# EFFECT OF THE OPENINGS IN THE STRENGTH AND STIFFNESS OF REINFORCED CONCRETE STRUCTURAL WALLS

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## ABSTRACT

The purpose of this investigation is to study the openings effect (windows, doors, etc) in the lateral strength and stiffness of RC structural walls. One solid wall and fifteen walls with different opening shapes and opening positions were modeled in Displacement Method Analyzer software (DIANA). The AIJ Guideline lateral strength equation, the ACI lateral strength equation and the strength reduction factors due to openings proposed by AIJ Standard Calculation were used to predict the lateral strengths of the fifteen walls with openings and the solid wall. Regarding the stiffness of walls with openings, it is calculated by means of two methods; one is a hand method procedure and the other one is using the stiffness reduction factor proposed in AIJ Standard Calculation. It was found that for those walls with same opening area but different opening positions, the seismic codes equations predict the same lateral strength capacity for them; on the other hand, the DIANA simulations show that such walls have different lateral strengths depending on the opening position even if the walls have the same opening area.

Keywords: Structural Walls, Openings, Lateral Strength, Lateral Stiffness

## INTRODUCTION

A frequent problem in the seismic design of RC structural walls is how to consider the effect of openings (such as doors, windows or holes for ducts of conditioner air, or electrical installation) in the strength and lateral stiffness of the walls since it suggests that those structural characteristics will undergo a reduction or high stress concentrations could occur around the openings. Furthermore, the consideration of the openings effect in the walls seismic design is a big issue independently of the type of material that is used to build the walls. In addition, the fact that El Salvador is a tropical country with high temperatures and humidity, lead to houses or dwellings with large opening sizes for ventilation, which clearly affects the structural behavior of the dwellings or buildings. This situation in El Salvador shows the importance of taking into account the effect of the openings in the structural capacity not only in RC structural walls but also in masonry structures.

## REINFORCED CONCRETE (RC) STRUCTURAL WALLS WITH OPENINGS. THEORETICAL BACKGROUND

The Architectural Institute of Japan (AIJ) has two Guidelines for Reinforced Concrete Structures, one of them based on the Ultimate Strength Concept (AIJ Design Guidelines for Earthquake Resistant Reinforced Concrete Buildings, 1990) and the other one based on the Allowable Stress Design (AIJ Standard Calculation). On the Guidelines based on the Ultimate Strength concept a lateral strength

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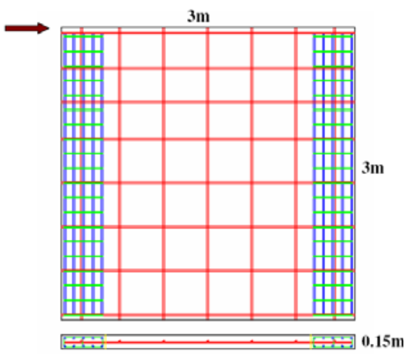
equation taking into account the truss and arch mechanism is proposed to estimate the lateral strength of RC walls without openings. A method to calculate the reduction in the strength and stiffness due to openings is no specified in this guideline. On the other hand, the AIJ Standard Calculation proposes reduction factors to take into account the effect of openings in both lateral strength and lateral stiffness, so it is common that the Japanese Designers or Researchers combine the two guidelines, and to apply the strength reduction factors presented in the AIJ Standard Calculation to the lateral strength equation proposed for walls without openings in the AIJ Guidelines based on the Ultimate Strength Concept. The value of the strength reduction factor "$r$" shall be the lower value among three reductions factors called "$r_1$", "$r_2$" and "$r_3$". These reduction factors consider the opening dimensions but not the opening positions. In the case of the elastic stiffness a reduction factor "$r$" is presented in the AIJ Standard Calculation. On the other hand in the American Concrete Institute Code (ACI-318 Code) a lateral strength equation taking into account the concrete and steel reinforcement contribution is proposed for RC structural walls without openings. But when an opening is placed on RC walls, the ACI code does not propose any reduction factors for both the strength and the stiffness of RC walls with openings. Also regarding the stiffness for RC walls with openings Neuenhofer (2006) presents a hand method procedure to calculate the lateral stiffness of cantilever walls with an opening.

## MODELING RC STRUCTURAL WALLS WITH OPENINGS IN DIANA

One solid RC wall and fifteen RC walls with openings are modeled in DIANA. Beforehand, a solid wall was designed according to the requirements and equations established for walls seismic design in ACI Code. In ACI Code, the chapter 11, chapter 14 and chapter 21 contain the sections related to structural wall design. Both the wall length and wall height are 3000mm (3m), therefore the wall slender (*hw/lw*) ratio is 1. The wall thickness is 150mm (0.15m). The figure 1 shows the details reinforcement for solid wall and edge members. The properties materials are a concrete compressive strength of 20.6MPa and a steel yield stress of 275 MPa; both properties are used to model in DIANA.




**Wall Reinforcement:**

Transversal: 8 bars (φ=15.24mm) spaced at 450mm

Longitudinal: 7 bars (φ=15.24mm) spaced at 450mm

**Edge member reinforcement:**

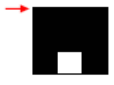
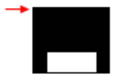
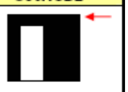
Transversal: Hoops (φ=15.24mm) spaced at 100mm

Longitudinal: 10 bars (φ=15.24mm)

Figure 1 Details of Wall Reinforcement

The lateral strength of solid wall was predicted using the seismic codes. According to ACI lateral strength equations, the solid walls strength is 564 kN and using a strength reduction value of 0.6 the lateral strength is 339 kN. It is important to say that such strength reduction factor is not for openings, the philosophy of the factor is due to the fact of safety reasons in the design. According to AIJ Guideline equation the lateral strength value is 579 kN. Regarding to the model in DIANA of the fifteen specimens with openings, the materials and geometric properties used in the modeled are the same as those used for the solid wall. The table 1 shows the information of each specimen. The solid wall was taken as base of the analysis in comparison with the walls with openings. The openings reinforcement consists in to replace around the openings the same volume of reinforcement located within the openings area. Thus, the specimens with opening area ratio of 11.11%, 22.22%, 30% and 44% were reinforced with a steel volume around them of $1.2x10^{-3}$ $m^3$, $2.2x10^{-3}$ $m^3$, $3.02x10^{-3}$ $m^3$ and $4.0x10^{-3}$ $m^3$ respectively.

Table 1 RC walls with openings modeled in DIANA

| Specimen | O11B | O11M | O11U |
|---|---|---|---|
| Drawing specimen and load condition |  |  |  |
| Opening area (*lo*x*ho*) | 1x1m | 1x1m | 1x1m |
| % Ratio Area | 11.11 | 11.11 | 11.11 |
| **Specimen** | **O22B** | **O22M** | **O22U** |
| Drawing specimen and load condition |  |  |  |
| Opening area (*lo*x*ho*) | 2x1m | 2x1m | 2x1m |
| % Ratio Area | 22.22 | 22.22 | 22.22 |
| **Specimen** | **O22DB** | **O30DB** | **O44B** |
| Drawing specimen and load condition |  |  |  |
| Opening area (*lo*x*ho*) | 1x2m | 1x2.7m | 2x2m |
| % Ratio Area | 22.22 | 30.00 | 44.44 |
| **Specimen** | **O11NCW** | **O22NCD** | **O30NCD** |
| Drawing specimen and load condition |  |  |  |
| Opening area (*lo*x*ho*) | 1x1m | 1x2m | 1x2.7m |
| % Ratio Area | 11.11 | 22.22 | 30.00 |
| **Specimen** | **O11NCW2** | **O22NCD2** | **O30NCD2** |
| Drawing specimen and load condition |  |  |  |
| Opening area (*lo*x*ho*) | 1x1m | 1x2m | 1x2.7m |
| % Ratio Area | 11.11 | 22.22 | 30.00 |

To calculate the lateral strength of walls with openings the strength reduction factors proposed by AIJ Standard Calculation were applied to the solid wall strength determined by ACI Code and AIJ Guideline. To calculate the stiffness of walls two methods were used, one consists in to apply the stiffness reduction factor due to openings of AIJ Standard Calculation to the elastic solid wall stiffness; and the other one is the hand method procedure mentioned in the previous section. By using DIANA the capacity curves of all specimens were obtained. The analytical results together with the DIANA simulations are compared and discussed in the next section.

## DISCUSSION

For the walls with openings, it is notable that the lateral strength equations of AIJ Guideline and ACI Code predict the same strength for walls with same opening area ratio and those equations do not take into account the effect of the variation of opening position in the wall. The same situation happens when the stiffness is predicted by analytical methods (for instance the AIJ Guideline stiffness reduction factor) and later compared with the stiffness in DIANA. The strength and stiffness reduction factors do not take into account the effect of the variation of opening position in the walls. For instance, the specimens O11B, O11M and O11U (see chart 1 below) with same opening ratio of 11.11% but different opening position have the same strength value predicted by AIJ Guideline and ACI Code, 386 kN and 226 kN respectively. In comparison with DIANA results, the three specimens reached different strengths; the AIJ Guideline overestimated the strengths of the three specimens and ACI Code is conservative for O11B but not so conservative for O11M and O11U. For the stiffness values, the hand method procedure overestimated the stiffness of the specimens and predicted the same value for three of them. The stiffnesses obtained by using the AIJ stiffness reduction factor overestimated the stiffnesses of O11M and O11U, but predicted very well the O11B stiffness (see chart 2 below). Both strength and stiffness values decreased when the opening is closer to the upper part of the wall.

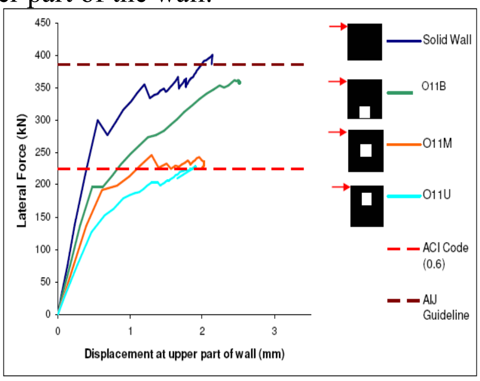



Chart 1 Capacity Curves of specimens O11B, O11M, O11U and lateral strengths values predicted by seismic codes equations

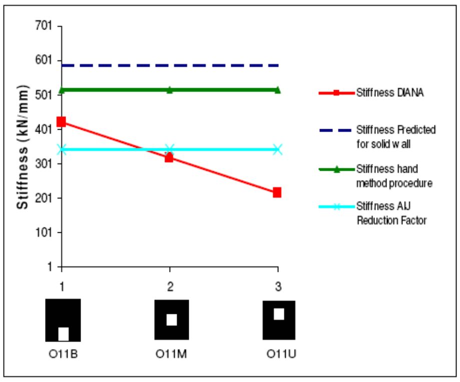



Chart 2 Stiffness behavior O11B, O11M, O11U and stiffness predicted for solid wall

The same situation is seen when the specimens O22B, O22M and O22U are analyzed and compared with DIANA results. The difference is that for these specimens the AIJ Guideline is conservative for O22B and O22M but not for O22U, on the other hand ACI Code is conservative for three of them (see chart 3 below). For the stiffness, the hand method procedure overestimated the specimens stiffness, but now, also the AIJ Guideline overestimated the stiffness values (see chart 4 below). Again, both strength and stiffness values decreased when the opening is closer to the upper part of the wall.

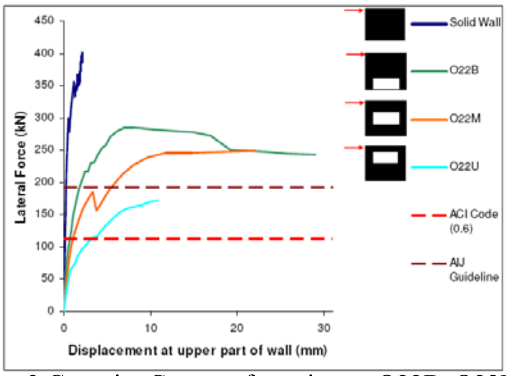



Chart 3 Capacity Curves of specimens O22B, O22M, O22U and lateral strengths values predicted by seismic codes equations

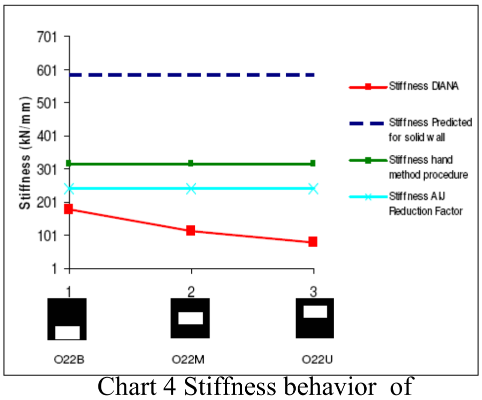



Chart 4 Stiffness behavior of O11B,O11M,O11U and stiffness predicted for solid wall

It is notable that when the opening height is increasing, both stiffness and strength decrease, it is understood when the results for O11B, O22DB and O30DB are compared. The wall behavior trends to be more flexible when the opening height is increasing (see charts 5 and 6).

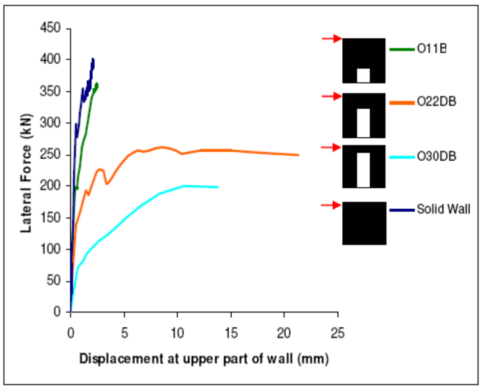



Chart 5 Capacity Curves of specimens O11B, O22DB and O30DB

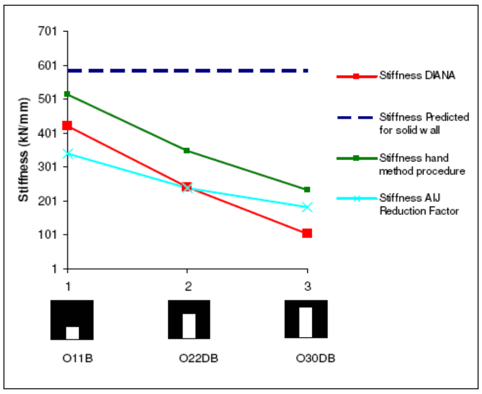
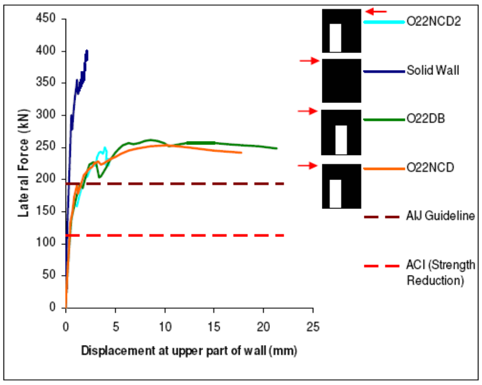



Chart 6 Stiffness behavior of O11B, O22DB and O30DB

Another important issue, it is that mainly the seismic codes consider the openings on walls centered and the analysis of not centered openings is not presented in codes. It was observed according to the stress distribution and cracking pattern obtained by DIANA that the behavior of specimens without centered openings depend on the load condition (forward loading or backward loading). The principal compressive stress distributions and cracking patterns of the specimens are presented in the full version of this investigation. For instance, the specimens O22NCD and O22NCD2 reached almost the same lateral strength (see charts 7 and 8 on the next page), but O22NCD (forward loading) was more flexible than O22NCD2 (backward loading), it is understood when the principal compressive stress distribution is studied. Also the specimen O30NCD (forward loading) was more flexible than O30NCD2 (backward loading), but in this case O30NCD2 reached a higher value of lateral strength than O30NCD (see charts 9 and 10). On the other hand, the specimens O11NCW and O11NCW2 showed similar behaviors (see charts 11 and 12), not so big difference in the strengths, similar initial stiffness and rigid behavior.



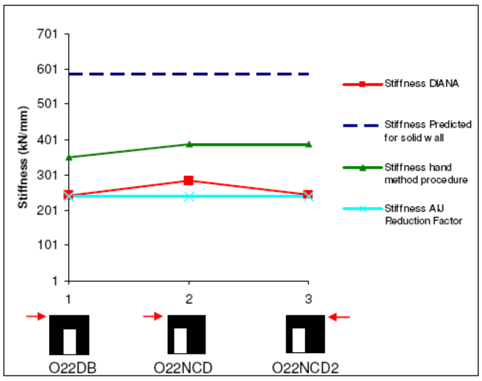
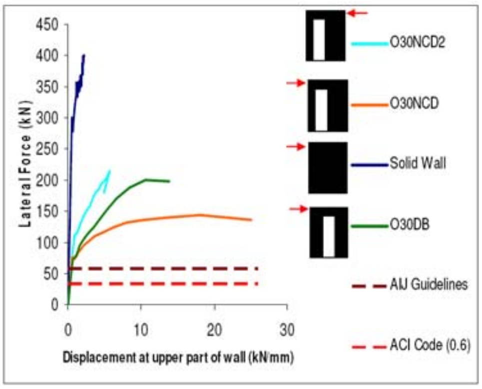




Chart 7 Capacity Curves of specimens O22DB, O22NCD, O22NCD2 and lateral strengths values predicted by seismic codes equations for them

Chart 8 Stiffness behavior of O22DB, O22NCD and O22NCD2



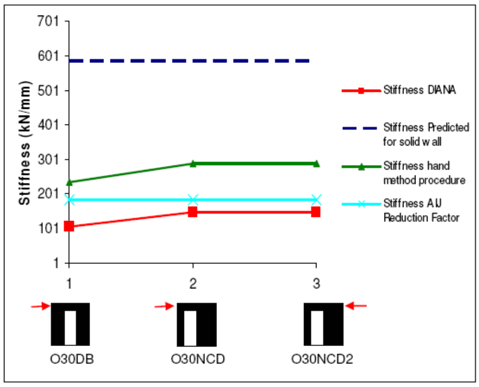
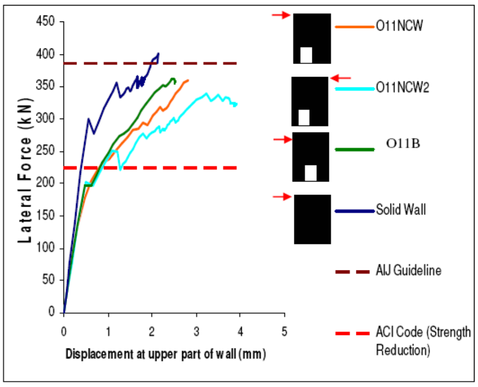




Chart 9 Capacity Curves of specimens O30DB, O30NCD, O30NCD2 and lateral strengths values predicted by seismic codes equations for them

Chart 10 Stiffness behavior of O30DB, O30NCD and O30NCD2



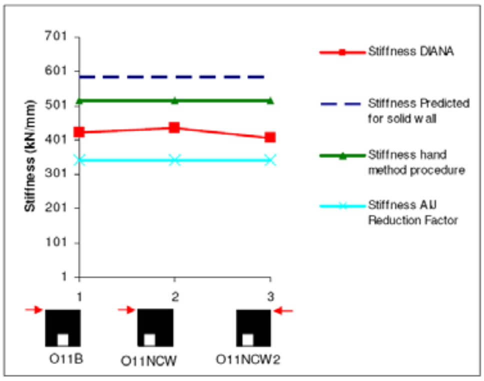




Chart 11 Capacity Curves of specimens O11B, O11NCD, O11NCD2 and lateral strengths values predicted by seismic codes equations for them

Chart 12 Stiffness behavior of O11B, O11NCD and O11NCD2

## CONCLUSIONS

It is notable that only the Japanese Seismic Codes consider strength and stiffness reduction factors when an opening is placed on RC structural walls. The others seismic codes are not so clear about this topic especially in the stiffness calculation. During the investigation it was verified a strength and stiffness reduction when an opening is placed on RC walls. About DIANA, it is valid to say the software can simulate experimental testing successfully; therefore the results obtained in DIANA can be used as whether DIANA simulation is a real testing. Of course a real testing never can be represented one hundred percent accurate by software.

The seismic codes do not take into account the opening positions in the calculation on the strength; it was notable when walls with equal opening area ratio but different opening position reached distinct strengths in DIANA and the seismic codes equations predicted same strength values for them. It was found that for both strength and stiffness, the more critical position is when the opening is closer to the upper part of the wall since the lowest values of strength and stiffness were obtained in that case. The walls with openings showed a more flexible behavior in comparison with the solid wall, and such flexibility was increased when the opening area ratio was increased.

In some cases walls with opening area ratio greater than 0.2 reached more strength than the strength predicted by the codes equations, and some walls with opening area ratio less than 0.20 reached less strength than the strength predicted by the seismic codes equations. In most the specimens the lateral stiffness was overestimated by using both the hand method procedure and the AIJ stiffness reduction factor. Furthermore, it was seen that for walls with not centered openings and opening area ratio greater than 0.2, the walls behavior depends on loading direction (forward loading and backward loading). It was not the case for walls with not centered openings and opening area ratio less than 0.2 because the walls behavior was similar for both cases loading direction, forward and backward. Finally according to cracking patterns and principal compressive stress distributions of the specimens presented in the full version of this investigation, the walls damage was concentrated around the edges and corners of the openings or in the piers located next to the openings.

## ACKNOWLEDGMENT

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