_{i=1}^{n}(m_i \Delta_i) \quad (3)$$

Where m_i and Δ_i are the masses and displacements of the n significant mass locations respectively. Formulti-storey buildings, these will normally be at the n floors of the building. Where strain limits govern, the design displacement of the critical member can be determined byintegration of the curvatures corresponding to the limit strains. Similar conclusions apply when codedrift limits apply. For example, the design displacement for frame buildings will normally be governedby drift limits in the lower stories of the building. For a bridge, the design displacement will normallybe governed by the plastic rotation capacity of the shortest column. With knowledge of thedisplacement of the critical element and the design displacement shape, the displacements of theindividual masses are given by

$$\Delta_i = \delta_i \frac{\Delta_c}{\delta_c} \quad (4)$$

Where δ_i is the inelastic mode-shape, and Δ_c is the design displacement at the critical mass, and δ_c isthe value of the mode-shape at critical mass. Specific details on structural mode-shapes for DDBM ofdifferent structural types are given in (Priestley et al 2007).

2.2Effective Mass

From consideration of the mass participating in the first inelastic mode of vibration, the effective systemmass for the substitute structure is

$$m_e = \frac{\sum_{i=1}^{n}(m_i\Delta_i)}{\Delta_d} \quad (5)$$

Where Δ_d is the design displacement given by Eq.(3). Typically, the effective mass will range fromabout 70% of the total mass for multi-storey cantilever walls to more than 85% for frame buildings.

2.3 Structure Ductility Demand

Determination of the appropriate level of equivalent viscous damping requires that the structural ductilitybe known. This is a straightforward since the design displacement has already been determined, and the yield displacement depends only on geometry, not on strength. Relationships for yield curvature $(\emptyset_y)$ of structural elements, such as walls, columns, beams etc. have been established (Priestley 2003)in the general form:

$$\emptyset_y = c_1 \times \varepsilon_y / h \quad (6)$$

Where c_1 is a constant dependent on the type of element considered, ε_y is the yield strain of theflexural reinforcement and h is the section depth.

The effective height H_e is given by:

$$H_e = \sum_{i=1}^{n}(m_i\Delta_i H_i) \,/\, \sum_{i=1}^{n}(m_i\Delta_i) \quad (7)$$

Where H_i are the heights of the n stories.

The displacement ductility demand for the structures is thus known at the start of the design, byEq. (8), even though the strength is not yet established:

$$\mu = \Delta_d / \Delta_y (8)$$

The appropriate level of elastic damping to be used in Fig.1 (d) and directly obtain a corresponding period, and hence the base shear force to be calculated (Eq. (2)). This base shear force is thendistributed to the structural masses in accordance with Eq. (9), and then the structure be analyzed.

$$F_i = V_{Base} \,.\, (m_i\Delta_i) / \sum_{i=1}^{n} m_i\Delta_i \quad (9)$$

III. Developed Spread EXCEL Sheet

Based on the above procedure, we developed a spread EXCEL sheet that contains all of the above equations and can solve a wide range of structural systems with different structural plans, elevations, number of stories up to 20 stories with different story heights, and dimensions of columns and beams. The developed EXCELsheet uses DDBM seismic analysis formulas and draws, with high accuracy, charts for the distribution of the base shear force at different building stories, shear forces and moments of the frames and also draw the drift displacement profile of the seismic forces acting on the frame buildings.

The input data of these sheets include: the description of buildings (floor dimensions, number of stories, height of first floor, height of typical story, width and depth of columns, beams and walls, and their eccentricity from center of mass of floors). The material properties of concrete (F_{cu}, E_c) and also of steel (F_y, E_s) are entered as inputs for calculation of stress- strain curves and building strength and its stiffness.

IV. The verification of DDBM using Eurocode modal analysis model

A **Eurocode** example of 6 floors building as shown in Fig. 2& 3 solved by modal analysis was used to verify the developed EXCEL sheet. The investigated building is a multi-storey reinforced concrete structure. The buildinghas 6 stories above ground level (level 0) and two basement stories. The total height of the building above the basement is 19 m. The height of the first storey (between levels 0 and 1) is 4 m, whereas the heights of other typical stories are equal to 3.0 m.

The dimensions of the basement floors are 30m x 21 m, whereas the area of floors (above the level 0) is smaller being 30m x 14 m.

The seismic actions are summarized and represented by the **elastic response spectrum**, for soil B. The reference peak ground acceleration amounts to a_g = 0.25g. The values of the periods (TB, TC, TD) and the soil factor (S), which describe the shape of the elastic response spectrum, are TB = 0.15s, TC = 0.5 s, TD = 2.0s and S = 1.2. The building is classified as importance class II and the correspondingimportance factor is I = 1.0. The elastic response spectrum was defined for 5% damping, and Reduction Factor of R=3.

By modeling the building on ETABS program, the base shear in the major direction was found to be 3452 kN. When solved by Force Based Design Method (**FBDM)** it was found to be 6181 kN, double of the **Eurocode** model,this is because it depends on initial stiffness of the building. The example is then solved by Direct Displacement Based Design Method (**DDBM**) throughout the developed Excel sheet where the base shear was found to be 4125 kN which is about 1.2 of that of the Eurocode model.These results indicate clearly that **DDBM** is more reliable and feasible concerning the real modeling of the structure as it depends on secant stiffness as initial stiffness which is not known at the start of the design process.

Method of analysis	**analytical Model**	**DDBM**	**FBM**
Base Shear (kN)	3452	4125	6181

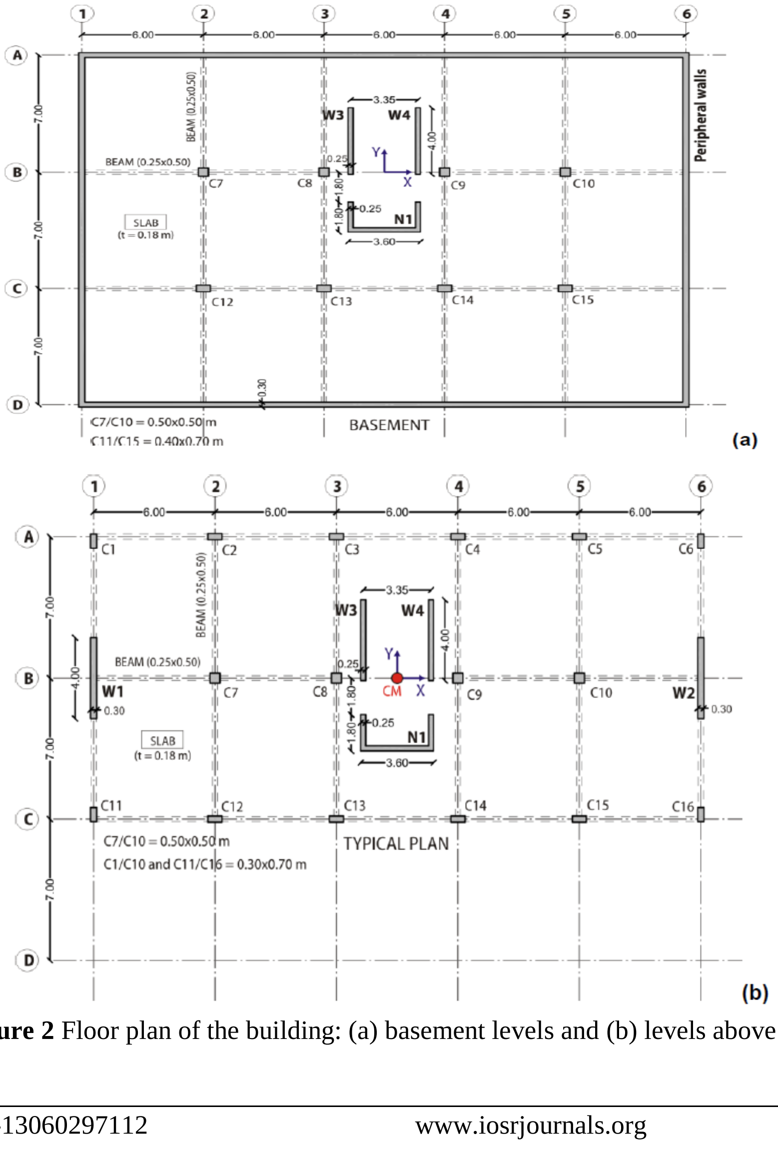


Figure 2 Floor plan of the building: (a) basement levels and (b) levels above 0.

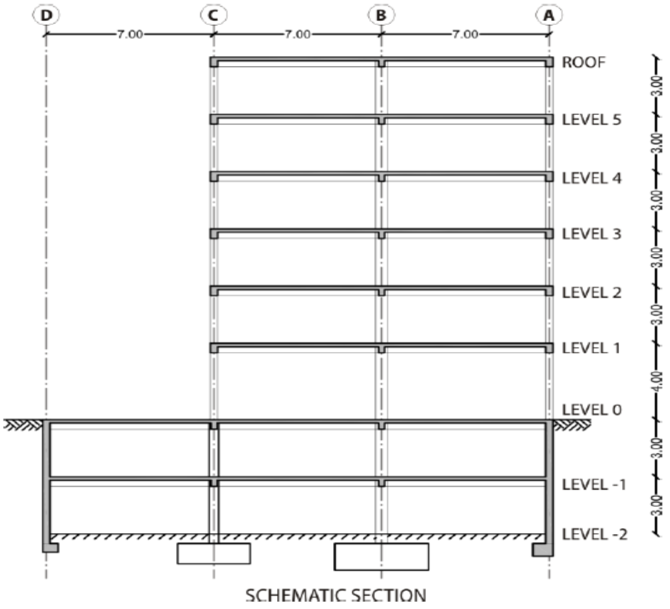


Figure 3 Schematic cross-section of the building

A second example used for the verification of developed DDBM Excel sheet is a practical Eurocode model consisted of two-bay frames connected by an interposed deck shown in Fig.4 & 5. Prototypes were designed to sustain a dead load equal to 27 kN/m^2 (including the self-weight of the slab but not the self-weight of the beams) Vertical jacks, were positioned on the deckto apply the vertical loads necessary to have the proper values of axial loadsin the columns. Horizontal jacks for applying seismic horizontal forces were positioned according to EC 8 response spectrum. The resulting recorded base shear was 218.8 kN.

Fig. 4 Loading the practical frames.

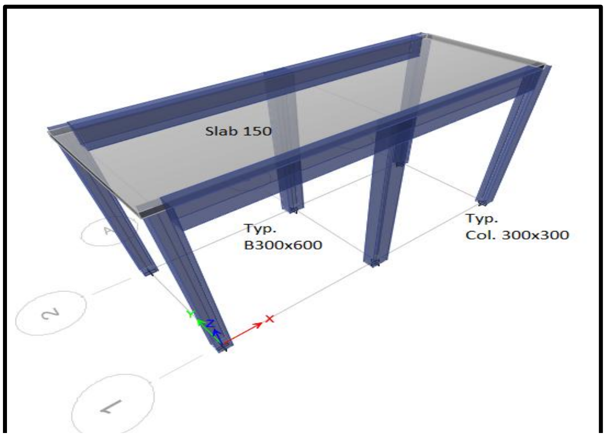


Fig. 5 Modeling of the practical frames

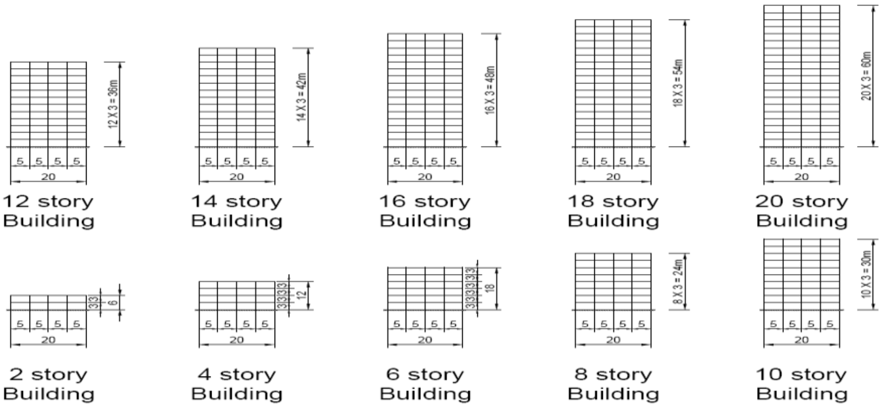
By modeling this Eurocode practical model by FBDM and also by DDBM, the resulting calculated base shears were 113.6 kN and 228.4 kN respectively with deviation from the practical model value by -48% and+4.4%respectively.These results prove the credibility of the developed DDBM Excel sheet and its capability to predict reasonable base shears with respect to FBDM. The difference in results may be attributed to the fact that FBDM period depends on the height of building ($T=C_tH^{(3/4)}$ where C_t is a constant depending on type of structure "C_t=0.075 for frame buildings") which affects the resulting base shear while the DDBM period does not depend on the structure height.

Method of analysis	**Practical Model**	**DDBM**	**FBM**
Base Shear (kN)	218.8	228.4	113.6

V. Geometry of the Analyzed Buildings

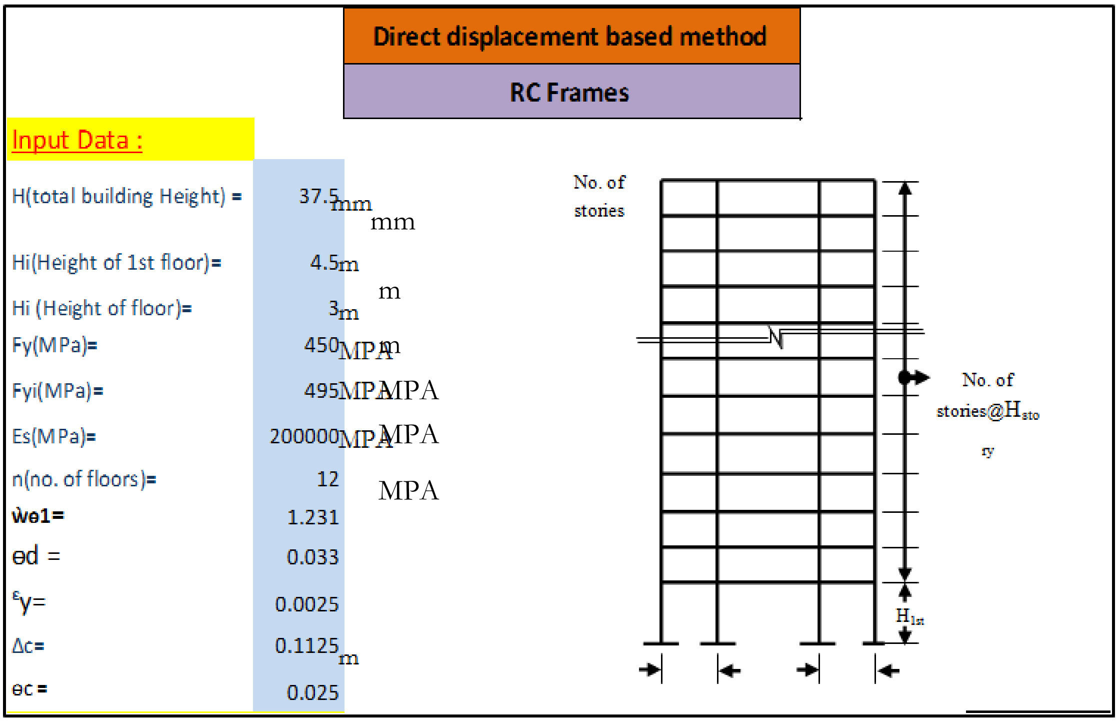
5.1 Structural System 1 (Frame Buildings)

The proposed 2, 4,6,8,10,12,14,16,18 and 20 stories building shown in Fig. 2 have been modeled using the developed Excel Sheet based on DDBM to promote the capability of this method to give reasonable results. As an example, details of the 12 stories frame building shown in Fig.6 are provided in this paper and the summery of inputs, analysis and outputs are shown in Figs. 7 and 8 as well as in tables 1 and 2.



12 story Building
14 story Building
16 story Building
18 story Building
20 story Building
2 story Building
4 story Building
6 story Building
8 story Building
10 story Building

Fig. 6 Elevation View of the Studied Moment Resisting Frame Buildings.



Direct displacement based method

RC Frames

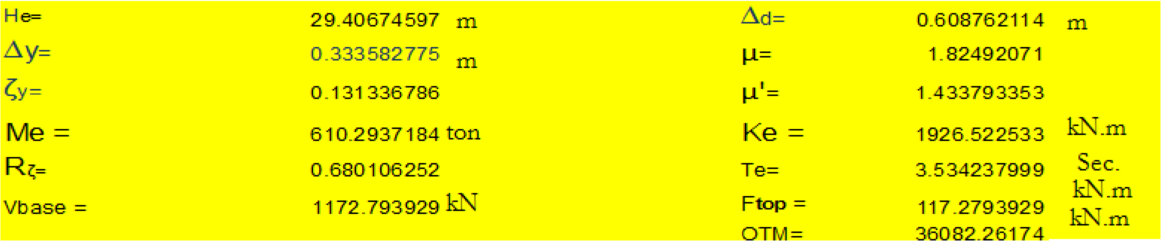
Input Data :

H(total building Height) =	37.5	mm	mm
Hi(Height of 1st floor)=	4.5	m	m
Hi (Height of floor)=	3	m	
Fy(MPa)=	450	MPA	m
Fyi(MPa)=	495	MPA	MPA
Es(MPa)=	200000	MPA	MPA
n(no. of floors)=	12		MPA
ẁe1=	1.231		
ed =	0.033		
ᵋy=	0.0025		
Δc=	0.1125	m	
ec =	0.025		

Fig. 7 Excel Sheet data for12 stories Frame Building.

Table 1 Excel Sheet Calculations for 12 Stories Frame Building.

Story	Hi	Mass m_i(t)	Φ_i	Δ_i (m)	$m_i * \Delta_i$	$m_i * \Delta_i 2$	$m_i * \Delta_i * H_i$
1	4.5	65	0.1455	0.1125	7.3125	0.82265625	32.90625
2	7.5	60	0.2375	0.183634021	11.01804	2.02328721	82.63530928
3	10.5	60	0.3255	0.251675258	15.10052	3.80042612	158.5554124
4	13.5	60	0.4095	0.316623711	18.99742	6.01503447	256.4652062
5	16.5	60	0.4895	0.378479381	22.70876	8.59479853	374.6945876
6	19.5	60	0.5655	0.437242268	26.23454	11.4708481	511.5734536
7	22.5	60	0.6375	0.492912371	29.57474	14.5777563	665.431701
8	25.5	60	0.7055	0.545489691	32.72938	17.8535402	834.5992268
9	28.5	60	0.7695	0.594974227	35.69845	21.2396598	1017.405928
10	31.5	60	0.8295	0.641365979	38.48196	24.6810192	1212.181701
11	34.5	60	0.8855	0.684664948	41.0799	28.1259655	1417.256443
12	37.5	70	0.9375	0.724871134	50.74098	36.7806713	1902.786727



He=	29.40674597	m	Δd=	0.608762114	m
Δy=	0.333582775	m	μ=	1.82492071	
ζy=	0.131336786		μ'=	1.433793353	
Me =	610.2937184	ton	Ke =	1926.522533	kN.m
Rζ=	0.680106252		Te=	3.534237999	Sec.
Vbase =	1172.793929	kN	Ftop =	117.2793929	kN.m
			OTM=	36082.26174	kN.m

Fig. 8 Excel Sheet Data for 12 Stories Frame Building.

The force acting on each floor, the distribution of the shear on the stories, and shear forces and moments of the columns and beams taking into consideration the different spans of the beam are shown in Table 2.

Table 2 Excel Sheet Calculations for 12 stories Frame Building

Story	H (m)	F_i (kN)	V_i (kN)	$F_i(H_i-H_j)$	OTM (kN.m)	V_{beam} (kN)	M_{beam} (kN.m)
1	**4.5**	**20.77**	**1172.79**	**5277.57**	**30804.68**	**286.69**	**654.05**
2	**7.5**	**33.38**	**1152.01**	**4032.06**	**26772.62**	**281.61**	**633.63**
3	**10.5**	**46.95**	**1118.63**	**3915.23**	**22857.38**	**273.45**	**615.27**
4	**13.5**	**59.91**	**1071.67**	**3750.87**	**19106.51**	**261.97**	**589.44**
5	**16.5**	**72.24**	**1011.76**	**3541.16**	**15565.34**	**247.37**	**556.48**
6	**19.5**	**83.95**	**939.51**	**3288.29**	**12277.04**	**229.66**	**516.74**
7	**22.5**	**95.04**	**855.55**	**2994.43**	**9282.6**	**209.14**	**470.57**
8	**25.5**	**105.5**	**760.5**	**2661.77**	**6620.82**	**185.9**	**418.29**
9	**28.5**	**115.34**	**654.99**	**2292.49**	**4328.3**	**160.11**	**360.26**
10	**31.5**	**124.56**	**539.65**	**1888.77**	**2439.55**	**131.91**	**296.81**
11	**34.5**	**133.15**	**415.08**	**1452.8**	**986.74**	**101.46**	**228.3**
12	**37.5**	**281.92**	**281.92**	**986.49**	**0**	**68.91**	**155.06**

The frame buildings shown in figure 6 are reanalyzed using the Force Based Design approach. The Simplified Modal Response Spectrum Method (elastic response) recommended by the Egyptian Code for load calculation of structures 2012 was applied for base shear calculation. The computer programs SAP and ETABS were used also for the inelastic modeling of the frame buildings. This last modeling was executed with reduced stiffness to 70 % of the gross section (cracked sections) as recommended by the Egyptian Code for load calculation of structures 2012. The results of these analyses (adopting FBDM approach) will be compared with those of the DDBM, and also the drift of DDBM are compared with that of SAP and ETABS after reduced to 70 % as recommended by the Egyptian Code.

5.1.1 Comparison between DDBM and FDBM

The comparison between base shear forces applying the DDBM released from the above described developed Excel sheet results and those of FBDM which are developed from both Simplified Modal Response Spectrum Method (referred in subsequent tables and figures by FBDM)and inelastic modeling using computer programs SAP and ETABS are shown in Table 3 and presented in Fig.9. Results of comparison between drifts of total heights of buildings are presented in Table 4.

Table3 Comparison of Base Shears (kN) for the Studied Frames

Number of Floors	Total height	DDBM	FBDM (Equivalent Static Loading)	FBDM (Multi R.S using ETABS)	FBDM(Multi R.S using SAP)
2	**6**	**357**	**250**	**223**	**227**
4	**12**	**450**	**500**	**264**	**231**
6	**18**	**532**	**687**	**298**	**303**
8	**24**	**588**	**738**	**316**	**317**
10	**30**	**710**	**781**	**492**	**493**
12	**36**	**880**	**817**	**505**	**530**
14	**42**	**1100**	**999**	**590**	**572**
16	**48**	**1260**	**1033**	**668**	**667**
18	**54**	**1480**	**1064**	**809**	**807**
20	**60**	**1529**	**1092**	**889**	**891**

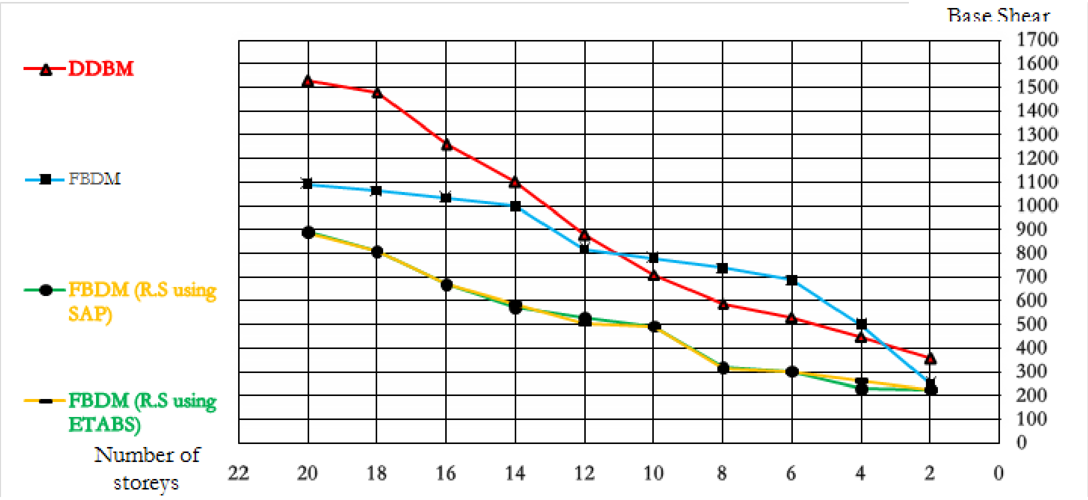


Fig.7 Comparison of Base Shears (kN) for the Studied Frame Buildings

From table 3 and figure 7 one can deduce the following:

- Generally FBDM (recommended by the Egyptian Code for Loads) overestimates the base shear relative to both DDBM and SAP for frame buildings with heights up to 30 m (10 stories), then it underestimates the base shear for buildings with higher heights.
- ETABS reduced stiffness gives values of base shear within ± 20% of those given by FBD
- Average values 0f ETABS "reduced" and SAP "reduced" match well with base shear values given by DDBM for frame buildings with heights lower than 30 m (10 stories). So for buildings with less stories, ETABS "reduced" may be considered as a good alternative to DDBM.

Table4 Comparison of Drifts (m) of Total Height for the Studied Frame Buildings

Frames Building					
Storey	Height	DDBM	FBDM (R.S using ETABS)	FBDM (R.S using SAP)	Drift limit 2.5% Height
2	6	0.129	0.1043	0.1064	0.15
4	12	0.240	0.2439	0.2506	0.3
6	18	0.352	0.4023	0.3906	0.45
8	24	0.465	0.5467	0.5362	0.6
10	30	0.577	0.6737	0.6888	0.75
12	36	0.689	0.8617	0.8491	0.9
14	42	0.802	1.0374	1.0185	1.05
16	48	0.914	1.2257	1.1977	1.2
18	54	1.027	1.4287	1.3888	1.35
20	60	1.139	1.6471	1.5939	1.5

From table 4, we can observe that the drift Values given by DDBM satisfy the drift limit imposed by the Egyptian Code for Loads whatever is the height of the frame building. Drift values given by both SAP and ETABS respect the Code limit for relatively low rise buildings (up to 14 stories). ETABS and SAP drift values violate the Code limit for building stories 16,18, and 20.

5.2 Structural System 2 (Wall Buildings)

The proposed 2,4,6, 8, 10, 12,14,16,18 and 20 stories wall buildingspossessing the plan shown in Fig. 10have been modeled using the DDBM approach through the developed Excel Sheet to ensure the capability of the methodto give reasonable values for the displacement at each floor. As an example, the input data, calculation details, and outputs of the 6 stories wall building are provided in this paper in Figs 11 to 15 as well as in table 5.

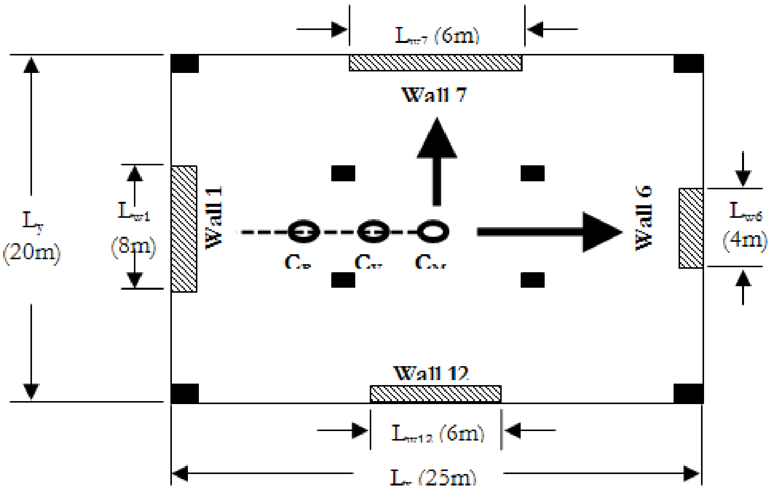
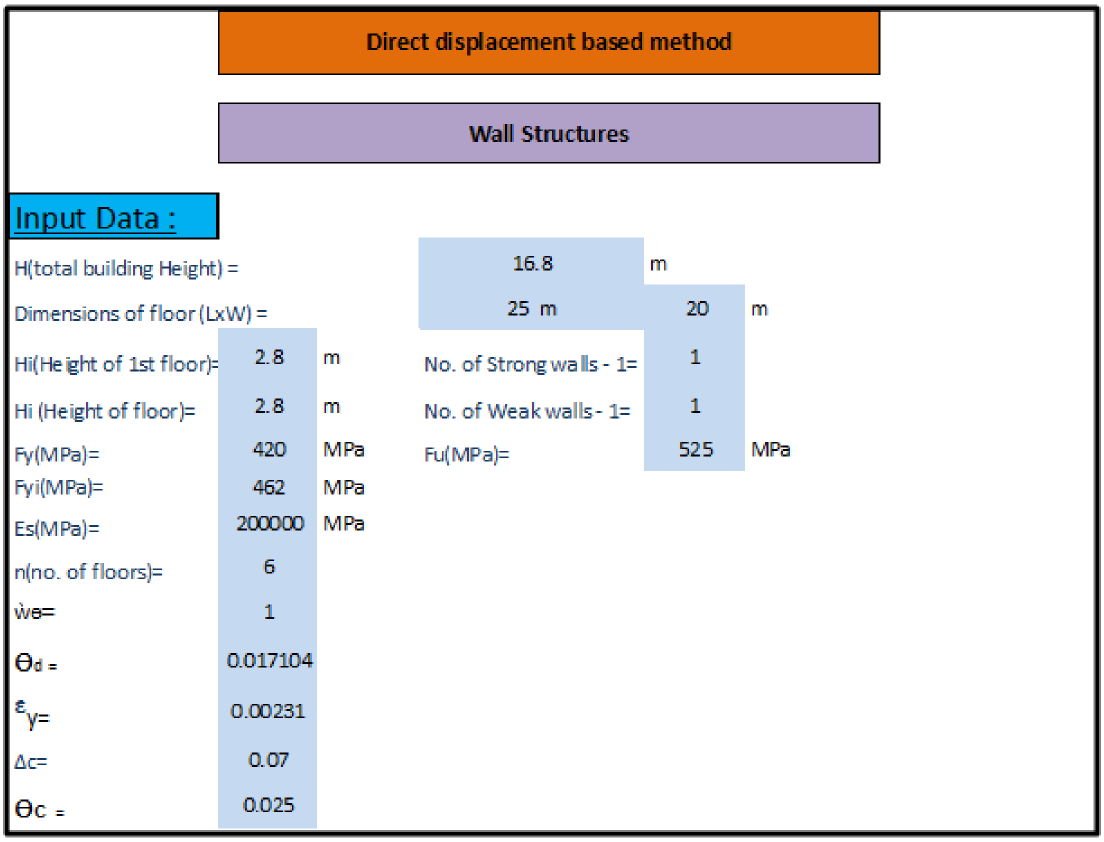


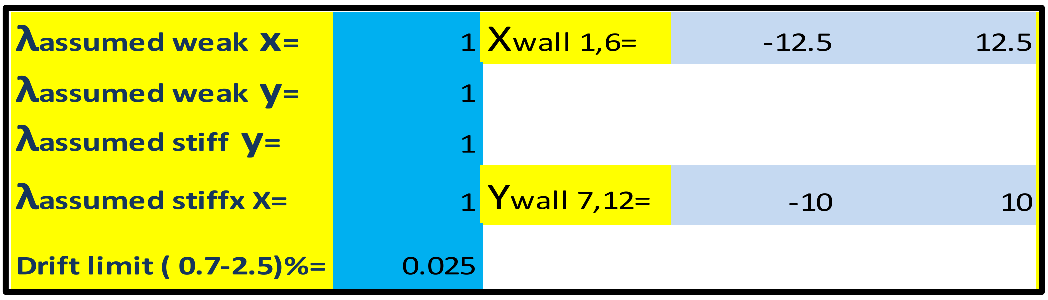
Fig.10 Plan view for the studied wall buildings



Input Data :

H(total building Height) =			16.8	m		
Dimensions of floor (LxW) =			25 m	20	m	
Hi(Height of 1st floor)=	2.8	m	No. of Strong walls - 1=	1		
Hi (Height of floor)=	2.8	m	No. of Weak walls - 1=	1		
Fy(MPa)=	420	MPa	Fu(MPa)=	525	MPa	
Fyi(MPa)=	462	MPa				
Es(MPa)=	200000	MPa				
n(no. of floors)=	6					
ẇe=	1					
θ_d =	0.017104					
ε_y=	0.00231					
Δc=	0.07					
θc =	0.025					

Fig. 11 Excel Sheet Inputs for 6 Stories Wall Building.

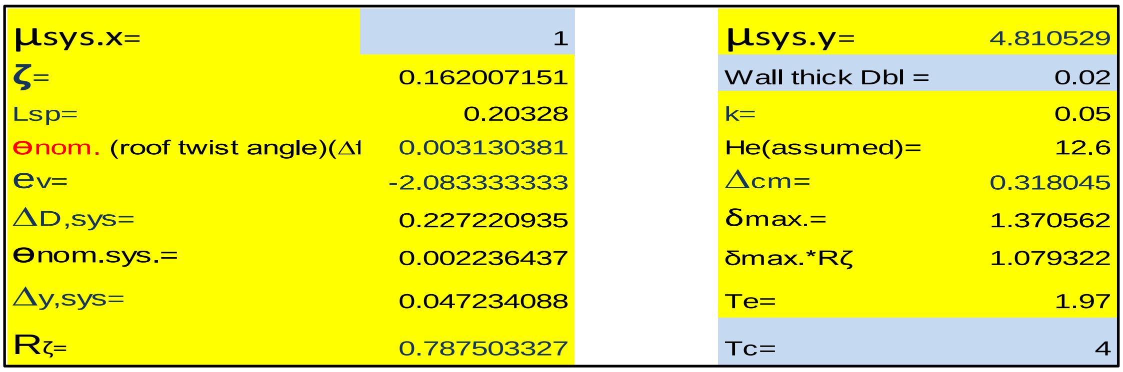


λassumed weak x=	1	Xwall 1,6=	-12.5	12.5
λassumed weak y=	1			
λassumed stiff y=	1			
λassumed stiffx x=	1	Ywall 7,12=	-10	10
Drift limit (0.7-2.5)%=	0.025			

Fig. 12 Excel Sheet Inputs for 6 Stories Wall Building.

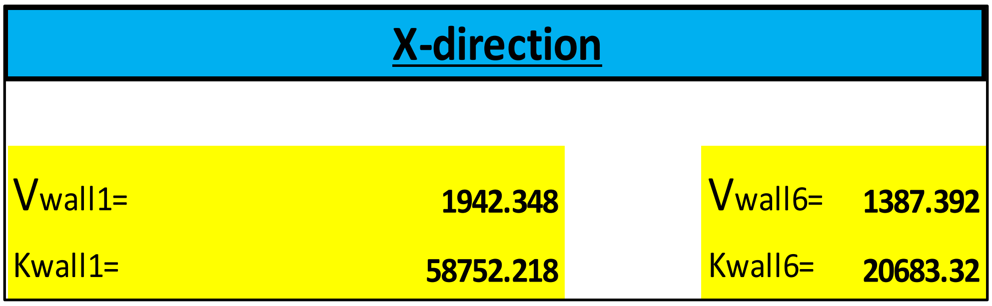
Table 5 W1, W6, W7and W12 Design Data for 6 Stories Wall Building.

Wall no	L_w	L_p	Φ_y	Δ_{yn}	θ_{yn}	θ_p	θ_n	Δ_n
1	8	1.63328	0.0005775	0.05565397	0.00491	0.013756	0.018666	0.28676
6	4	1.23328	0.001155	0.111307939	0.009819	0.020775	0.030594	0.460321
7	6	1.43328	0.00077	0.074205293	0.006546	0.016096	0.022642	0.344614
12	6	1.43328	0.00077	0.074205293	0.006546	0.016096	0.022642	0.344614



μsys.x=	1	μsys.y=	4.810529
ζ=	0.162007151	Wall thick Dbl =	0.02
Lsp=	0.20328	k=	0.05
ɵnom. (roof twist angle)(Δ1	0.003130381	He(assumed)=	12.6
ev=	-2.083333333	Δcm=	0.318045
ΔD,sys=	0.227220935	δmax.=	1.370562
ɵnom.sys.=	0.002236437	δmax.*Rζ	1.079322
Δy,sys=	0.047234088	Te=	1.97
Rζ=	0.787503327	Tc=	4

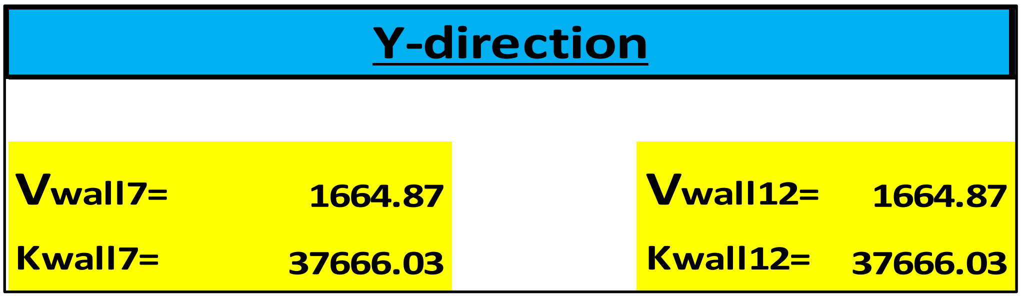
Fig. 13 Excel Sheet Calculations for 6 Stories Wall Building



X-direction

Vwall1=	1942.348	Vwall6=	1387.392
Kwall1=	58752.218	Kwall6=	20683.32

Fig. 14 Excel Sheet Base Shear in X-direction for 6 Stories Wall Building.



Y-direction

Vwall7=	1664.87	Vwall12=	1664.87
Kwall7=	37666.03	Kwall12=	37666.03

Fig. 15 Excel Sheet Base Shear in Y-direction for 6 Stories Wall Building.

The wall buildings possessing the plane shown in figure 6 are reanalyzed using the Force Based Design approach. The Simplified Modal Response Spectrum Method (elastic response) recommended by the Egyptian Code for load calculation of structures 2012 was applied for base shear calculation. The computer programs SAP and ETABS were used also for theinelastic modeling of the wall buildings. This modeling was executed with reduced stiffness to 70 % of the gross section (cracked sections) as recommended by the Egyptian Code for load calculation of structures 2012. The results of these analyses (adopting FBDM approach) will be compared with those of the DDBM.

Also the drifts of DDBM are compared with that of SAP and ETABS after its reduction to 70% as recommended in the Egyptian code.

5.2.1 Comparison between DDBM and FDBM

The comparison between base shear forces applying the DDBM released from mentioned Excel sheet results and those of FBDM which are developed from both Simplified Modal Response Spectrum Method (referred in subsequent tables and figures by FBDM) and inelastic modeling using computer programs SAP and ETABS are shown in Table 6 and presented in Fig.16. Results of comparison between drifts of total heights of buildings are presented in Table 7.

Table6 Comparison of Base Shear (kN) for the Studied Walls Buildings

Number of Floors	Total height	DDBM	FBDM(Equivalent Static Loading)	FBDM (Multi-R.S using ETABS)	FBDM (Multi-R.S using SAP)
2	**6**	**1701**	**1051**	**1098**	**1063**
4	**12**	**1983**	**2085**	**1137**	**1136**
6	**18**	**2158**	**3127**	**1520**	**1529**
8	**24**	**2383**	**4169**	**1574**	**1558**
10	**30**	**2949**	**4879**	**2104**	**2008**
12	**36**	**3001**	**5106**	**2324**	**2255**
14	**42**	**3238**	**5307**	**3092**	**2899**
16	**48**	**3444**	**5487**	**3118**	**3014**
18	**54**	**3554**	**5651**	**3717**	**3590**
20	**60**	**3690**	**5802**	**4023**	**3888**

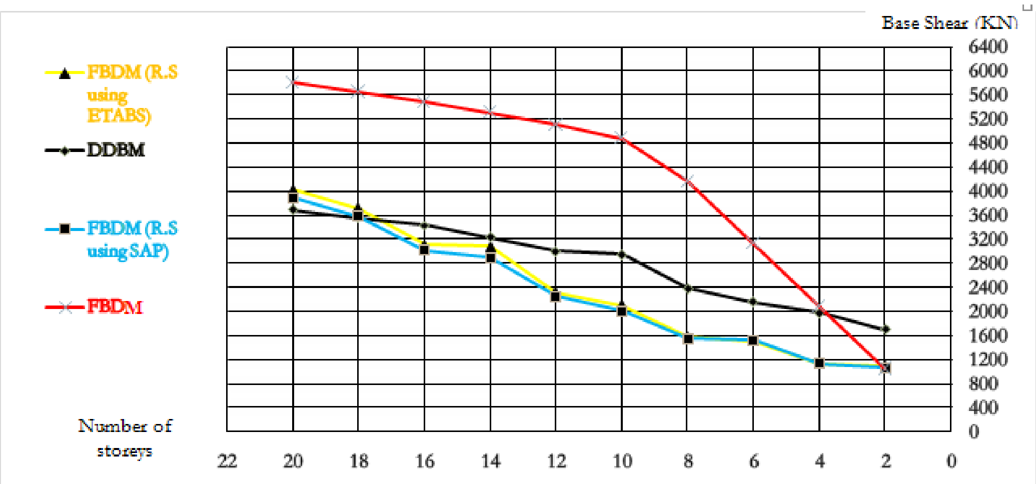


Fig. 16 Comparison of Base Shear (kN) for the Studied Wall Buildings

From table 6 and figure 16 one can deduce the following:

- Generally, FBDM (recommended by the Egyptian Code for Loads) overestimates the base shear for wall buildings relative to DDBM, ETABS, and SAP. This overestimation may reach to 2.25 times the base shear value in case of ETABS and SAP, and 1.75times in case Of DDBM.
- SAP &ETABS underestimates the base shear relative to DDBM for wall buildings with heights up to 48 m (16 stories), then it overestimates the base shear for buildings with higher heights.
- ETABS gives values of base shear within -20% of those given by DDBM for 12 stories up to 20 stories but the difference increase as height decrease, so ETABS can be a good alternative of DDBM in higher heights.

Table 7 Comparison of Drifts of Total Height (m) for the Studied Wall Buildings

Walls Buildings					
Storey	Height	DDBM	FBDM (Multi-R.S using ETABS)	FBDM(Multi-R.S using SAP)	Drift limit 2.5% Height
2	6	0.098	0.0805	0.084	0.15
4	12	0.268	0.3024	0.3535	0.3
6	18	0.386	0.6286	0.6433	0.45
8	24	0.486	0.8463	0.8834	0.6
10	30	0.573	0.8827	0.959	0.75
12	36	0.646	1.0199	1.0017	0.9
14	42	0.705	1.1277	1.1284	1.05
16	48	1.031	1.1984	1.2663	1.2
18	54	1.192	1.3069	1.5603	1.35
20	60	1.394	1.4679	1.7507	1.5

Table 7 indicates that drift values given by DDBM satisfy the drift limit imposed by the Egyptian Code for Loads whatever is the height of the wall building. Drift values given by both ETABS and SAP are under the Code limit for all building heights except for SAP 16,18, 20 stories buildings which are near equal to Code limits.

5.3 Structural System 3 (Dual Wall-Frame buildings)

For dual wall-frame buildings the proposed 2,4, 6, 8, 10, 12,14,16,18 and 20 stories buildings possessing the plan shown in Fig. 17have been modeled usingthe DDBM approach through the developed Excel Sheet to ensure capability of this method to give reliable values for the displacements and shear at each floor. As an example, the input data, details of calculation, and outputs of the 12 stories dual frame - wall building are provided in this paper in Figs 18 and 20 as well as in tables 8 and 9.

The procedure adopted for applying DDBM in analyzing dual frame-wall building system goes through the following steps:

1) Assign the percentage of distribution of base shear between frames and walls
2) Determine the walls contra flexure heights
3) Calculate the walls yield displacements
4) Draw the design displacement profile for the building
5) Design of the SDOF displacement scheme
6) Determine the Effective Height of walls
7) Evaluate the displacement ductility demands of walls and frames
8) Calculate the base shear forces in frames and walls

These steps are presented in tables 8 and 9

The dual wall-frame buildings possessing the plane shown in figure 17 are reanalyzed using the Force Based Design approach. The Simplified Modal Response Spectrum Method (elastic response) recommended by the Egyptian Code for load calculation of structures 2012 was applied for base shear calculation. The computer programs Multi-response spectrum SAP and ETABS were used also for the inelastic modeling of the dual wall-frame buildings. This modeling was executed with reduced stiffness to 70 % of the gross section (cracked sections) as recommended by the Egyptian Code for load calculation of structures 2012. The results of these analyses (adopting FBD approach) will be compared with those of the DDBM. As also drifts of DDBM are also compared with that of 70% (as recommended by Egyptian code) of SAP and ETABS.

5.3.1 Comparison between DDBM and FDBM

The comparison between base shear forces applying the DDBM released from mentioned Excel sheet results and those of FBDM which are developed from both Simplified Modal Response SpectrumMethod(referred in subsequent tables and figures by FBD) and inelastic modeling using computer programs SAP and ETABS are shown in Table 10 and presented in Fig. 20. Results of comparison between drifts of total heights of buildings are presented in Table 11.

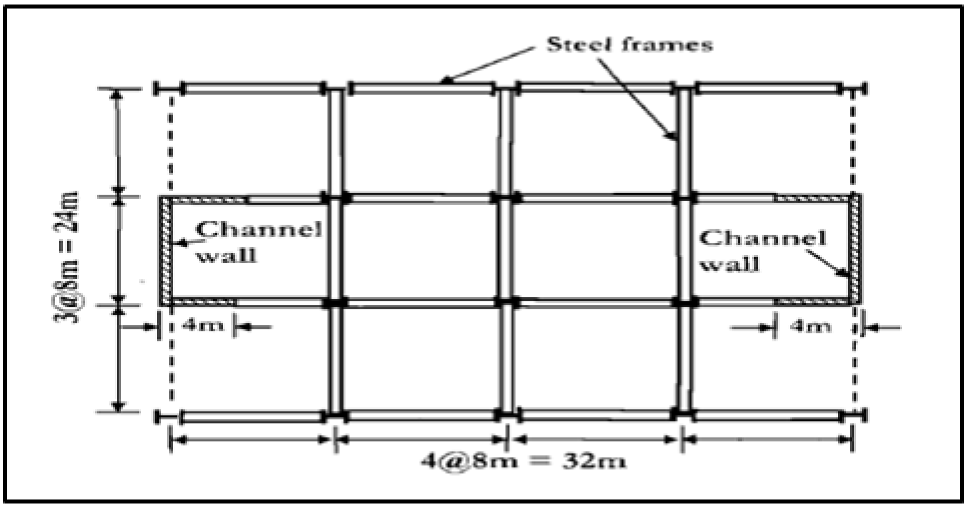
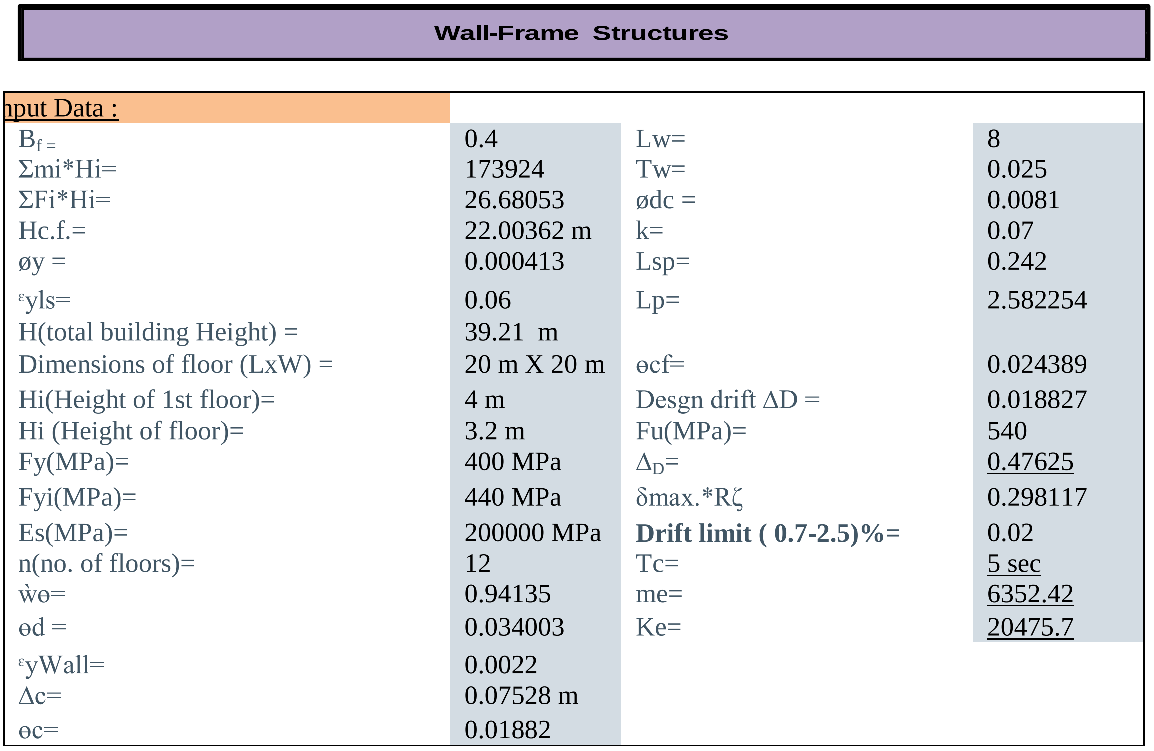


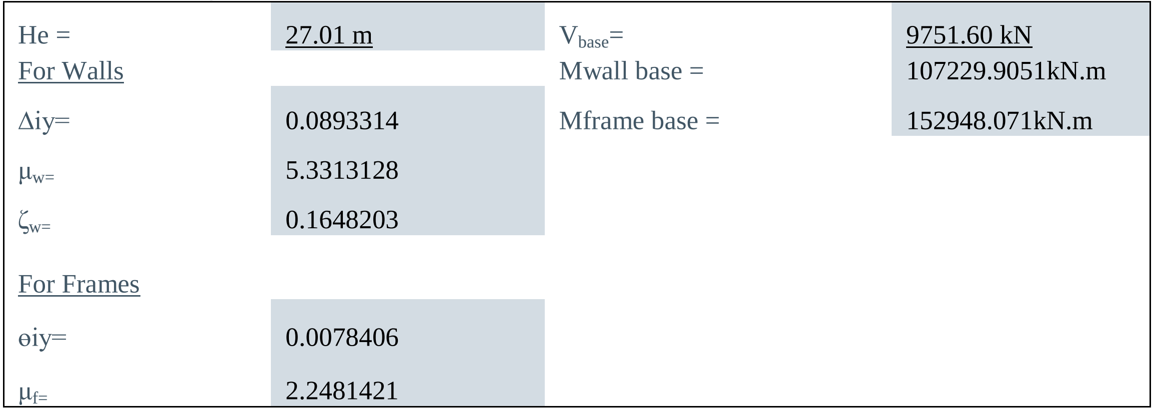
Fig. 17 Plan View for the Studied Dual Frame-Wall Buildings



Wall-Frame Structures

nput Data :			
B_{f} =	0.4	Lw=	8
Σmi*Hi=	173924	Tw=	0.025
ΣFi*Hi=	26.68053	ødc =	0.0081
Hc.f.=	22.00362 m	k=	0.07
øy =	0.000413	Lsp=	0.242
$^{\varepsilon}$yls=	0.06	Lp=	2.582254
H(total building Height) =	39.21 m		
Dimensions of floor (LxW) =	20 m X 20 m	өcf=	0.024389
Hi(Height of 1st floor)=	4 m	Desgn drift ΔD =	0.018827
Hi (Height of floor)=	3.2 m	Fu(MPa)=	540
Fy(MPa)=	400 MPa	Δ_{D}=	0.47625
Fyi(MPa)=	440 MPa	δmax.*Rζ	0.298117
Es(MPa)=	200000 MPa	**Drift limit (0.7-2.5)%=**	0.02
n(no. of floors)=	12	Tc=	5 sec
ẁө=	0.94135	me=	6352.42
өd =	0.034003	Ke=	20475.7
$^{\varepsilon}$yWall=	0.0022		
Δc=	0.07528 m		
өc=	0.01882		

Fig. 18 Excel Sheet Calculations for 12 Stories Dual Wall-Frame Building.



He =	27.01 m	V_{base}=	9751.60 kN
For Walls		Mwall base =	107229.9051kN.m
Δiy=	0.0893314	Mframe base =	152948.071kN.m
$\mu_{w=}$	5.3313128		
$\zeta_{w=}$	0.1648203		
For Frames			
өiy=	0.0078406		
$\mu_{f=}$	2.2481421		

$\zeta_{f=}$	0.1498479
$\zeta_{sys=}$	0.15865
R	0.6259621
Te=	3.4996973
Δ_{Tc}=	1.087

Fig. 19 Excel Sheet Calculations for12 Stories Dual Wall-Frame Building

Table 8 Excel Sheet Calculations for 12 Stories Dual Wall-Frame Building

1	2	3	4	5	6	7	8	9	10
Level	**Height H_i (m)**	**Mass m_i (t)**	**m_iH_i**	**F_i (rel.)**	**V_{Ti} (rel.)**	**$M_{OTM,i}$ (rel.)**	**$V_{F,i}$ Frame**	**$V_{w,i}$ Wall**	**$M_{w,i}$ Wall**
0	0	0	0	0	0	0	0	0.6	10.996
1	4.0	770	3080	0.0177	1.000	26.681	0.4	0.6	8.596
2	7.2	700	5040.7	0.0290	0.982	22.681	0.4	0.582	6.732
3	10.4	700	7281.4	0.0419	0.953	19.536	0.4	0.553	4.961
4	13.6	700	9522.1	0.0547	0.911	16.485	0.4	0.511	3.324
5	16.8	700	11762.8	0.0676	0.857	13.567	0.4	0.457	1.862
6	20.0	700	14003.5	0.0805	0.789	10.825	0.4	0.389	0.617
7	23.2	700	16244.2	0.0934	0.709	8.299	0.4	0.309	-0.371
8	26.4	700	18484.9	0.1063	0.615	6.031	0.4	0.215	-1.060
9	29.6	700	20725.6	0.1192	0.509	4.062	0.4	0.109	-1.408
10	32.8	700	22966.3	0.1320	0.390	2.433	0.4	-0.010	-1.375
11	36.0	700	25207	0.1449	0.258	1.186	0.4	-0.142	-0.920
12	39.2	500	19605.5	0.1127	0.113	0.361	0.4	-0.287	0

Table 9 Excel Sheet Calculations for 12 Stories Dual Wall-Frame Building

1	2	3	4	5	6	7	8
Level	**Height H_i (m)**	**Mass m_i (t)**	**$\square_{yi}$ (m)**	**$\square_{Di}$ (m)**	**$m_i \square^2_{Di}$**	**$m_i \square_{Di}$**	**$m_i \square_{Di}H_i$**
1	4.0	770	0.003	0.060	46.396	2.796	185.585
2	7.2	700	0.010	0.112	78.695	8.847	566.683
3	10.4	700	0.019	0.167	117.202	19.623	1219.136
4	13.6	700	0.030	0.225	157.269	35.334	2139.330
5	16.8	700	0.043	0.284	198.465	56.269	3335.014
6	20.0	700	0.058	0.343	240.361	82.534	4808.425
7	23.2	700	0.072	0.404	282.529	114.033	6556.376
8	26.4	700	0.087	0.464	324.715	150.628	8574.748
9	29.6	700	0.101	0.524	366.901	192.309	10863.194
10	32.8	700	0.116	0.584	409.086	239.074	13421.712
11	36.0	700	0.130	0.645	451.272	290.923	16250.302
12	39.2	500	0.145	0.705	352.470	248.470	13820.690

Table10 Comparison of Base Shears (kN) for the Studied Dual Wall-Frame Buildings

Number of Floors	Total height	DDBM	FBDM (Equivalent Static Loading)	FBDM (Multi-R.S using ETABS)	FBDM (Multi-R.S using SAP)
2	**6**	**4006**	**1443**	**1335**	**1300**
4	**12**	**4473**	**2862**	**1991**	**1993**
6	**18**	**4744**	**4292**	**2312**	**2381**
8	**24**	**4925**	**5723**	**2357**	**2346**
10	**30**	**5099**	**6697**	**3152**	**3149**
12	**36**	**5277**	**7010**	**3175**	**3171**
14	**42**	**5463**	**7286**	**3553**	**3602**
16	**48**	**5661**	**7535**	**3771**	**3738**
18	**54**	**5874**	**7758**	**4619**	**4593**
20	**60**	**6104**	**7965**	**5026**	**4985**

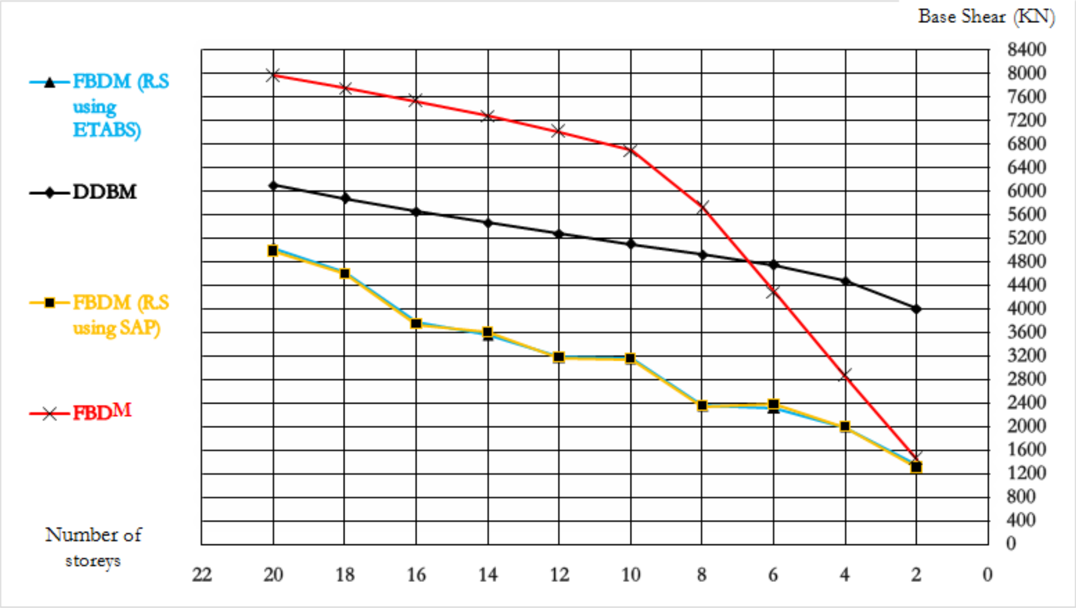


Fig. 20 Comparison of base shears (kN) for the studied dual Wall-frame buildings

- Generally, FBD (recommended by the Egyptian Code for Loads) overestimates the base shear of dual frame-wall buildings relative to ETABS, SAP, while it underestimates the base shear relative to DDBM up to height of 18 m (6 stories) then it overestimates the base shear for higher buildings.
- This overestimation is about two times in case of ETABS, and SAP, and about 1.3 times in case Of DDBM.
- Both ETABS and SAP severely underestimate the base shear relative to DDBM for low rise buildings, this underestimation decreases as the building height increases to reach 70% only of that of DDBM in case of ETABS and SAP.

Table 11 Comparison of Drifts of Total Height for the Studied Dual Wall-Frame Buildings

Dual Frame-Walls Buildings					
Storey	Height	DDBM	FBDM (R.S using ETABS)	FBDM (R.S using SAP)	Drift limit 2.5% Height
2	6	0.098	0.0805	0.084	0.15
4	12	0.251	0.3059	0.3535	0.3
6	18	0.347	0.4375	0.4585	0.45
8	24	0.456	0.5957	0.6258	0.6
10	30	0.564	0.7322	0.7896	0.75
12	36	0.670	0.8659	0.9184	0.9
14	42	0.774	0.9576	1.0227	1.05
16	48	0.877	1.022	1.0997	1.2
18	54	0.978	1.0906	1.1837	1.35
20	60	1.078	1.169	1.2019	1.5

Drift Values given by DDBM satisfy the drift limit imposed by the Egyptian Code for Loads whatever is the height of the dual wall-frame building. Drift values given by both ETABS and SAP are lower than the Code limit for all building heights.

VI. Conclusions

A comprehensive Excel sheet is developed to deal with the seismic analysis of RC buildings using the direct displacement based design method (DDBM). The applications covered different structural systems (framed, walled, and dual frame-wall buildings) with variable height ranging from 6 m to 60 m. The results of DDBM are compared with those of the force based design methods (FBDM) including the Egyptian Code Method as well as the finite element modeling through the computer programs ETABS and SAP.

From the extensive work carried out in the present study, the following conclusions could be stated:

- The DDBM is more reliable in the seismic analysis as it depends on the secant stiffness of the buildings rather than on the initial stiffness as being adopted in FBDM. The initial stiffness is unknown at the start of the design process, even if member sizes have been selected, as the increasing or decreasing of

reinforcement content to satisfy results of the force-based design proportionally changes the member's stiffness.
- Whatever is the type or the height of the RC building, the effective period given by (FBDM) proposed by the Egyptian Code is less than the effective period given by (DDBM). This fact can be attributed to the fact that the period given by (FBDM) represents the building at its elastic stage while the period given by (DDBM) represents it at its inelastic phase.
- Applying DDBM, the building ductility capacity is function of its structural geometry, not just of its structural type (RC, Steel,...). Hence this method is more realisticone.
- DDBM is more dependable by assuming a level of damping equivalent to the combined effects of elastic and hysteretic damping in such a way that it is extremely simple to apply, and very successful in providing predictable seismic response.
- Generally FBDM (recommended by the Egyptian Code for Loads) overestimates the base shear relative to other methods of analysis specially for buildings with relatively limited heights (30 m) whatever is the building structural system (frame, wall or dual frame-wall)
- F.E. modeling using ETABS, based on reduced stiffness of building members, may be considered an acceptable alternative to DDBM for some building structural systems.
- Drift Values given by DDBM satisfy the drift limit imposed by the Egyptian Code for Loads whatever is the building structural system (frame, wall or dual frame-wall) or the height of the frame building. On the contrary, the FBDMs violate the Code drift limit.

Although the procedure is very simple and results can be obtained faster in comparison to force methods, development of future computer algorithms is the key to the application of the DDBD method in practical engineering.

It should be noted that there are some limitations for the application of DDBM which can be summarized in the following points:
- Accurate calculation of the real displacements is needed.
- The use of displacement design spectra is problematic, due to many uncertainties.
- The distribution of the deformation at the maximum displacement of MDOF systems is needed.
- The plastic rotation capacity of a section is not easy to be calculated (empirical formulas exist for simple cross sections only).
- Definition of seismic excitation is one of the biggest drawbacks of this method, but a great number of high quality digital accelerograms recorded till today partially solved this problem.
- Although the DDBD has been tested for various structural types by many dynamic analyses, the authors suggest that additional analyses be carried out for various structures in the sense of testing the method and sorting out any problems for use in practice.

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