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EFFECT OF SHEAR WALLS ON THE BEHAVIOR OF NON-LINEAR STRUCTURES IN SEISMIC ZONES

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Abstract: In some regions of the world subjected to frequent severe earthquakes, such as Algeria, attention is focused on seismic design in order to assure the public welfare. When, for many countries most of the building consists of constructions of "self-steady frames" type system. The last seismic events have shown the inefficiency of such a type of to avoid evident disaster. On the other hand, the use of shear walls as "Lateral Load Resisting System" (LLRS) seems to be a good alternative. This study tries to confirm the requirement of shear walls in seismic zones by highlighting their beneficial effect on structures subjected to strong motions. For this purpose, a comparison is made between the two types using both linear and nonlinear analysis with a focus on two parameters which are of great im-portance, the base shear and the lateral drift in particular. Applications are made on two types of Reinforced Concrete (RC) multistory structures: with shear walls (dual systems) and without (w/o) shear walls (self-steady structures). The results permit to emphasize the need of shear walls as LLRS in seismic zones and confirm the restrictions imposed by the Algerian code, amongst others, concern-ing the use of self-steady frames system for structures in such area.

Keywords: *Seismic zone, Shear wall, nonlinear structures*

1. INTRODUCTION

Earthquakes are a major problem for mankind, killing thousands each year. The great loss of life is almost invariably due to inadequate resistance of building struc-

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tural elements. As earthquakes are unpredictable phenomena, the solution lies in the earthquake-resistant design, which consists of providing structures with efficient bracing.

The North of Algeria is very sensitive to seismic events as it groups a most dense inhabitant area population and vital structures of the state in one hand and is often subjected to strong earth motions in the other hand.

These two particularities led to dramatic consequences as it has been the case on May 2003, when a terrible earthquake struck the region of Boumerdes (East of the capital Algiers), killing more than 2000 persons and causing a big economic loss.

During their investigation, experts have noted that the considerable damage was due, for a large part, to the type of lateral loading resisting system (LLRS) which was predominant in the Algerian housing stock, namely the self-steady frame building systems. Consequently, the Algerian seismic code, "RPA 2003" began to limit or, sometimes, banned the use of such constructions in seismic zones. The good alternative was, of course, the use of shear wall systems in built constructions.

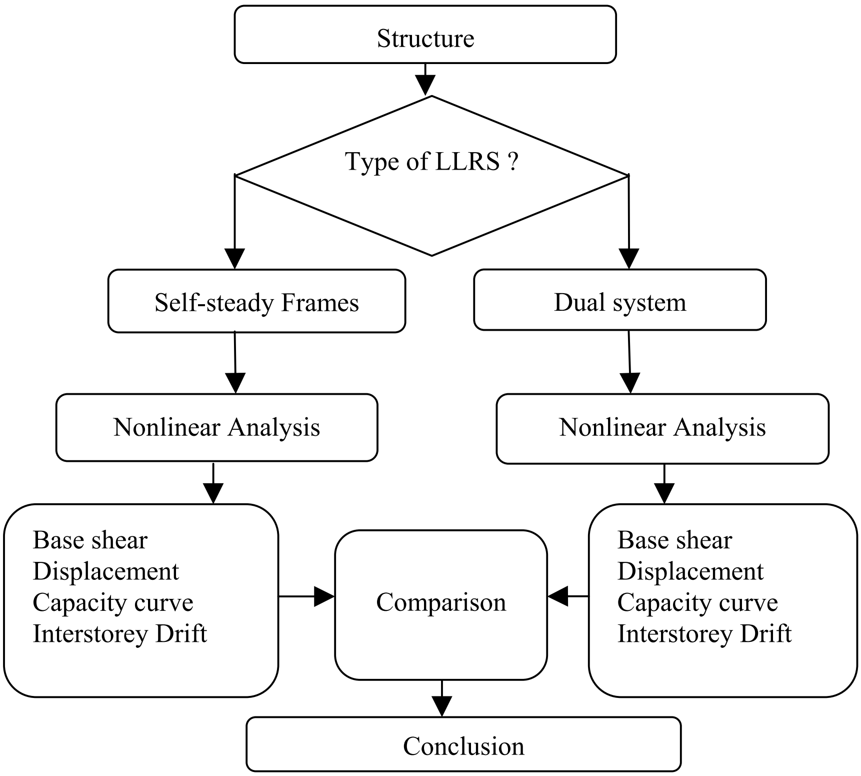


Fig 1. Development of the analysis flowchart

The aim of this study is to show the favorable effect of shear walls on constructions and at the same time confirm the restrictions imposed by the Algerian code of practice for seismic areas (RPA), amongst others, concerning the use of self-steady structures. For this purpose, a comparison is made between two types of multistory structures: with shear walls and without shear walls using both linear and nonlinear analysis with a focus on two parameters which are of great importance: the base shear and the lateral drift.

The results show the great need for shear walls and lead us to propose a ban on the use of self-steady structures in seismic zones. The methodology of the research is illustrated by the following flowchart given in figure 1.

NOTATIONS

RC: Reinforced Concrete.
LLRS: Lateral Load Resisting System".
SSF : Self Steady Systems.
DSS: Dual Structural System .
RPA: Parasismic Algerian code of practice.
SAP : Structural Analysis Program.
A: Acceleration coefficient of zone.
T: The fundamental period.
(T1, T2): The characteristic periods.
Q: Quality factor
R: The behavior factor.
ξ : The damping ratio.
V: The base shear.
FB : Force-Based method
AB: Acceleration-Based method.
PB: Performance-Based method.
ATC: Applied Technology Council.
MDF: Multi-Degree-of-Freedom.
SDF: Single-Degree-of-Freedom.

2. LATERAL LOAD RESISTING SYSTEM (LLRS)

2.1. TYPES OF LLRS

It is known that buildings are designed to deal with lateral loads caused by earthquake force or wind pressure as well as vertical gravity loads (dead load, live load and snow load). In seismic zones such as Algeria, the first type of loads is more dangerous and the structural system must be strengthened by providing an appropriate lateral load resisting system.

For this purpose, the specific seismic codes have defined many types of LLRS that depend on the type of construction and the nature of constitutive materials. The impact of the selection of a LLRS type on the design is the assignment of a numerical value to the behavior factor, noted R (q in the EC 8), which is used to account for the inelastic behavior of the structure by reducing the earthquake load, hence the name of reduction factor too. The behavior factor R emerges among the parameters defining the RPA design spectrum Sa/g used in the estimation of both base shear and displacement of the structure (Equation 1).

$$\frac{S_a}{g} = \begin{cases} 1.25.A\left[1+\frac{T}{T_1}\left(2.5\eta\frac{Q}{R}-1\right)\right] & \text{if} \quad 0 \le T \le T_1 \quad \text{(1a)} \\ 3.125\,\eta\,A\,\frac{Q}{R} & \text{if} \quad T_1 \le T \le T_2 \quad \text{(1b)} \\ 3.125\,\eta\,A\left(\frac{Q}{R}\right)\left(\frac{T_2}{T}\right)^{\frac{2}{3}} & \text{if} \quad T_2 \le T \le 3.0s \quad \text{(1c)} \\ 3.125\,\eta\,A\left(\frac{Q}{R}\right)\left(\frac{T_2}{3}\right)^{\frac{2}{3}}\left(\frac{3}{T}\right)^{\frac{5}{3}} & \text{if} \quad T \ge 3.0s \quad \text{(1d)} \end{cases} \tag{1}$$

In these formulas, A, T, T1, T2, Q, R and η represent, respectively, the acceleration coefficient of zone, the fundamental period, the characteristic periods, the quality factor, the behavior factor and the damping correction factor given in terms of the damping ratio ξ, by Eq. 2:

$$\eta = \sqrt{7/(2+\xi)} \ge 0.7 \tag{2}$$

The base shear V is given by Equation 3:

$$V = M.g.Sa/g \tag{3}$$

The main types of LLRS adopted by the RPA code are: the Self-steady frame (SSF) with or without (w/o) masonry rigid infill and the Dual structural system (DSS), or wall-frame structure (DTR B C 2 48. 2003).

Table 1 shows values assigned to the behavior factor according to the type of LLRS (DTR B C 2 48, 2003).

Table 1. Values of the global behavior factor, R

Type of LLRS	Global behavior factor, R
Self-steady frame without masonry rigid infill	5
Dual structural system (wall- frame structure)	5
Frame with walls as LLRS	4
Self-steady frame with masonry rigid infill	3.5

2.2. SHEAR WALLS

In past earthquakes, buildings with a sufficient number of walls and enough well-distributed reinforcement were saved from collapse. This means that RC structural walls, known as shear-walls, provide an efficient bracing system and offer great potential for lateral load resistance. These walls generally start at foundation level and are continuous throughout the building height. They are usually provided along both length and width of constructed building. Their thickness varies from 150 mm as a minimum value to 400 mm for high rise buildings. Shear wall with frame which is known as dual structural system or wall-frame structure, is most effective and adequate in resisting lateral forces like earthquake load.

The non-linear behavior of shear wall is generally based on plastic hinge concept and a bilinear rotation relationships.

Shear walls can then be designed to limit building damage to the specified degree. The load-deformation response of the structural walls must be accurately predicted and related to structural damage in order to achieve these performance goals under loading actions of various magnitudes. In addition to that, shear walls are efficient both in terms of construction cost and easy implementation on site. Finally, this type of construction is a popular choice in many seismic countries like USA, Chile and New Zealand.

3. NONLINEAR STATIC METHOD

3.1. INTRODUCTION

During strong motions, the forces and displacements induced by seismic excitations can exceed the elasticity limit of structural elements causing, thus, nonlinearities in structural elements which may lead to collapse. In the classical method, known as force-based (FB) or acceleration-based (AB) method, these nonlinearities are taken into account by a reduction of the forces derived from an elastic analysis while the displacements are approximately checked at the end (Fajfar and Eeri, 1999; 2000).

After the terrible Northridge 1994 earthquake and similar further earthquakes (Kobe 1995; Kocaeli 1999; Boumerdes, 2003), the classical approach implemented in design codes proved to be unsuccessful in the prevention of earthquake consequences. The use of more perfect approaches that clearly takes into account the nonlinearities of structures became necessary.

In this perspective, we have to choose among two analysis tools that differ in complexity, accuracy and time consuming: nonlinear time-history procedure and non-linear static (pushover) one. The first procedure is relatively more accurate especially with finite element modeling and the use of high-performance software such as the SAP for reinforced concrete, the MIDAS/GTS for soils which can do elastic analysis, nonlinear static analysis, dynamic analysis, etc. (Zhang et al, 2017). But this procedure is complex because "Seismic inputs assumed for the assessment of constructions subjected to seismic hazard are one of the most unpredictable quantities in-volved in the analyses. In particular, when nonlinear dynamic analyses are considered, two main issues need to be considered: the choice of the ground motions to use for analysis and the soil representation" (Forcellini et al, 2018).

Because of its complexity, this procedure is used only for special cases. For current use, in order to meet the requirements for the several limit states provided by the different codes, a number of simpler design procedures were recently developed and jointly termed “Performance Based Seismic Design” (Boulaouad and Amour, 2010).

Such procedures are more and more used for two reasons:

- They seem to be more realistic and consequently more accurate than the conventional method as they take directly into account the displacement and permit the evaluation of the behavior expected on each structural element.
- They are simpler than the nonlinear time-history one which is theoretically more accurate but practically more complex.

3.2. DEFINITION OF A NONLINEAR STATIC METHOD

A nonlinear static method, which is one of the so called “Performance-Based” (PB) methods, consists to compare the capacity of a structure with a target displace-ment derived from a pushover analysis. This target displacement corresponds actually to the maximal displacement predicted in the structure during an earthquake.

The applications of such an approach are: the capacity spectrum method of ATC (Applied Technology Council), the nonlinear static procedure of FEMA (American Society of Civil Engineers) and the N2 method (Fajfar, 1999) implemented in the Eurocode 8 (Euro Code 8, 2003). In these methods, the pushover analysis of a multi-degree-of-freedom (MDF) model is combined with the response spectrum analysis of an equivalent single-degree-of-freedom (SDF) system.

The most important steps of a simplified method are given in the following:

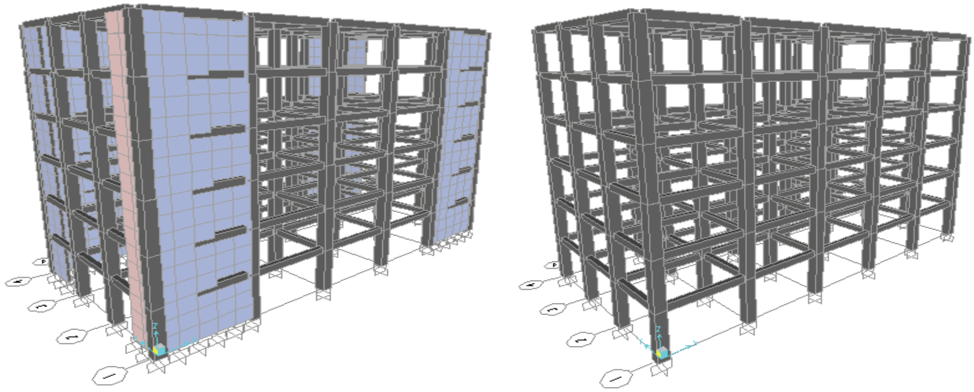
3.3. MAIN STEPS OF A NONLINEAR STATIC METHOD

– A planar MDF model is used vibrating predominantly in the first mode.
– Seismic demand is defined by an elastic acceleration spectrum.
– A nonlinear force-displacement relationship of the MDF system is determined using a pushover analysis. For this purpose, force and displacement are usually rep-resented by base shear and top displacement, respectively for different types of lateral load distribution.
– Structure is modeled as an equivalent SDF system.
– A simplified bilinear acceleration-displacement relationship is determined by the idealization of the pushover curve on the basis of some criteria.
– Target displacement of the SDF model is determined by two approaches. The first one (ATC) uses equivalent elastic systems whereas the second one (FEMA, N2) is based on inelastic spectra derived from a nonlinear time history analysis, or a typi-cal elastic design spectrum reduced by appropriate behavior factors.
– The target displacement for the MDF system is obtained from the SDF dis-placement demand by using the inverse MDF to SDF equivalence procedure.
– Finally, comparison between the seismic demands and the capacities gives the ex-pected performance.

4. MAIN APPLICATION FEATURES

Applications are made on a regular RC structure with two types of lateral loading re-sisting systems (LLRS); self-steady frame (SSF) and dual structural system (DSS). The number of stories was taken varying from 3 to 6.

Static and dynamic nonlinear analyses were performed with the well known SAP (Structural Analysis Program) developed by Computers and Structures, Inc.



(a) (b)

Fig 2. Perspective view of a 6-storey structure:
(a) with shear wall
(b) w/o shear wall

5. RESULTS AND ANALYSIS

5.1. MAIN RESULTS

The most important results are those relative to performance analysis, that is to say displacement and capacity curve. In addition, the inter-storey drift is so important for structure safety that it is strictly limited by seismic codes. In the Algerian code RPA, the inter-storey drift for a level must not exceed one per cent of its height. This means that for a displacement (d) and a height (h): $d \leq 0.01$ h or $(d / h) \leq 0.01$.

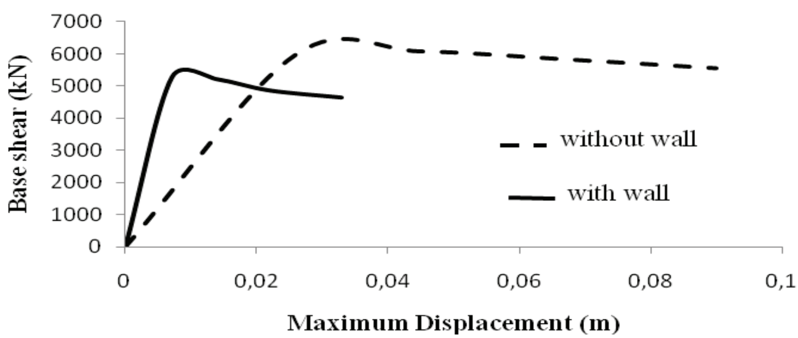


Fig 3. Capacity curves for the two cases: with and without shear walls

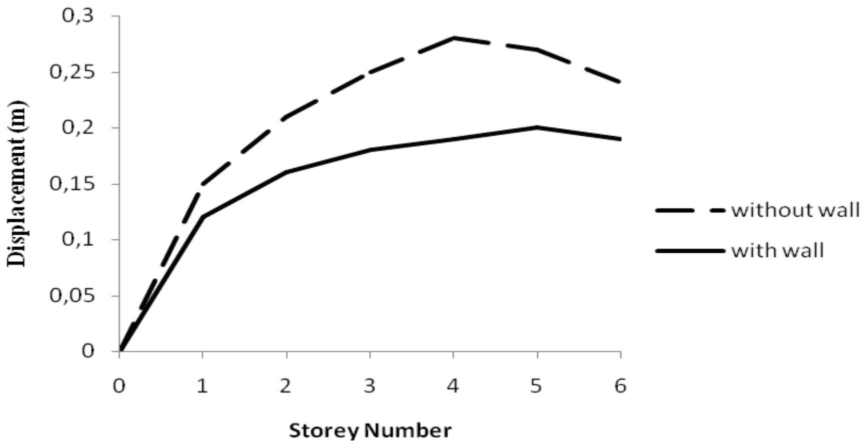


Fig 4. Displacements for the two cases: with and without shear walls

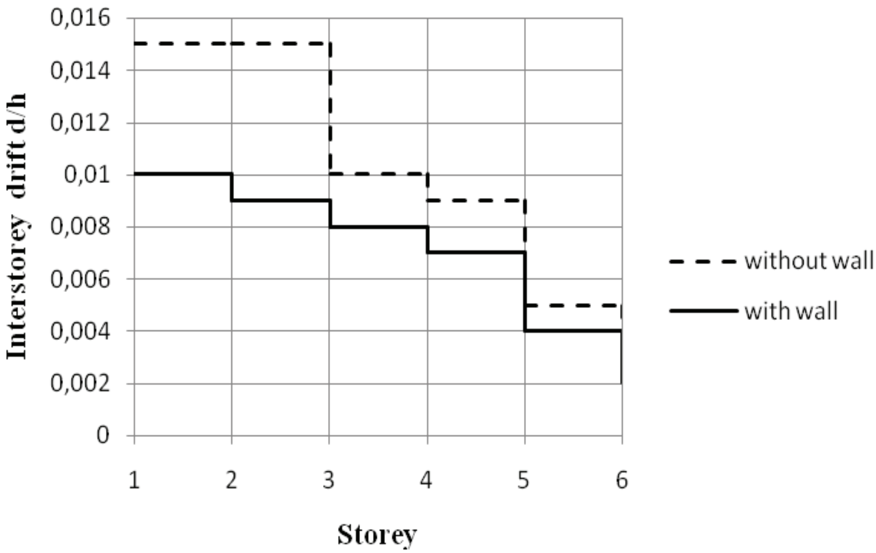


Fig 5. Inter storey drifts for the two cases: with and without shear walls

5.2. ANALYSIS OF THE RESULTS

Figure 3 shows that the capacity of strengthening is more important in the case of structure with shear wall. The curves present inclinations and drops characterizing the stiffness degradation due to the progressive plasticization of the elements.

Figure 4 indicates that the presence of walls in a structure reduces significantly the lateral displacement. This reduction increases with storey number. So, the type of structure without shear walls for tall buildings could be hazardous. This fact partly explains the restrictions measures imposed by seismic codes on the use of this type of LLRS.

The great advantage provided by the walls also appears when it comes to inter-storey drift that is strictly limited by codes as mentioned previously. Figure 5 shows clearly that only structures with walls meet the requirements of codes concerning the imposed limits. Indeed, one can note easily that all the values of the ratio d/h are less than 1 in the case of dual systems whereas some values of this ratio exceed this limit in the case of self-steady frames. A shake table test by Weixiao et al (2017) led to the same result. On the other hand, we notice that the greatest excess is recorded at the level of the lower floors. This further aggravates the problem given the im-portance of these floors, especially the first one that governs the upper floor levels. Care must be taken with lower floors to avoid the phenomenon of commonly called as flexible floor prohibited by seismic codes of practice applied so far.

6. CONCLUSION AND FURTHER WORK

In order to highlight the good effect of shear walls on structures subjected to strong motion and confirm the requirement of shear walls in seismic zones as prescribed in the Algerian seismic code, comparison was made between structures braced with two different types of LLRS: shear walls and self-steady frames. For this purpose, seismic performance was evaluated using nonlinear static method. Attention has been focused on three parameters which may be considered as the main parameters of analysis in seismic design: the base shear, the lateral drift and the inter-storey drift.

Based on the analysis and discussion above, one can give the following conclusions:

Shear walls are very much suitable for resisting earthquake induced lateral forces in multistoried systems when compared to similar systems without shear walls.

When shear walls are strong enough, they will transfer these horizontal forces to the element below such as slab, wall or footings. They also provide lateral stiffness to prevent the roof or floor above from excessive side-sway.

Walls are less ductile than portal frames, but their ductility can be improved by adopting proper detailing techniques.

All the results obtained for different cases of study, support the restrictions imposed to the use of self-steady structures in seismic zones.

The authors even suggest interdicting the use of such structures in the region of Algiers which is very particular as it groups most people and vital structures of the state in one hand and is often subjected to severe earthquakes in the other hand. The last strong earthquake of Boumerdes, 20 km far from Algiers, is very instructive in this sense.

Finally, the authors draw attention to the importance of the arrangement of the sails in the structure. They therefore recommend the detailed study of this question, particularly for asymmetric structures where the effect of torsion can be dangerous.

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