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Validity of iterative static procedure for analyzing rectangular box-shaped building under blast loading

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Nowadays the explosion of bombs or explosive materials such as gas and oil near or inside the buildings cause some losses in installations and building components. This has made the engineers to make the buildings and their components resistance against the effects of explosion. These activities lead to provide regulations and different methods. The above regulations are mostly focused on the explosion effects resulting from the explosive materials around the buildings. Therefore, the explosion resulting from the explosive materials outside the buildings will be studied in this research. In the present study, the main goals are to investigate the explosion load effects on the rectangular box-shaped building with the specific quantity of ductility and observing the permissible response of these structures. The Unified Facility Criteria - UFC 3-340 (2002) are presented as two methods for this purpose. The first procedure is static analysis. This method shall be used as iterative method. Second procedure is nonlinear dynamic analysis. Nonlinear dynamic analysis presents a numerical analysis of the nonlinear dynamic response subjected to impact and explosive loading. The finite-element system and the layered\nonlinear shell were used to study the structural system. Based on an investigative project, several concrete buildings have been modeled using SAP2000. These models were subjected to two types of blast loadings. By using the analysis one may gain a clearer understanding of the validity of static analysis and of the deflections transferred throughout the structures.

Key words: Control building, substation, blast, nonlinear dynamic analysis, iterative static analysis.

INTRODUCTION

The combined manual TM 5-1300/NAVFAC P-397/AFR 88-22, Structures to Resist the Effects of Accidental Explosions, published by the joint departments of the Army, the Navy, and the Air Force, has been used in all NATO countries for the past 50 years for protective design applications. The manual was recently reformatted to meet the Department of Defense Unified Facility Criteria (UFC 3-340-02) (2002). As a first step, the current production of the new document, UFC 3-340-02 (2002), focused on making the original TM 5-1300 available in a more functional format so that future technical updates can be facilitated.

In this study, a shell and frame model, based on the guidelines of the UFC 3-340-02 (2002) and ASCE 42 (1389), was used to model a SAP2000 to predict the response of nonlinear systems under blast.

The iterative static analysis was used to calculate deflection and displacement for a two-way reinforced concrete (RC) slabs and walls. These predictions were compared to the results of numerically nonlinear dynamic finite-element analyses and significant differences in deflection were observed.

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The general trend of results and the major characteristics of deflection were discussed in terms of the discrepancies between the iterative static and the nonlinear dynamic analyses predictions.

The work presented in this paper is expected to contribute to improving the analyzing provisions of the Rectangular box-shaped building in the future edition of the UFC 3-340-02 (2002) and ASCE 42 (1389) by understanding the limitations of static analysis (ASCE 42, 1389).

DYNAMIC MATERIAL STRENGTH

The considered building in this study is a concrete rectangular box-shaped building under the explosion load. The dynamic capacity of any structural element has been determined according to the Ultimate Strength Method as provided by the ACI 318 (ACI 318-05).

The mechanical properties of the reinforced concrete under the dynamic loads are completely different from the static ones. These differences will be manifested while system is placed under the dynamic loading in a specific period of time. Since the dynamic and static hardness of a system are not very different from each other. But with increasing the strain rate of the concrete, the compression strength and the tensile strength increase. Increasing the mentioned resistance is under the strain rate. This high strain rate (loading) will affect its components. The structures of the reinforced concrete also affect the concrete and reinforcement properties which will be mentioned below individually.

However, to consider actual dynamic strength of materials, the design strength shall be modified as follows (ASCE 1999):

Dynamic Design Stress, F_{dy}, shall be calculated as follow:

$F_{dy} = F_y$ (DIF) (SIF)

Where:
SIF, Strength Increase Factor = 1.1
DIF, Dynamic Increase Factor =1.17 for flexure, 1.10 for compression and direct shear, 1.00 diagonal tension

Dynamic Design Stress, f'_{dc}, shall be calculated as follows:

$f'_{dc} = f'_c$ (DIF) (SIF)

Where:
SIF, Strength Increase Factor = 1.0.
DIF, Dynamic Increase Factor = 1.19 for flexure, 1.12 for compression, 1.00 for diagonal tension, 1.00 for bond, 1.10 for direct shear.
f'_c = 28 days standard cylinder compressive strength of concrete.

The concepts use for structure design against the explosion is different from the concepts use in the usual building design. These differences are because of the loads resulting from the explosion which basically are different from the usual loading. The very restricted repetition of this kind of loading once or twice permits the designer to take the advantage of structure energy absorption.

In order to use this property, the structure has a permission to deform more than its elastic form otherwise the structure system exits the economic mode of system. So, using the plasticity of components and materials is necessary. For this reason the over deformation of yield is essential for the economic design of the structure. The maximum proportion of the elastic-plastic leap to the yield point one is called “the proportion or the plasticity coefficient”. In equal circumstances for the structures, the more the plasticity rate is, the less the required resistance power will be. So, the plasticity effect should be investigated in the structure well. In this research, we have studied the effect of utilized elastic plastic diagram on the structure response. As we know, the utilized diagram in an ideal model is a two-line diagram whose behavior is different from the real behavior of the structure. For this reason, in nonlinear dynamic procedure the elastic-plastic two-line diagram in analyzing the ideal model will be substituted with a Takeda and kinematic model. But in static procedure the elastic-plastic two-line diagram will be used.

BLAST LOADING

Blast resistant structures are defined as buildings and other structures capable of withstanding an external explosion which generates a side-on overpressure of 69 kPa with duration of 20 ms for high pressure case and a side-on overpressure of 21 kPa with duration of 100 ms. This is roughly equivalent to the overpressure created by a free-air explosion of one metric ton of TNT at 31.5 m. In resisting such an explosion, moderate structural damage, with a margin of safety of at least 2.5 against collapse, is considered acceptable. The intent is that personnel are kept safe and facilities remain operable in such an event.

Therefore, following blast overpressure shall be considered for building spaced 30 m from vapor cloud explosion hazard.

(a) High pressure, short duration, triangular shock loading: side-on overpressure of 10 psi (69 kPa) with duration of 20 ms..
(b) Low pressure, long duration, triangular loading: side-on overpressure of 3 psi (21 kPa) with duration of 100 ms.

For slab and walls of Rectangular box-shaped buildings, High pressure is calculated by ASCE (1389) procedure as follows:

(i) Front wall shall be designed for a peak Reflected pressure (P_r) of 172 kPa and Duration (t_d) of 20 ms, (t_e) of 18 ms.
(ii) Flat roof slabs and side wall shall be designed for an incident overpressure (Po) of 25.4 kPa and duration (t_d) of 20 ms, (t_1) of 18.6 ms, (t_2) of 38.6 ms.

For slab and walls of Rectangular box-shaped buildings, Low pressure is calculated by ASCE (1389) procedure as follows:

(iii) Front wall shall be designed for a peak Reflected pressure (P_r) of 46.1 kPa and Duration (t_d) of 100 ms, (t_e) of 79 ms.
(iv) Flat roof slabs and side wall shall be designed for an incident overpressure (Po) of 16.5 kPa and duration (t_d) of 100 ms, (t_1) of 21.5 ms, (t_2) of 121 ms.

ITERATIVE STATIC PROCEDURE

In accordance with ASCE (1389), required dynamic resistance shall be calculated in formula accordance with the general following (ASCE, 1999):

$$R = \frac{\mathrm{P}}{\frac{\sqrt{\alpha}}{\pi\tau} + \frac{\alpha\tau}{2\delta_m(\tau + 0.7)}}$$

R shall not be less than (13.8 kPa) and need not be greater than 86 kPa.

Where:
P is peak blast load = P_r or P_o or P_f as appropriate for the element under consideration, kPa.
α is energy absorption factor = $2\delta_m$-1.
δ_m is maximum displacement factor = X_m/X_e.
τ is duration factor = t_o/T.
X_m is maximum dynamic displacement (mm).
X_e is effective displacement at initial yield (mm).
t_d is duration of blast load (ms).
T is fundamental period of vibration of structure or element under consideration (ms).

According to ASCE 42 (1389):

For one way slabs or beams:

$$\mathrm{T} = \frac{\mathrm{L}^2}{1{,}080{,}000\mathrm{d}\sqrt{1.5(\rho_{e1} + \rho_{e2}) + \rho_c}}$$

T: period of a one way slab, L: span of slab (cm), d: effective depth of slab (cm), ρ_c: tension steel ratio At center span and $\rho_{e1,2}$: tension steel ratio at ends of span.

For two way slabs:

$$\mathrm{T}_2 = \frac{\mathrm{T}_{1S}.\mathrm{T}_{1L}}{\mathrm{T}_{1L} + \mathrm{T}_{1S}}$$

T: period of a two way slab (s), T1s: period of a one way slab for the short span direction of a two way slab, T1L :period of a one way slab for the long span direction of a two way slab.

According to UFC (UFC 3-340-02) (2002), the ultimate resistance of slabs and walls shall satisfy the required dynamic resistance. In fact because of the very large magnitudes of the forces induced by explosions, roof slab and exterior walls deformed into its inelastic region. The ultimate resistance of slabs and walls has been calculated in accordance with UFC (2002) charts and equations.

Also, the closer members of slab and walls are designed for maximum expected strength of roof slab and exterior walls.

In design of member under blast load, ultimate deflection of structural walls and roofs shall be checked. Therefore, the maximum dynamic displacement factors shall be limited as follows:

(i) For structural steel, $\delta_m \leq 5.0$.
(ii) For reinforced concrete loaded primarily in flexure, $\delta_m \leq 3.0$.
(iii) For reinforced concrete subjected primarily to axial compression or shear, $\delta_m \leq 1.5$.
(iv) For a steel or reinforced concrete girder forming a part of the main structural frame which resists both vertical and lateral loads, $\delta_m \leq 1.0$.

And also, the maximum allowable plastic joint gradient Δ = Xm/L shall be limited as follows:

(i) For structural steel, Δ ≤ 0.03.
(ii) For reinforced concrete, Δ ≤0.02.

Where:
L is segment length between plastic hinges in the structural element under consideration (mm) (Figure 1).
X_m is δ_m*X_e (mm).
X_e is effective displacement at initial yield (mm)
δ_m is computed according to following simplified equation. In this equation, R shall be replaced to ultimate resistance of slabs and walls, calculated by UFC (2002) charts and equations.

$$R = \frac{\mathrm{P}}{\frac{\sqrt{\alpha}}{\pi\tau} + \frac{\alpha\tau}{2\delta_m(\tau + 0.7)}}$$

All parameters are described above. The design result is show in Table 1

NONLINEAR TIME HISTORY PROCEDURE

SAP2000 program was used to calculate the dynamic response of walls and slabs. Therefore, slabs and walls have been modeled in SAP2000 and also the nonlinear behavior of reinforced concrete has been considered by layered/nonlinear shell element.

The nonlinear behavior of rebar and concrete is shown in Figure 2. The reinforced concrete elements are contained two rebar mesh at bottom and top and also concrete shell on center. In nonlinear analysis, this section is converted to fibered element to apply the nonlinear behavior of reinforced concrete elements.

In this method, ultimate deflection of structural walls and roofs shall be derived. Therefore, the maximum dynamic displacement factors and also the maximum allowable plastic joint gradient shall be limited.

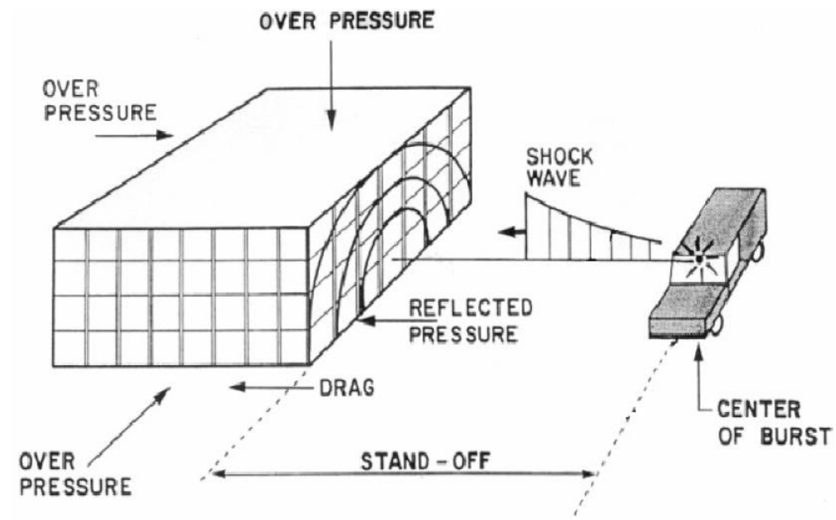

Figure 1. Blast loading.

Table 1. Iterative static procedure.

Slab and wall	L_l (cm)	L_s (cm)	T_s (cm)	ρ_{e1}	ρ_{e2}	ρ_c	R (kg/m²)	T (ms)	δ_m	R_u (kg/m²)	X_y (mm)	X_m (δ_m*X_y) (mm)	X OR Y FIG3-17 (mm)	Δ≤0.02
Slab	800	540	30	0.0054	0.0054	0.0054	3333	51	0.57	19903	8.82	5.04	3200	0.0016
Wall	800	270	40	0.0045	0.0045	0.0045	16788	13	1.96	91658	1.04	2.04	2080	0.0010
Wall	800	540	40	0.0045	0.0045	0.0045	9916	40	1.03	32862	5.84	6.03	3440	0.0018
Wall	540	540	40	0.0045	0.0045	0.0045	12104	29	1.26	45615	4.31	5.44	2700	0.0020
Wall	540	270	40	0.0045	0.0045	0.0045	17321	12	2.07	109476	1.21	2.50	1728	0.0014
Wall	810	790	55	0.0031	0.0045	0.0045	5303	87	0.67	7523	96.30	64.52	7900	0.0080
Wall	810	440	40	0.0045	0.0045	0.0045	8568	49	0.91	10789	14.24	12.95	4400	0.0030

Slab and wall	L_l (cm)	L_s (cm)	T_s (cm)	ρ_{e1}	ρ_{e2}	ρ_c	R (kg/m²)	T (ms)	δ_m	R_u (kg/m²)	X_y (mm)	X_m (δ_m*X_y) (mm)	X OR Y FIG3-17 (mm)	Δ≤0.02
Slab	800	540	30	0.0054	0.0054	0.0054	3333	51	0.41	19903	8.82	3.66	3200	0.0011
Wall	800	270	40	0.0045	0.0045	0.0045	16788	13	1.08	91658	1.04	1.13	2080	0.0005
Wall	800	540	40	0.0045	0.0045	0.0045	9916	40	1.68	32862	5.84	9.80	3440	0.0028
Wall	540	540	40	0.0045	0.0045	0.0045	12104	29	6.78	45615	4.31	29.20	2700	0.0108
Wall	540	270	40	0.0045	0.0045	0.0045	17321	12	3.88	109476	1.21	4.69	1728	0.0027
Wall	810	790	55	0.0031	0.0045	0.0045	5303	87	8.16	7523	96.30	786.00	7900	0.0990
Wall	810	440	40	0.0045	0.0045	0.0045	8568	49	11.16	10789	14.24	159.00	4400	0.0360

These parameters are computed by the following equations:

$\Delta = X_m/L$

$\delta_m = X_m/X_e$

Where:

L is segment length between plastic hinges in the structural element under consideration, mm. this parameter is calculated by FIG 3.17 in UFC (2002).

X_e is effective displacement at initial yield (mm).

X_m is computed according to displacement time history response on central node.

The design result is as shown in Table 2.

RESULTS

In order to investigate the effect of natural period on analyzing the structure response, the model was

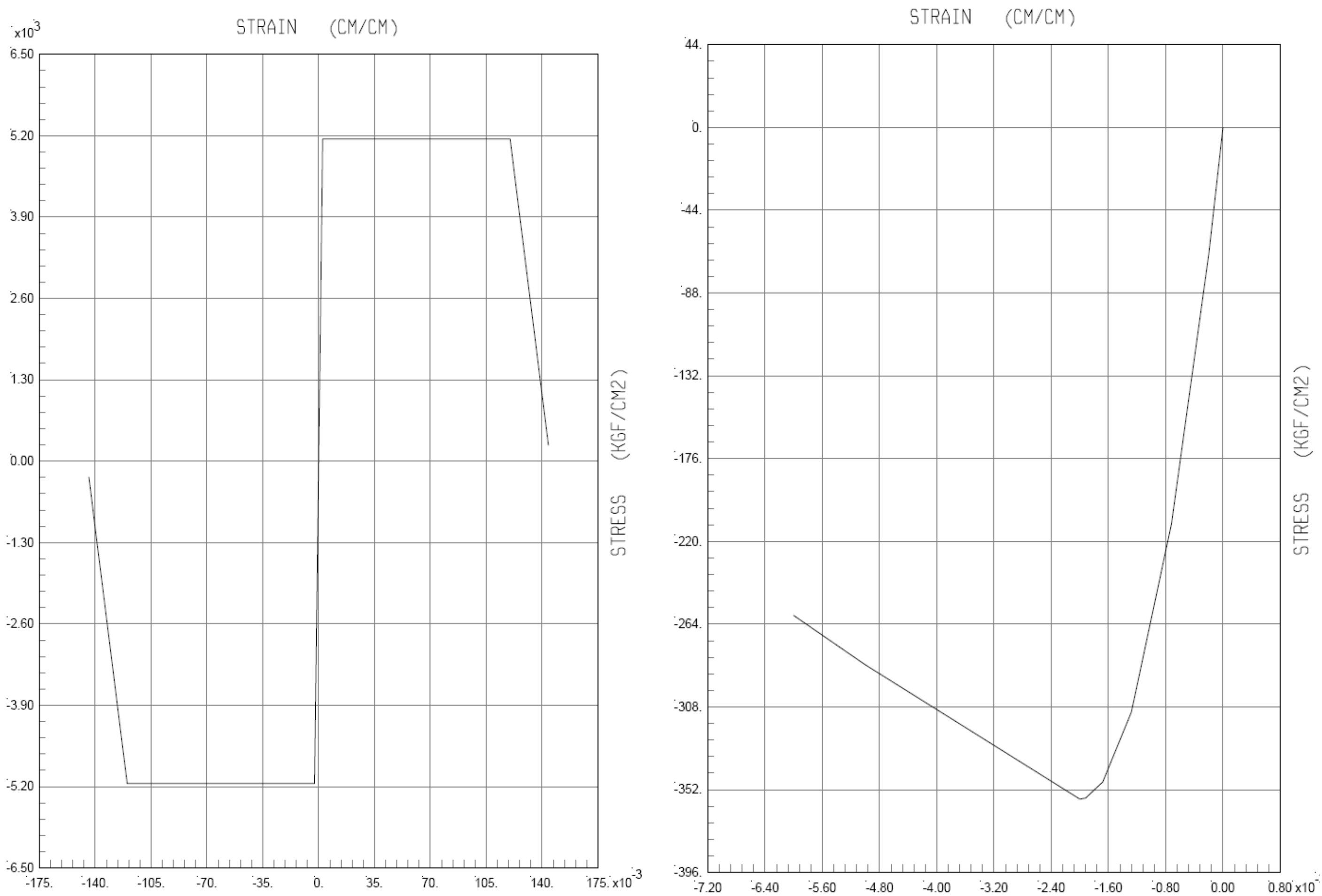

Figure 2. Nonlinear behavior of rebar and concrete material.

Table 2. Nonlinear time history procedure for wall and slab.

Wall						
T **(ms)**	R_u **(t/m^2)**	X_y	**Static-δm**	**Static-Xm**	**Dynamic-δm**	**Dynamic-Xm**
			Static	**Static (mm)**	**Dynamic**	**Dynamic (mm)**
11.94	109.48	0.80	0.57	0.46	1.00	0.80
12.50	98.66	0.90	0.58	0.52	1.11	1.00
13.43	91.66	1.04	0.59	0.61	1.08	1.13
15.46	80.13	1.60	0.60	0.96	1.13	1.80
17.92	68.99	2.30	0.61	1.41	1.13	2.60
22.99	55.27	3.30	0.64	2.10	1.21	4.00
25.69	50.27	3.80	0.65	2.46	1.32	5.00
29.12	45.62	4.31	0.66	2.83	1.39	6.00
32.60	39.88	4.80	0.68	3.25	1.46	7.00
35.69	35.60	5.30	0.69	3.65	1.51	8.00
39.93	32.86	5.84	0.70	4.10	1.68	9.80

Slab					
	T	R_u	**Dynamic-δ$_m$**	**Dynamic-X_m**	**Dynamic-Δ**
Slab	50.896	19903	0.414	3.66	0.0011

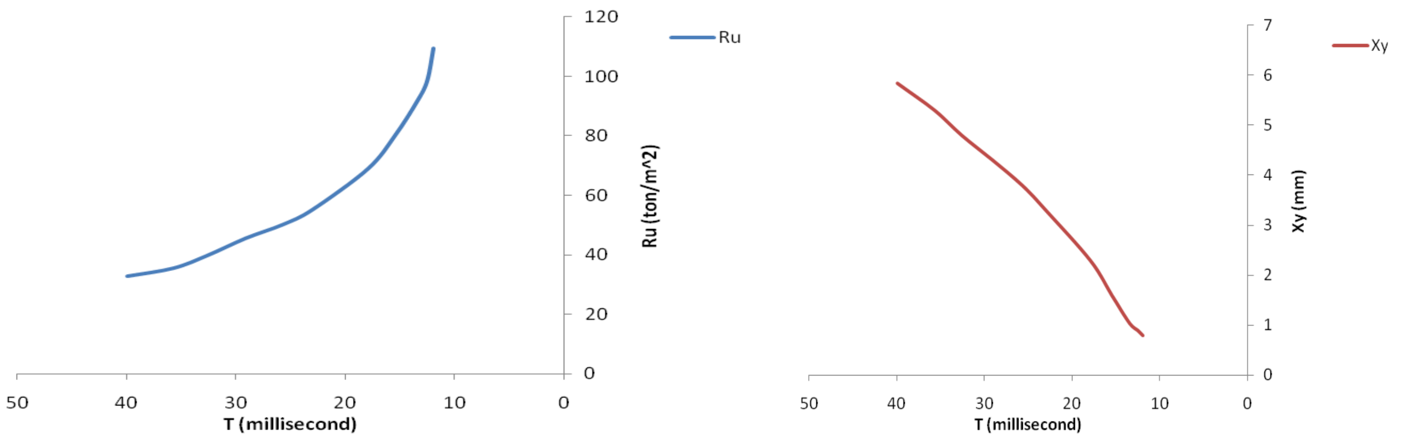

Figure 3. Results of static analysis.

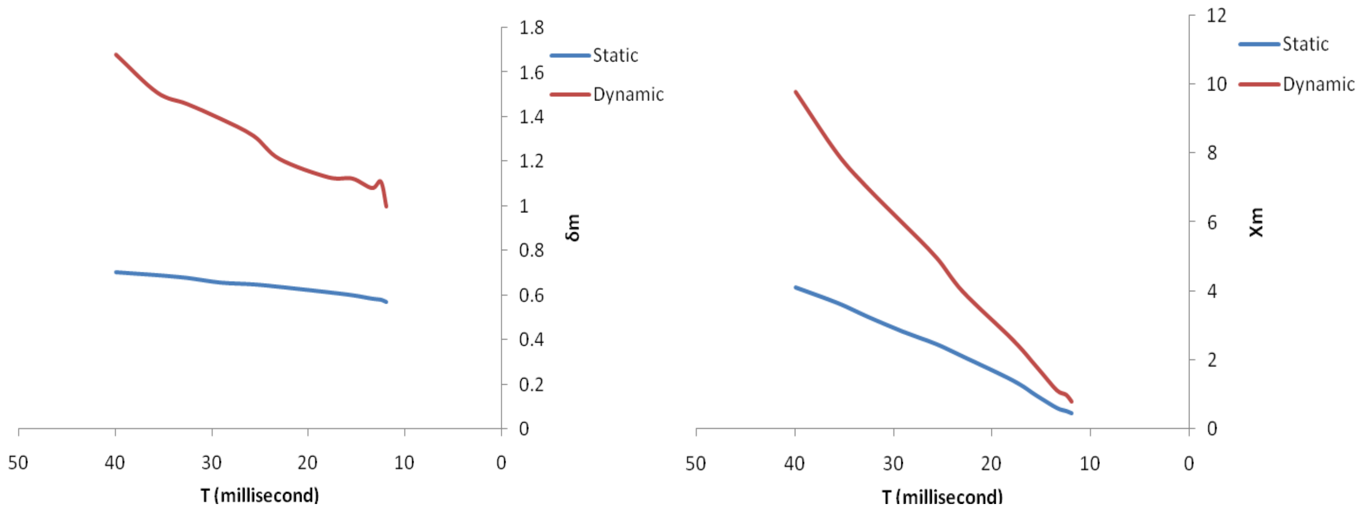

Figure 4. Results of nonlinear dynamic and static analysis.

analyzed for various periods and the results were examined. For a comprehensive investigation, we analyze the analytic model for different model resistance and different structure period, and then we compare effective displacement at initial yield and ultimate resistance in Figure 3. Finally, we present the results of dynamic analysis comparison with a static analysis on the structure deflection in Figure 4.

In this study which was presented as “designing the Rectangular box-shaped building and examining its behavior under the explosion load”, it was determined that the great changes appear in the deflection of the systems with static and dynamic analysis.

Usually, in more precise methods, a system presents more economic results. But in Figure 4, the dynamic analysis does not present this result. With decreasing the natural period of the system in Figure 4, the amount of difference of the static and dynamic analysis decrease in the deflection. Also, the ductility of all components of system (walls and slabs) is sensitive to the system period. This sensitivity is presented in Figure 4 (δ_m = ductility of components).

The ductility is almost compatible with the system period.

Here is an important point: if the natural period of one of the system components (wall or slab) changes, the changes patterns in the ductility of both analysis will be same as each other. With increasing the period in dynamic analysis, the ductility increases meaningfully, but with increasing the period in static analysis, the ductility increases with lower speed so that it shows about 10% increase in ductility instead of 100% increase in the period.

In order of reforming the elastic-plastic diagram and

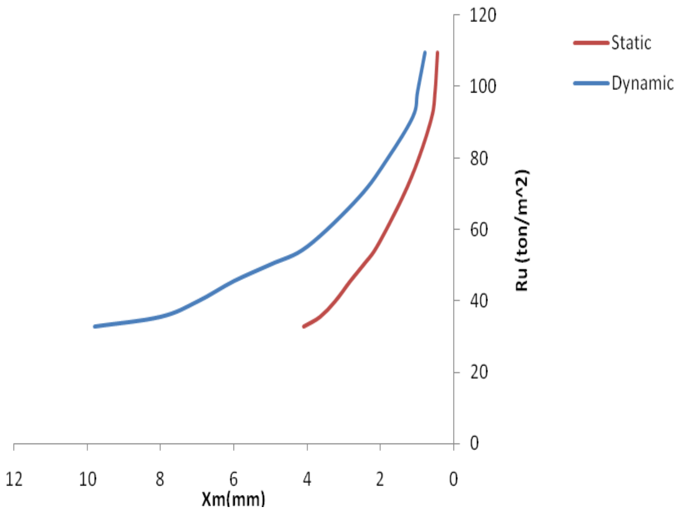

Figure 5. Ultimate displacement and resistance for nonlinear dynamic and static analysis.

making closer the ideal model behavior to the structure real ones, the three-line diagram instead of the two-line ones has been used in the analysis, but as it was presented in the results, the amount of difference is between 0/5 to 5%. This small error witnesses that the type of utilized diagram in the analysis, has a small effect on the structure response.

The system resistance is inverse the system deflection. This result is presented in Figure 5. If the ultimate deflection changes, the changes patterns in the resistance of both analysis will be same as each other.

Conclusion

From the numerical results obtained by using iterative static and nonlinear dynamic analysis method for the slab, front wall, side wall of the studied building, the following conclusions can be drawn:

1. Ultimate displacement in all walls and slabs in static method do not matched to nonlinear dynamic analysis.
2. Ultimate deflection in all walls and slabs in static method do not matched to nonlinear dynamic analysis.
3. The nonlinear dynamic method is obtained as stronger elements.
4. The ductility is almost compatible with the system period
5. The system resistance is inverse the system deflection
6. With decreasing the natural period, the amount of difference of the static and dynamic analysis decrease in the deflection.

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