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ENGLISH VERSION..

Seismic design for performance in non-structural elements using the direct displacement methodology in reinforced concrete buildings

Diseño sísmico por desempeño en elementos no estructurales mediante la metodología de desplazamiento directo en edificios de concreto armado

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Abstract

One of the under-investigated branches of performance design approaches is the design of non-structural elements. Non-structural elements are all those that do not participate directly in the structural resistance of a building, however, they present damage in the event of an earthquake. One of the methods developed in recent years is through direct displacement, which consists of restricting the non-structural element by giving it a maximum allowable displacement and calculating the allowable force by Hooke's law. Therefore, the nonstructural elements for different configurations of a reinforced concrete building were designed using the direct displacement methodology and compared with the design according to the force-based design. Five reinforced concrete buildings (structural wall system) with the same floor were modeled for five different seismic movements and the design was carried out by the two methods for a certain anchoring system. In conclusion, the design based on direct displacement is more efficient than the traditional design, since it considers inelastic parameters. In addition, any non-structural element must be designed by both methods and apply the envelope criteria so as not to violate local regulations.

Keywords: *Performance design, direct displacement, force-based design, non-structural elements, reinforced concrete buildings*

Resumen

Una de las ramas poco investigadas en los enfoques de diseño por desempeño es el diseño de elementos no estructurales. Los elementos no estructurales son todos los que no participan de manera directa en la resistencia estructural de una edificación, sin embargo, presentan daños frente a la ocurrencia de un sismo. Uno de los métodos desarrollados en los últimos años es mediante el desplazamiento directo, que consta de restringir al elemento no estructural dándole un máximo desplazamiento permisible y calcular la fuerza permisible por la ley de Hooke. Por lo tanto, se diseñó mediante la metodología de desplazamiento directo los elementos no estructurales para diferentes configuraciones de un edificio de concreto armado y se los comparó con el diseño según el diseño basado en fuerzas. Se modeló cinco edificios de concreto armado (sistema de muros estructurales) con la misma planta para cinco diferentes movimientos sísmicos y se realizó el diseñó por los dos métodos para un determinado sistema de anclajes. En conclusión, el diseño basado en el desplazamiento directo es más eficiente que el diseño tradicional, ya que considera parámetros inelásticos. Además, cualquier elemento no estructural debe ser diseñado por los dos métodos y aplicar el criterio de envolvente para no incumplir normas locales.

Palabras clave: Diseño por desempeño, desplazamiento directo, diseño basado en fuerzas, elementos no estructurales, edificios de concreto armado

1. Introduction

Two decades ago strength and performance were taken as synonyms in terms of design, however this philosophy was criticized and gave rise to performance design incorporated in international construction standards such as the (ASCE, 2000), (ASCE, 2017) and (SEAOC, 1995) that consider the inelastic properties of the elements (Park, 1975). It is important to define non-structural elements, that is why (FEMA, 2018), (Porter, 2005), (Bachman and Dowty, 2008), (Christopoulos and Filiatrault, 2006) Y (Tatarsky and Filiatrault, 2019) provided guidelines on the concept, taxonomy and different protection systems for non-structural elements.

(Pantoli et al., 2015) tested different non-structural elements in a full-scale reinforced concrete building at the University of California on a fixed vibrating base. On the other hand, in Latin American countries only a qualitative comparison has been made between design methods for these elements by (Castro, 2019) Y (Cordova Shedan, 2017) with (Morales, 2020) applied the method to dual system structures (walls and columns). However, the application of performance design to nonstructural element systems remains largely unexplored.

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The non-structural elements comprise 90% of the total investments in essential buildings and this includes electrical installations, sanitation and gas according to (Taghavi and Miranda, 2004) Y (FEMA, 2018). Most of the earthquakes leave the structural elements in functional conditions, but it is the non-structural elements that present the greatest damage after an earthquake, since they also depend on the seismic responses of the structure (Perrone and Filiatrault, 2017). In Latin America, seismic design for non-structural elements is governed by standards that are deficient, since they are based on empirical concepts, judgment and intuition rather than on experimental data and analytical results (Filiatrault and Sullivan, 2014).

Displacement-Based Direct Design (DBDD) was created by (Priestley, 2000) which proposes starting from a maximum demand displacement to the calculation of the maximum force required. The scope of the DBDD considers a "substitute structure", an analysis procedure developed by (Shibata and Sozen, 1976) which represents the entire structure as an equivalent SD1L oscillator, for the non-structural elements it is easy to meet this requirement since they are all idealized as SD1L. The DBDD also characterizes the secant stiffness structure at a maximum displacement and a level of visco-equivalent damping appropriate to the hysteresis energy absorbed during the inelastic response.

According to the deficient problems presented by the classical design (elastic) and to the little intervention of design for performance in non-structural elements, the non-structural elements were designed by DBDD for some configurations of reinforced concrete buildings and they were compared with the traditional design.

2. Methodology

2.1 Direct Displacement Seismic Design:

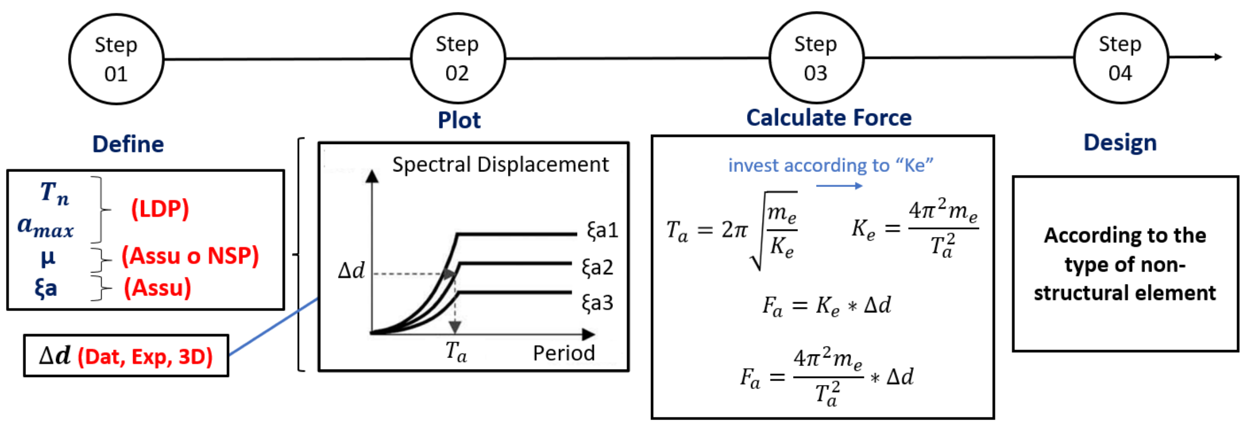

Figure 1. Methodology for the DBDD in non-structural elements.

5 parameters will be defined: For the Natural Elastic Period of the structure (T_n) and the maximum modal acceleration (a_{max}), an LDP (Linear dynamic process) will be carried out, also called a Linear Dynamic Analysis, which is already known by the scientific community. Since the required acceleration is modal, the LDP will also be a modal analysis. In addition, it must be maximum, therefore, it is recommended to choose the most critical among the accelerations of all floors. Then, with good judgment and/or based on the literature, the ductility of the structure (μ) and the equivalent damping of the non-structural element ($\mathcal{E}_a$). It is recommended to use values between 0.01 to 0.15 for the equivalent damping. On the other hand, if you want to obtain the ductility more accurately, you should perform an NSP (Nonlinear static process) or also known as Pushover, but for practical purposes assume a ductility of 1 with which you will get the best response. Finally, the direct displacement (Δ_d) will be defined, which can be obtained in three ways: The data can be collected from some literature, an experimental laboratory test can be performed or a computational modeling can be performed, these results should be similar to a cyclic-hysteretic curve.

The displacement spectrum will be plotted with the first 4 parameters of step 01 following (Equation 1) that (Filiatrault et al., 2018), transformed the acceleration spectra formula of (Sullivan et al., 2013)to a displacement spectrum as a function of the Period for non-structural elements:

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$$S_{DF}(T_a) = \frac{{T_a}^3}{4\pi^2 T_n}\left[a_{max}\left(\frac{1}{\sqrt{\mathcal{E}_a}} - 1\right)\right] + \frac{{T_a}^2 a_{max}}{4\pi^2} \quad ; T_a < T_n$$

$$S_{DF}(T_a) = \frac{{T_a}^2 a_{max}}{4\pi^2\sqrt{\mathcal{E}_a}} \quad ; T_n \leq T_a < T_{eq}$$

$$S_{DF}(T_a) = \frac{{T_a}^2 a_{max}}{4\pi^2\sqrt{(1 - \frac{T_a}{T_{eq}})^2 + \mathcal{E}_a}} \quad ; T_a \geq T_{eq}$$

Such that:

$$T_{eq} = T_n \; para \; \mu \leq 1$$

$$T_{eq} = T_n\sqrt{\mu} \; para \; \mu \leq 1 \qquad (1)$$

Where:

T_a= *Period of the nonstructural element*
T_{eq}= *Equivalent period of the non-structural element*
T_n= *Elastic natural period of the structural system*
μ = *Ductility of the structural system*
a_{max}= *maximum modal lightening*
$\mathcal{E}_a$= *Equivalent damping of the non-structural element*

With the direct displacement (Δd = $S_{DF}(T_a)$) defined in step 01, the effective period of the nonstructural element is read (T_a) as shown in step 02 of (Figure 1). Then, solve the effective stiffness of the formula for (Thomson, 1998), (Chopra, 2000) Y (Chopra, 2014) for SD1L and is replaced in Hook's equation obtaining (Equation 2) for the design force.

$$F_a = \frac{4\pi^2 m_e \Delta_d}{{T_a}^2} \qquad (2)$$

Where:

m_e= *Effective mass of the non-structural element*
Δ_d = *Direct displacement*

Finally, the reinforcement of the non-structural elements is designed according to their type and the regulations that govern it.

2.2 Seismic design by forces:

For seismic design of non-structural elements we will use as an example the Technical Standard E.030 Seismic Design in Chapter VI: Non-Structural Elements: The anchors and connections of non-structural elements are designed to resist a horizontal seismic force (F) in any direction associated with its weight (Pe), whose resultant is applied to the center of mass of the element, as indicated in (Equation 3) (RNE E.030):

$$F = \frac{a_i}{g} C_1 P_e \qquad (3)$$

Where:

a_i= *Horizontal acceleration at the level of the nonstructural element*
g= *Acceleration of gravity (9.81m/s2)*

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C_1= safety factor
P_e= Weight of the non-structural element

The values of C_1 (safety coefficient) are taken from Table N° 12 cited in said standard (Table 1):

Table 1. Values of C_1

C1 VALUES	
Elements that, when failing, can fall out of the building and be dangerous for people or other structures.	*3.0*
Walls and partitions inside a building.	*2.0*
Tanks and parapets on the roof, powerhouse, pergolas.	*3.0*
Rigid equipment rigidly connected to the floor.	*1.5*

Source: (RNE, 2019)

2.3 Object of Study:

Generally, a reinforced concrete building can be varied in two ways: in plan and in height. For the formulation of direct displacement in non-structural elements, the variation in floor plan is not as significant as the variation in height, since this formula depends directly on the structural period (Pérez Martínez, 2019). In addition, in many investigations the authors propose different configurations that do not obey any pattern in plan and height for their designs, so the choice of the object of study is left to the discretion of the researcher. Therefore, five reinforced concrete buildings similar in plan, but variable in height, were modeled in the ETABS Program and it was verified that they meet a "regular" classification. The buildings have the characteristics as shown in (Figure 2) and in (Table 2) adapted from PM (Calvi and Sullivan, 2014):

Table 2. Configuration for reinforced concrete building.

Description	***Building 1***	***Building 2***	***Building 3***	***Building 4***	***Building 5***
Number of storeys	*2*	*4*	*8*	*12*	*20*
Wall thickness (m)	*0.15*	*0.25*	*0.25*	*0.25*	*0.25*
L(m) (Figure 2)	*2.00*	*2.00*	*4.00*	*6.00*	*10.00*

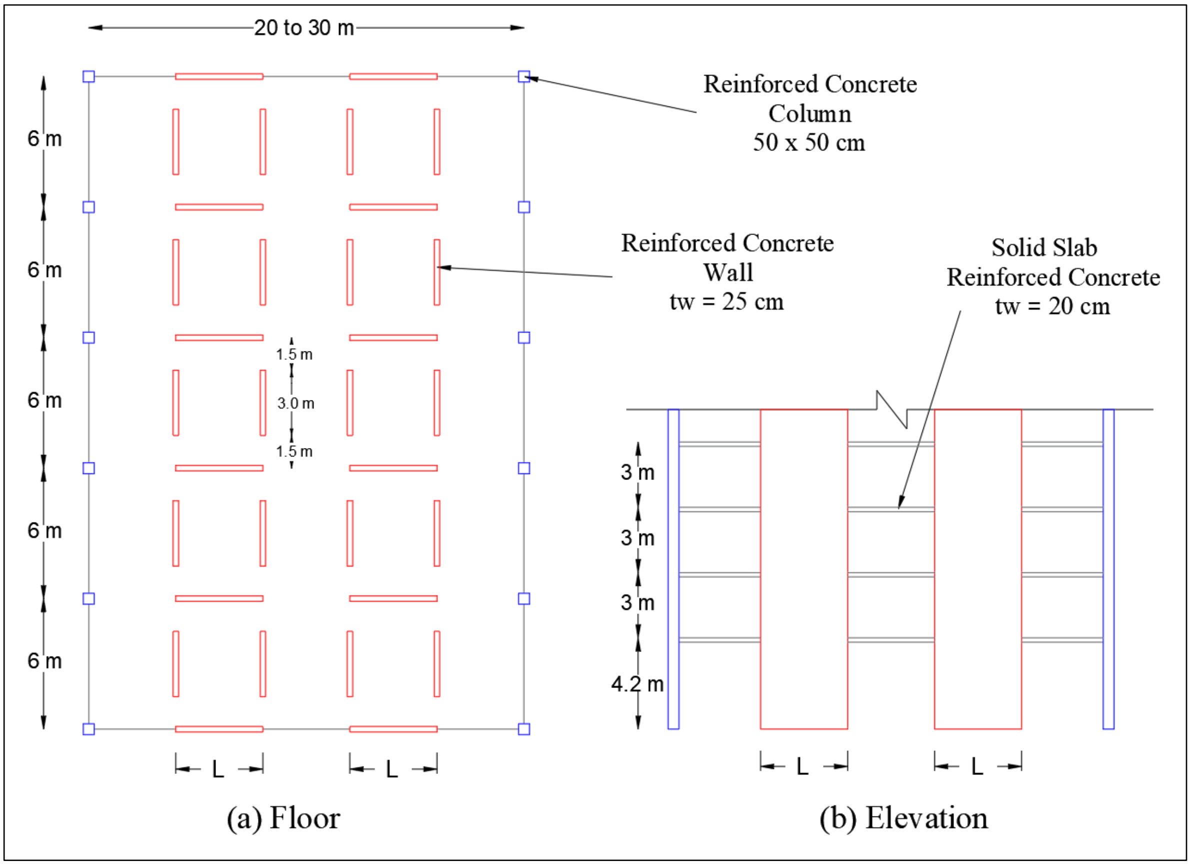

Figure 2. (a) Plan and (b) elevation of the reinforced concrete building.
Source: Adapted from Calvi and Sullivan (2014)

The structure has been categorized as essential building use and the proposed structural system is "structural walls". In the same way, five different seismic movements have been permuted: four of them have been carried out through spectral analysis and varying the resistance of the soil, the fifth movement has been obtained through analysis of the time history of the earthquake: North-West of Pastaza, Alto Amazonas – Loreto described in (Table 3) also this last analysis only considered the elastic properties of the structures (CENSIS, 2019).

Table 3. Earthquake data Northwest of Pastaza, Alto Amazonas – Loreto.

ICG DATA	
Date	*02/22/2019*
Time	*05:17:00*
Latitude	*-2.25*
Length	*-77.19*
Magnitude	***7.7ML***
Depth	*139km*

Source: (CENSIS, 2019)

The structure was considered in an essential structural category (Health Establishment without Seismic Isolation) the loads were chosen according to said category as shown in (Table 4) (RNE, 2006). In addition, the criterion of increasing the S/c by 100 Kg/m2 was taken in order to maximize the period of the entire structure and permute the responses.

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Table 4. Loads for the design of the reinforced concrete building for essential buildings. category

Set	Description	Load Kg/m2 (KPa)	mass multiple
Storeys	non-structural elements	100 (1.0)	1.00
	live load	500 (5.0)	0.50
	masonry	150 (1.5)	0.50
Last storey	non-structural elements	100 (1.0)	1.00
	live load	100 (1.0)	0.25

The non-structural elements will be a system of 3 pipes reinforced with anchors. The design anchors are shown in (Figure 3), they consist of 4 anchor supports (with 2 vertical elements and 2 diagonal elements), 3 rings that hold the pipes and hinges to join all the elements. These anchors have a resistance of and according to the experimental tests of$F_n = 11.9\ KN \Delta_d = 15mm$ *(Wood et al., 2014).*

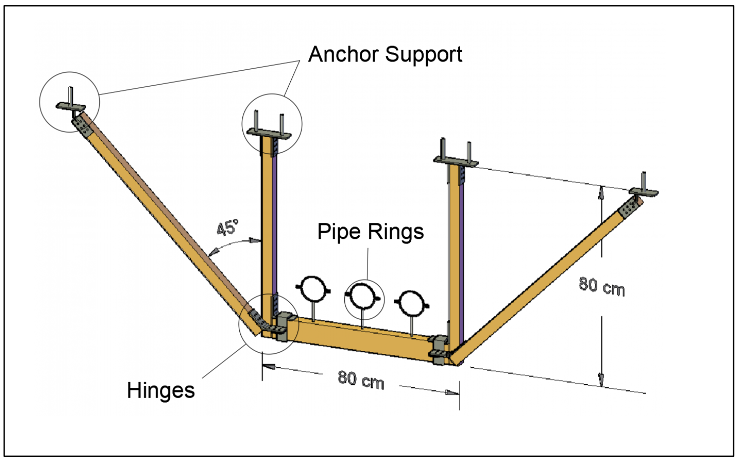

Figure 3. Anchors for pipes.

From the modeling in the ETABS software, the following results were obtained considering the maximum acceleration in the last floor (a_{max}*) and the fundamental module for the Period of the structural system (*T_n*). Both (*a_{max}*) and (*T_n*) were compared with all the results in both directions to verify that they are the best response for each building. For the Ductility of the structural system (*μ*), a so-called Pushover was performed (Table 5).*

Table 5. Structure response (maximum accelerations)

Description		Building 1	Building 2	Building 3	Building 4	Building 5
Number of storeys		2	4	8	12	20
Period (sec)		0.205	0.424	0.567	0.812	1,631
Ductility (μ)		10.18	4.95	5.51	5.77	7.13
	Earthquake 02/22/19 (m/s2)	4.19	5.69	9.22	10.77	7.74
	Z4-S3 (m/s2)	4.04	4.65	5.05	5.11	4.95
a_{max}	Z4-S2 (m/s2)	3.86	4.44	4.82	4.47	3.48
	Z4-S1 (m/s2)	3.68	4.03	3.60	3.30	2.84
	Z4-S0 (m/s2)	2.94	2.57	2.46	2.31	2.12

For the construction of the acceleration spectrum in (Figure 4) it can be seen that: for the same seismic risk zone, in this case zone 4, the platform being the maximum acceleration (in short periods) is directly proportional, in range (magnitude of acceleration) and domain (periods), to the type of soil.

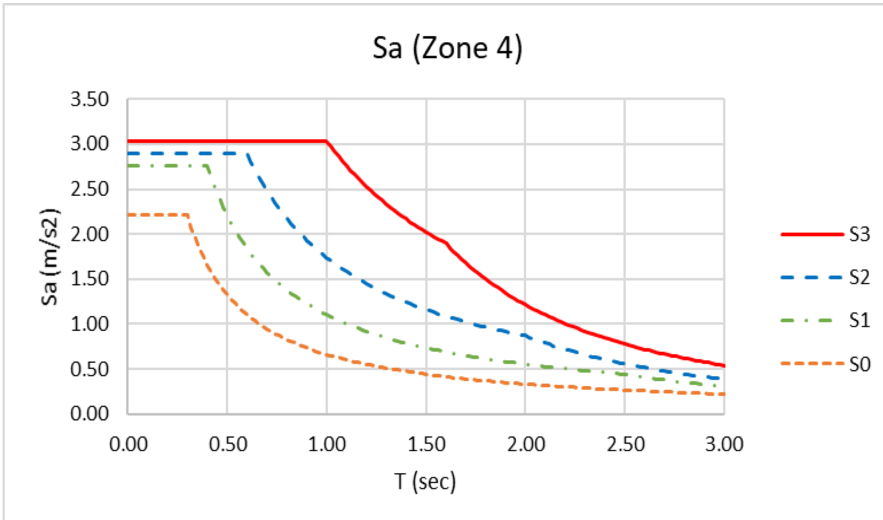

Figure 4. Acceleration spectrum for four different soils.

Next, the general criteria for comparing displacement spectra and their influence on the design force (Fa) are presented. In (Figure 5) four displacement spectra at different seismic intensities are shown, being Q4 > Q3 > Q2 > Q1. It is important to keep in mind that there are many factors that define seismic intensity. One of these factors is the soil, for example if we refer to a soft soil, it will have greater responses to the structure (seismic intensity). Another important factor is the percentage of equivalent damping ($\mathcal{E}_a$), which is defined by the amount of energy that a system can dissipate, in this case the non-structural element, against an earthquake, therefore, it is inversely proportional to the seismic intensity. Besides, (Figure 5) shows the decay of the curve when the intensity is reduced.

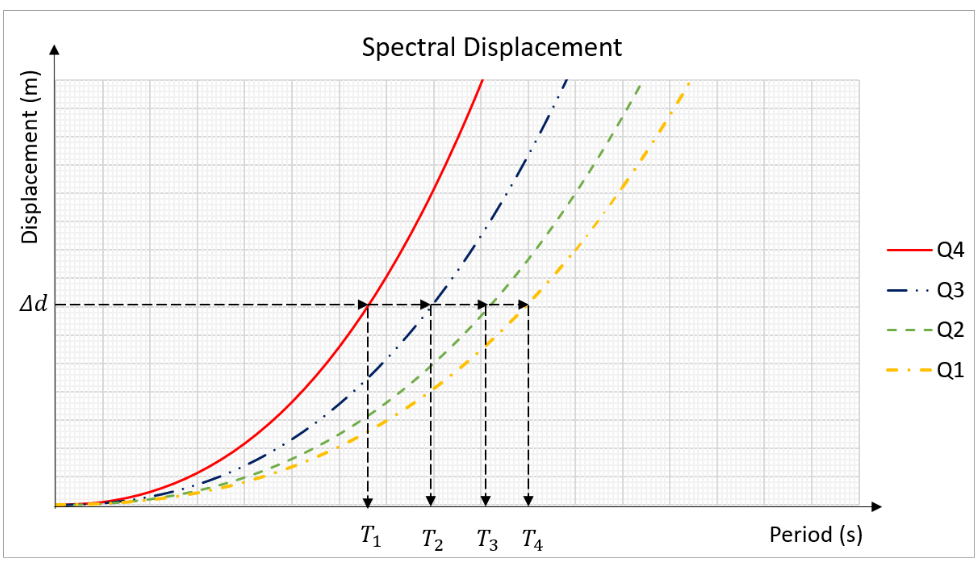

Figure 5. General interpretation of the Displacement Spectrum.
Own source

It can also be verified that for a certain non-structural element that is defined by a target displacement (Δ_d) we will obtain that the Effective Period of the non-structural element (T_i) is inversely proportional to the seismic intensity

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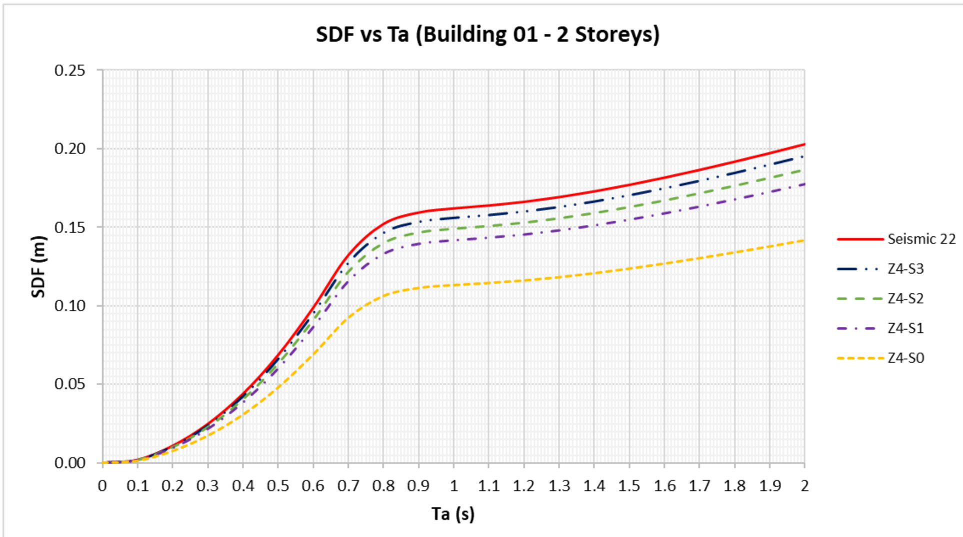
(Q_i). At the same time the Effective Period of the non-structural element (T_i) is also inversely proportional to the design strength (Fa).

The (Equation 1), which graphs the displacement spectra, is divided by 3 conditions which in turn are basic equations (quadratic, a cube and a root) whose independent variable is the Period of the non-structural element (T_a). These three conditions (equations) come together to give lower values of T_a with increasing Target Displacement (Δ_d), therefore, they reduce the slope at each point of the curve and make the graph decrease. This criterion guarantees that the curve is constantly decreasing to adopt an inelastic behavior.

From (Table 5) it is possible to extract 5 buildings at 5 different seismic intensities, being a total of 25 displacement spectra to be compared. The comparison criterion was to group them by buildings and by seismic intensities as shown in (Figure 6) and (Figure 7) respectively.



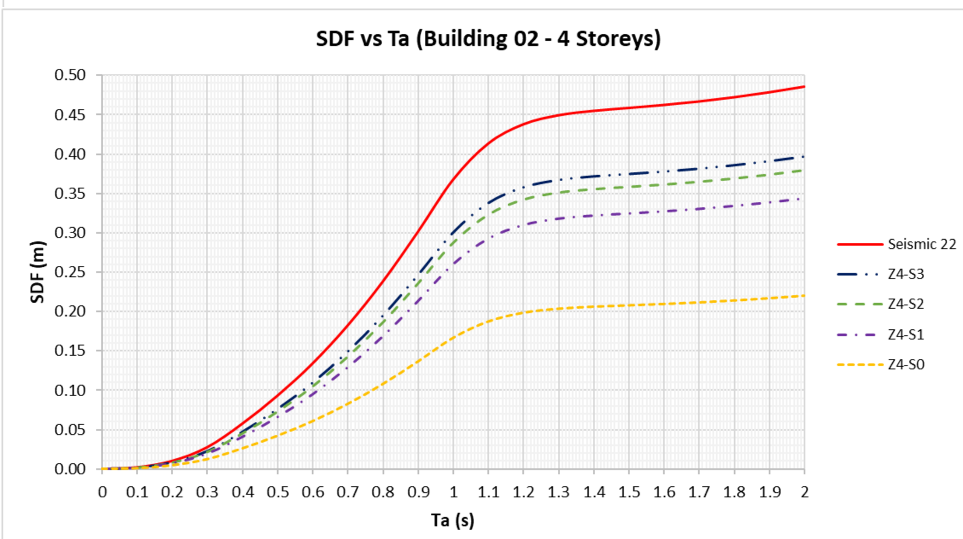


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Figure 6. Displacement spectrum for five buildings with variation in height.

From (Figure 7) it can be seen that the lower the height of the building, the greater the strength of the design and the reinforcements of the structural elements as analyzed in (Figure 5). These responses were similar for the other seismic intensities determined by the soil and the seismic zone according to (Table 5).

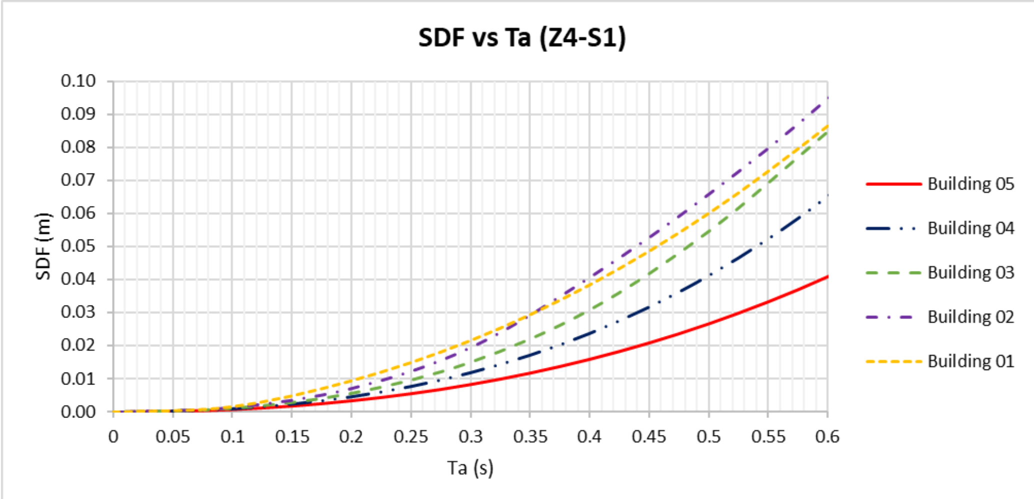

Figure 7. Displacement spectrum for five buildings (with variation in height) in a soil S1 (rigid soil) and a Zone 4 (high seismicity).

For the comparison of forces, "Earthquake 22" was selected, which is the seismic record with the greatest response. A target displacement of 15 mm approximated the results of the article by (Wood et al., 2014) for a system of steel anchors belonging to a functional performance level. The (Equation 2) and (Equations 3) are divided by the equivalent mass of the non-structural element (m_e) for greater simplicity of the calculation presented in (Table 6). From this table it can be seen that the design force based on forces (DBF) depends directly proportionally on the safety coefficient (C1) and on the horizontal acceleration (a_i), depending on the criterion, its dependence on the horizontal acceleration could be ignored since they are considered as constant for each structure. On the other hand, the design force by the DBDD has a directly proportional dependence on the Target Displacement (Δ_d) and inversely proportional to the equivalent period of the non-structural element (T_e).

Table 6. Design Strength: DBF vs DBDD

COMPARATIVE ANALYSIS - EARTHQUAKE 22						
BUILDING	**DBF**			**DBDD**		
	a_i (m/s2)	C1	**F(N)**	Δ_d (m)	T_e (s)	**Fa(N)**
1 (2 floors)	4.19	1.50	**6.29**	0.015	0.24	**9.25**
2 (4 floors)	5.69		**8.53**		0.23	**10.07**
3 (8 floors)	9.22		**13.83**		0.21	**12.68**
4 (12 floors)	10.77		**16.16**		0.20	**13.32**
5 (20 floors)	7.74		**11.62**		0.25	**8.53**

In (Figure 8) the forces of (Table 6) are presented and it can be seen that there is an inflection point where one force is greater than the other, this inflection point is storey 6. Therefore, for buildings less than 6 storeys the outside of DBDD is greater and for buildings greater than 6 storeys the strength of DBF is greater. It is worth mentioning that the force is related to the reinforcement that the non-structural element will have.

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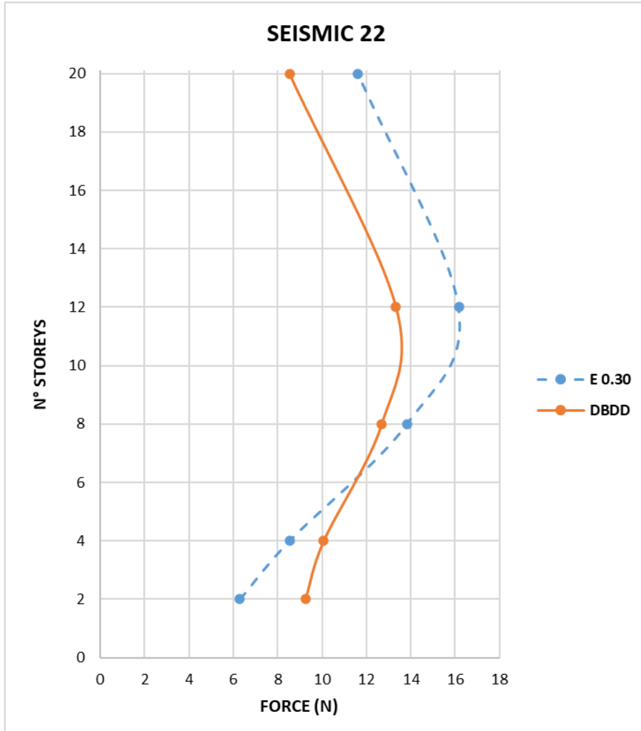

Figure 8. Design force according to DFB vs DBDD.

On the other hand, for a second case the forces of the DBDD could totally exceed those of the DBF (Figure 9(a)). However, there would also be a third case (Figure 9(b)) in which the DBF forces could totally exceed those of the DBDD due to the increase in the safety coefficient (C1):

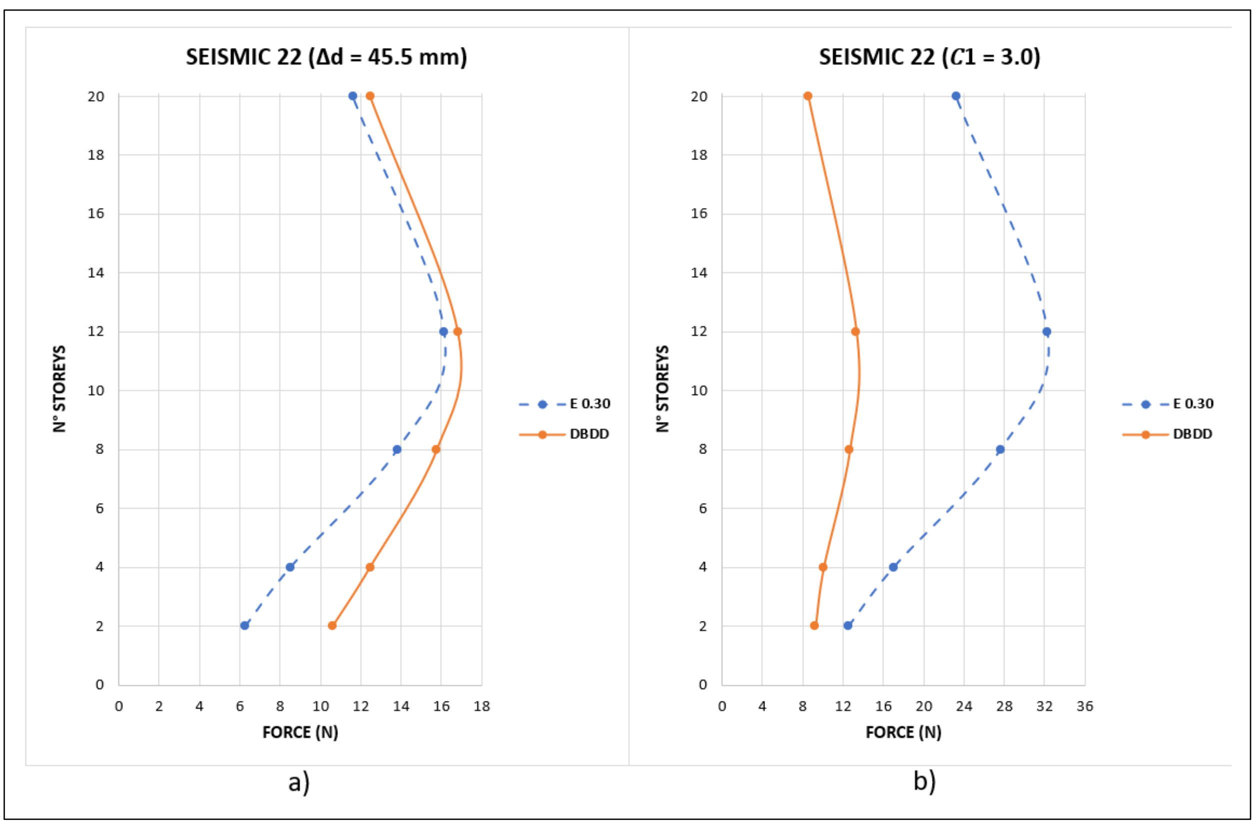

Figure 9. Design force according to DBF vs DBDD, (a) considering a Δd = 45.5 mm and (b) a C1 = 3.0

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Although the forces of the traditional design are greater for certain cases (Figure 9(b)), it has been proven that the DBDD is more effective and accurate, since it considers parameters in the inelastic range that the traditional design does not consider described above.

Lastly, the equivalent force (Fa) will be less than equal to the nominal force (F_n) divided by a resistance factor $\gamma_m = 1.25$

$$Fa \leq \frac{F_n}{\gamma_m} \tag{4}$$

Since the chosen non-structural element is a piping system, its weight (P_e) will be equal to $1.15 N_t w_a S$ *where N_t is the number of pipes (3 pipes according to (Figure 7)), w_a is the weight of the pipe per linear meter and S is the maximum separation required (CEN, 2018).*

3.1 Force Based Design

*Replacing (Equation 3) in (Equation 4), and solving for the maximum required separation (**S**) and we obtain:*

$$S \leq \frac{g}{\gamma_m a_i C_1} \frac{F_n}{1.15 N_t w_a} \tag{5}$$

In (Table 7) the summary of the design is presented where L_t is the total length of the main pipe equal to 27 m.

Table 7. Design according to DBF

Parameter	***Building 1***	***Building 2***	***Building 3***	***Building 4***	***Building 5***
Number of Storeys	*2*	*4*	*8*	*12*	*20*
g(m/s2)	*9.81*				
F_n*(KN)*	*11.90*				
a_i	*4.19*	*5.69*	*9.22*	*10.77*	*7.74*
C_1	*1.50*				
γ_m	*1.25*				
N_t	*3*				
w_a *(KN/m)*	*0.31*				
S(m)	*13.88*	*10.24*	*6.31*	*5.40*	*7.52*
L_t*(m)*	*27*				
N° Anchors	***1***	***2***	***4***	***4***	***3***

3.2 Design based on direct displacement

Replacing (Equation 2) in (Equation 4), and solving for the maximum required separation (S) and we obtain:

$$S \leq \frac{g {T_a}^2}{\gamma_m 4\pi^2 \Delta_d} \frac{F_n}{1.15 N_t w_a} \tag{6}$$

In (Table 8) the summary of the design is presented where L_t is the total length of the main pipe equal to 27 m.

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Table 8. Design according to DBDD

Parameter	Building 1	building 2	building 3	Building 4	Building 5
Number of Storeys	2	4	8	12	20
$g(m/s2)$	9.81				
$T_a(s)$	0.24	0.23	0.21	0.20	0.25
$F_n(KN)$	11.90				
Δ_d (m)	0.015				
γ_m	1.25				
N_t	3				
w_a (KN/m)	0.31				
$S(m)$	8.49	7.80	6.20	5.90	9.22
$L_t(m)$	27				
N° Anchors	**3**	**3**	**4**	**4**	**2**

Similarity was found in the number of anchorages with the results of the scientific paper by (Filiatrault et al., 2018), where 2 and 3 anchorages are presented for natural periods of 0.46sec and 0.53sec respectively of a 5-story reinforced concrete building designed with DBDD.

3.3 Design Comparison

(Figure 10) shows the comparison between the two designs where it is observed that for buildings with less than 8 floors the reinforcement is greater (number anchors) according to the DBDD and for buildings greater than 12 floors the reinforcement is greater (number anchors). In addition, we see that between the buildings with 8 to 10 floors, the reinforcement is equal and they are close to 4. This graph is proportional to (Figure 8), thus verifying that the reinforcement and the design force (F y Fa) are directly proportional.

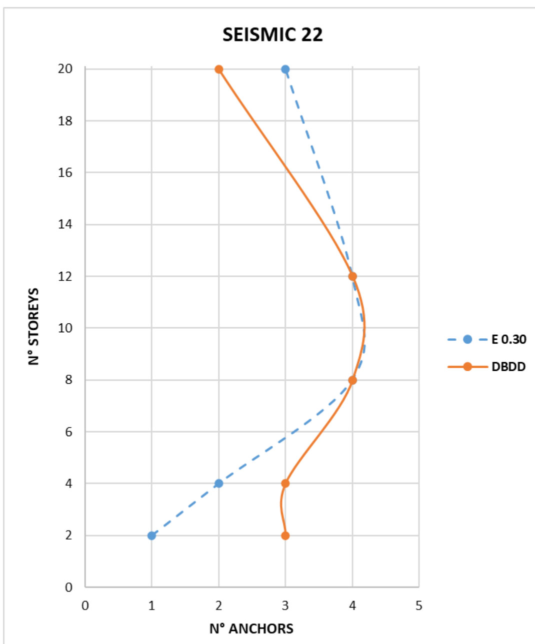

Figure 10. Design according to DBF vs DBDD.

The design has been standardized for all levels in each building since the most critical floor is being considered. As an example, in (Figure 11) the plan design for building 02 (4 storeys) is shown, which consists of 3 main piping lines of 3 tubes each referring to (Figure 3), the number of anchors and the separation required are those obtained in (Table 7) and (Table 8).

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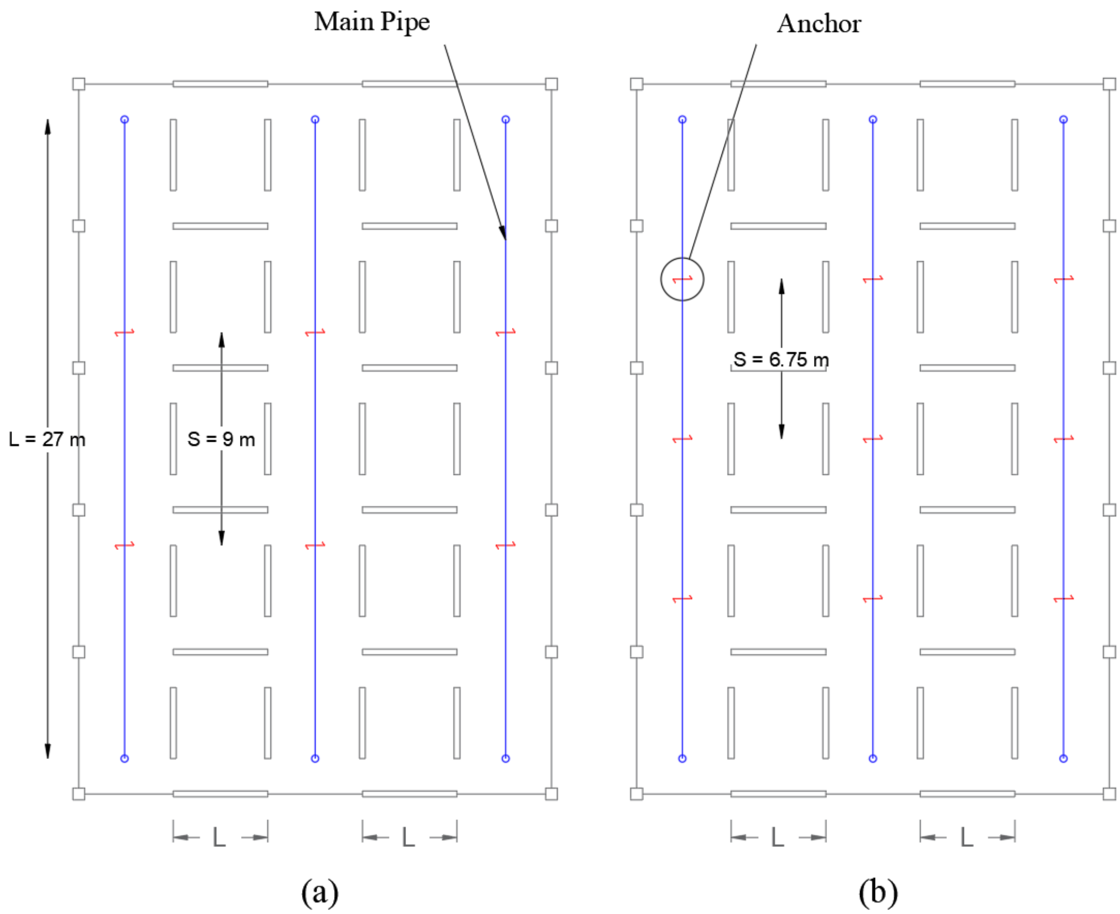

Figure 11. Plan view of the design of anchors in pipes according to (a) DBF and (b) DBDD for building 02 (4 storeys)

4. Conclusions:

The design based on direct displacement for non-structural elements is more effective than the DBF since it considers elastic and inelastic parameters of the element such as: the natural period of the structural system (T_n), the maximum modal acceleration of the floor (a_{max}), the ductility of the system structural (μ), the equivalent damping of the nonstructural element (ε_a), and the target displacement (Δ_d). Buildings 01 and 02 are reinforced with 3 anchors, buildings 03 and 04 are reinforced with 4 anchors, and building 05 is reinforced with 2 anchors on each main line (Table 8).

According to the DBDD for the same area, buildings 01 and 02 (lower height) are more reinforced than buildings 04 and 05 (higher height) as shown in (Figure 7). In addition, the DBDD reinforcement in non-structural elements is higher for buildings with less than 8 stories and less for buildings with more than 12 stories compared to the DBF as shown in (Figure 10). The effective criteria that the DBDD takes have been proven, however, in order not to breach the national regulations, it is recommended to work with the greatest strength of the two methods following the envelope criterion.

The safety factor (C1) and the horizontal acceleration (a_i) proportionally increase the design force in non-structural elements according to the DBF. From the DBDD it is concluded that the design force (Fa) or the reinforcement is directly proportional to the target displacement (Δ_d) and to the seismic intensity and inversely proportional to the Period of the non-structural element (T_a) and the equivalent damping of the non-structural element (ξ_a).

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