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EFFECT OF THE DIAPHRAGM FLEXIBILITY AND STRUT AXIAL STIFFNESS ON THE LOAD DISTRIBUTION IN THE LATERAL FORCE-RESISTING SYSTEM

Tesis para optar al grado de Magíster en Ciencias de la Ingeniería con Mención en Ingeniería Civil

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RESUMEN

El Sistema de Resistencia Lateral (SRL) es el responsable de transferir las cargas laterales desde los pisos superiores hasta las fundaciones de la estructura. Estos sistemas se componen principalmente de muros y diafragmas. La falta de investigación sobre diafragmas ha conllevado a que el diseño de estos sistemas se base en supuestos y recomendaciones que podrían no ser conservadores, lo que podría llevar a una posible falla de la estructura poniendo en riesgo la vida de sus ocupantes. Dentro de estos supuestos, se encuentra la flexibilidad del diafragma y también la suposición de que la viga colectora que conecta el diafragma con los muros es suficientemente rígida para proveer un desplazamiento uniforme a lo largo de la misma línea de resistencia. En este trabajo se compararon los comportamientos teóricos de un diafragma (rígido/flexible) con un comportamiento semi rígido, el cual incluye las propiedades del diafragma y sus componentes. Además, la influencia de la rigidez axial de la viga colectora en la distribución de carga y desplazamientos en muros compuestos por tramos de diferente longitud fue analizado.

Primero el efecto de la flexibilidad del diafragma respecto a la rigidez de los muros en la distribución de cargas en el SRL y los principales supuestos utilizados en el diseño de los componentes de este elemento son presentados, resumiendo el estado del arte en el tema. Luego, los análisis para distintas configuraciones son presentados, demostrando que el diseño por envolvente no es conservador en la mayoría de los casos, presentando errores de hasta un 75% en la distribución de cargas por muro. Se demostró que, para obtener un diafragma perfectamente flexible, es necesario incluir la viga colectora en los modelos. Además, se demostró que asumir solo deformaciones de paralelas a la carga en el SRL es impreciso, por ende, la flexión fuera de plano de muros y diafragmas deben ser considerados en la modelación de la estructura. También se demostró que asumir desplazamientos uniformes a lo largo de la línea resistente es impreciso a pesar de que los muros tengan longitudes similares y que la carga se distribuye dependiendo la longitud relativa de los tramos solo cuando la viga colectora es lo suficientemente rígida.

Finalmente, se concluyó que para un diseño seguro es necesario modelar las distintas propiedades de cada elemento en vez de asumir el comportamiento de estos.

SUMMARY

Lateral-Force-Resisting Systems (LFRS) transfer the lateral loads from the upper stories to the foundations of buildings. LFRSs are usually composed of diaphragms and shear walls. However, lack of research in diaphragms has led the design of the LFRS being based in assumptions and recommendations that may not be conservative and might lead to a possible failure of the structure, putting the life of its occupants at risk. The most common assumptions made in design are the diaphragm flexibility and assuming the strut element connecting the diaphragm to the shear walls is stiff enough to provide a uniform displacement within the shear wall line. Furthermore, the effect of the strut stiffness on the load distribution and displacements within a shear wall line composed by different lengths of piers is analyzed.

First, the effect of the diaphragm flexibility, relative to the shear wall line stiffness, on the load distribution of the LFRS is presented and the common assumptions made in the design of its elements are presented, summarizing the state-of-the-art on the topic. Then analyses of different configurations are presented, showing that the envelope design method is not conservative in most cases and leads to errors in magnitude of load attributed to each wall line in the building of up to 75%. It is shown that to achieve a perfect theoretical flexible diaphragm, the strut element must be included in the analysis. Furthermore, it is demonstrated that assuming only in-plane deflection pattern for the diaphragm is not accurate and that the out-of-plane bending of the diaphragm and the supporting shear walls must be considered in the computational models. It was also demonstrated that the assumption of a uniform displacement within a shear wall line is inaccurate and that the load distribution between the piers is distributed according to their relative stiffnesses only if the strut has high axial stiffness.

Finally, it was concluded that in order to obtain a safe design it is necessary to model the properties of the elements instead of assuming its behavior.

To my father Enrique and my mother Carmen Gloria for their constant support. To my girlfriend Ailin, whose love and company helped me overcome all the difficult moments of this process.

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INDEX OF CONTENTS

INDEX OF TABLES

INDEX OF FIGURES

CHAPTER 1 INTRODUCTION

1.1 Motivation

The most common Lateral-Force-Resisting Systems (LFRS) are composed of vertical shear walls and horizontal diaphragms. Both elements are responsible for the transfer of the external lateral loads through the upper stories of the structure to its foundation during earthquakes or high winds. However, the research on these systems is mainly focused on the behavior of the shear walls, as from past experiences diaphragms have remained elastic after big earthquakes events. The lack of investigation about diaphragms has led the representation of the behavior of these elements being based on the simplifying assumptions. Errors in estimating the proper load path associated with these assumptions might be the cause of the frequent failure of the supporting shear walls rather than the diaphragms themselves.

The most common assumption made during design pertains to the relative flexibility of the diaphragms and the stiffness of the supporting shear walls, which defines how the load is distributed between the adjacent walls. Most design standards allow the designer to represent the diaphragm as either rigid or flexible depending on the structural system. Furthermore, if the structure is not in the code classification, it can be classified according to the displacement ratio between diaphragms and shear walls. However, the displacement ratio limit varies depending on the standard, and the justification of these values is not presented. This might lead to the design of an unconservative structure.

Another big assumption usually made in design is that the frame element that transfers the forces around the opening in a shear wall (i.e., the strut) is stiff enough to provide continuity for the different wall piers that compose the line of resistance, so the entire wall line deflects uniformly. However, the design of this element is usually based simply on strength rather than stiffness. Hence, the displacement might not be a single value along the wall line, which can affect the load attributed to each wall pier and the estimate of the story drift, which in turn brings into question the design check of not exceeding the drift limits.

This investigation compares different structures via modelling to simulate the behavior of different diaphragms typically assumed in design and determines the accuracy of the common flexibility assumptions made in design. Furthermore, the effects of the strut axial stiffness on the load distribution to the wall lines and within the wall lines is investigated using displacement ratios of the individual wall piers.

1.2 Hypothesis

The actual recommendations on the Lateral Force-Resisting System are accurate enough to provide a safe design where each element is slightly over-designed.

1.3 Objectives

1.3.1 General Objective

Analyze the accuracy of the common assumptions made in the design of the LFRS using the envelope design method for the diaphragm flexibility and the uniform displacement assumption of the entire supporting shear wall line.

1.3.2 Specific Objectives

a) Calculate the load distribution per shear wall line when a flexible or rigid diaphragm is modelled and compare it with a semi-rigid diaphragm.
b) Compare the displacement ratios of the shear wall piers within shear wall lines with unequal length piers.
c) Calculate the load distribution within shear wall lines with unequal length piers.

1.4 Methodology

First, a review of relevant research on the subject was made, finding information about the diaphragm flexibility issue. From this state-of-the-art review, a typical footprint for a building was chosen, which includes a long corridor on the interior and various wall configurations on the exterior of the building. Different distributions of shear walls were selected. Then, computational models were created to analyze the effect of the diaphragm flexibility and the strut axial stiffness on the load distribution within the LFRS of the structure. To analyze the effects of the diaphragm flexibility, structures with equal length piers were used, while modelling flexible, rigid, and elastic diaphragm mechanical properties. To analyze the effect of the strut axial stiffness, both structures with equal length piers and varying length piers were analyzed with elastic diaphragm mechanical properties representative of concrete. Finally, the results were compared with the general recommendations and assumptions typically made during design, calculating the associated error in estimated load resisted by the individual wall lines. Recommendations for the different assumptions are given.

1.5 Principal Results and Conclusions

The computational simulations showed that the common recommendation of assuming a theoretical diaphragm (rigid, or flexible) or the use an envelope design methodology can lead to an overload of the shear walls which could result in the failure of the structure if the loads associated with a design level seismic of wind event are experienced by the structure. Furthermore, it was shown that to achieve a flexible diaphragm, the strut beam must be included in the model. The theorical calculations usually do not consider the out-of-plane bending stiffness of shear walls and diaphragms (specially for rigid diaphragms). It was shown that including this parameter into the models changes the load distribution from the diaphragm to the shear walls, leading again to inaccurate or unconservative designs. Hence, it is recommended to consider the realistic properties of the diaphragm and supporting shear walls in the models instead of assuming theoretical values.

The most common design procedures assume that the shear stress in the diaphragm is uniformly distributed to and within the shear wall line, and that all the piers composing this line of resistance will deflect the same amount. This implicitly assumes that the strut or collector element is rigid. However, the design of this element is based only on strength and not stiffness. Modelling a structure with different length piers, showed that the uniform deflection assumption is inaccurate and that the load is distributed among the piers is proportional to their length (stiffness) only when the strut has an axial stiffness of at least 60% of the longest pier lateral stiffness. Hence, it is recommended that the strut itself be designed as a continuous axial member with a uniform axial stress in proportion to the load and elastic reactions that represent the piers in addition to the bending produced by the loads.

1.6 Thesis Organization

This document is divided into five chapters. In Chapter 2, the theoretical framework is presented, describing the Lateral Force-Resisting system and its components. Then, diaphragms are described in detail and explaining the main issues on the design of these elements. In Chapter 3, the analytical procedure is presented, describing the conditions and parameters used in the computational simulations. In Chapter 4, the principal results of the study are presented, the theoretical calculations based on common assumptions made in design are compared against semi-rigid analyses. Finally, in Chapter 5, conclusions and future investigation lines are presented. Appendices are presented at the end of the document.

CHAPTER 2 THEORETICAL FRAMEWORK

2.1 Introduction

This chapter presents the Lateral Force-Resisting systems, describing its function and main components. Then, diaphragms are described, its general roles are presented and the specific function of each of its components are explained. The main assumptions and recommendations in the design of diaphragms are introduced. Finally, the deep beam/girder analogy is explained.

2.2 Lateral Force-Resisting Systems

In a building, the lateral forces (i.e., wind and seismic) are resisted by the Lateral-Force-Resisting System (LFRS). The most common LFRS is composed of horizontal diaphragms and vertical diaphragms (shear walls). In these systems, the horizontal diaphragm is responsible to transfer the load to the supporting shear walls and these walls transfer the load to either the next story below or to the foundations (FEMA, 2006). The design of the vertical elements of the LFRS (shear walls) is extensively covered in the design codes, however there is lack of information concerning the design of diaphragms (Moehle et al., 2010). This forces the designer to make assumptions that might not be conservative, such as the diaphragm flexibility.

According to Moehle et al. (2010), diaphragms serve multiple roles, which can be summarized as: resist gravity loads, provide lateral support to vertical elements (shear walls), resist gravity loads, resist thrust from inclined columns, transfer lateral applied and/or inertial forces to vertical elements of the LFRS, transfer forces from stories above, and support soil loads in the case of buildings with subterranean levels. Diaphragms can be made from different materials, like concrete, timber or concrete-steel composite decks, among others. Independently of the material, these structural elements are composed of chord beams, strut (collector) beams, plate elements, and the associated connections (Moroder, 2016). These elements are described next:

Chord elements are idealized as responsible to resist 100% of the in-plane bending forces induced in the diaphragm via concentrated compression and tension forces, similar to the flanges on an I-beam. this accomplished with either a specific edge beam or edge zone reinforcement. (Moroder, 2016, Sabelli et all., 2011).

The plate elements are idealized to resist the in-plane shear forces, that under the assumption of deep beam theory, are uniformly distributed across the depth of the diaphragm as unit shear. (Moroder, 2016, Sabelli et all., 2011).

The connections ensure that forces are transmitted between the plates, chords, struts and the vertical elements of the LFRS in the story below (supporting the diaphragm) (Moroder, 2016, Sabelli et all., 2011).

Collectors are elements oriented parallel to the applied load, which distribute the unit shear load from the diaphragm to the shear walls or vertical LFRS elements in the story below (ASCE, 2017). These are axial members and are usually beams, but some designers use extra reinforcement at the edge of the diaphragm (Moehle et al., 2010, Sabelli et all., 2011) to act as the strut element. Furthermore, the collector is intended to effectively drag the unit shear from the diaphragm from over the openings in the walls below to the adjacent wall piers.

There is little published research on the philosophy of the diaphragm design, and the few investigations have mainly focused in the effect of the diaphragm flexibility relative to the vertical elements of the LFS. For the diaphragm components, its design is based in assumptions and recommendations. Specifically, for the case of the struts the most common assumption is that it is a simply supported beam, subjected to a uniform load representing the unit shear from the diaphragm (Moehle et al., 2010). This load from the diaphragm is actually two loads 1) the gravity loads from the diaphragm and 2) the unit shear from the diaphragm (which is actually an axial stress in the strut). The design method does assume that any stiffness of the strut element is sufficient and that only the forces involved are important for design. So that simple statics is used to design the element. Similarly, in design it is commonly assumed that the whole line of resistance will deflect the same, assuming that the strut would have sufficient stiffness to transfer the loads through the axis and force all of the piers to deflect the same amount. These assumptions neglect the relative stiffness of the piers in the shear wall line and essentially assumes that all of the piers have the same stiffness.

2.3 Diaphragm load path and flexibility

The load path of a diaphragm is mostly defined by its flexibility. There are three classes of diaphragms: flexible, rigid, and semi-rigid. A flexible diaphragm distributes the lateral loads to the vertical elements according to their tributary areas, where a rigid diaphragm does it according to the relative stiffness of the supporting wall lines (FEMA P-1050-2). A semi-rigid diaphragm has an intermediate behavior where the in-plane stiffness of the diaphragm, as well as the wall line stiffness, must be considered in the analysis. In this study, the semi-rigid diaphragm is assumed to behave elastically. The deflection of a rigid diaphragm can be neglected in the analysis.

The design of a diaphragm is based on its capacity to resist gravity loads, providing enough out-of-plane strength and stiffness, and satisfying the design serviceability limits specified in the codes. This usually leads to a misconception that the diaphragm will behave as rigid. According to Scarry (2015) this misconception can be attributed to the lack of coverage of diaphragms in the design codes and literature; The rigid diaphragm assumption is almost always made for concrete buildings. In the other extreme, for timber structures, most analyses assume a flexible diaphragm, because of the relatively low Modulus of Elasticity (MOE) of the material and deformability of connections. These misconceptions of assumptions concerning the relative stiffness of the diaphragms are illustrated in the design examples provided by FEMA P-751 (FEMA, 2012), where the diaphragm flexibility is assumed just because of its material.

Due to the complex behavior of the LFRS, several design standards simplify the design by classifying the diaphragms according to the relative deflection between the supporting vertical elements and the diaphragm, itself. According to the US building code (ASCE 7), a diaphragm is assumed to be flexible if the deflection of the diaphragm is over two times the average deflection of the walls (ASCE ,2017). However, the explanation behind this limit is mostly unknown. It must be noted that assuming a rigid diaphragm where it should be flexible would underestimate the period of the structure, overestimate the seismic demand on the structure, and underestimate its displacement (Sadashiva et al., 2012). Assuming that the diaphragm is flexible when it should be rigid or semi-rigid also has adverse consequences for estimating the response and associated load path.

Many projects have analyzed the effects of diaphragm flexibility. Saffarini and Qudaimat (1992) demonstrated that for reinforced concrete structures, assuming a rigid diaphragm is a good assumption when a framed building is modeled; however, if shear walls are used, the load path depends on parameters like the diaphragm aspect ratio. Pathak (2008) analyzed light-frame timber structures with flexible and rigid diaphragms, and found around a 30% difference in the base shears of the structures estimated based on flexible and rigid diaphragm assumptions. Ju and Lin (1999) compared structures using flexible and rigid diaphragms, concluding when frame structures are modelled, it is sufficiently accurate to use rigid analysis, similar to Saffarini and Qudaimat (2012), but this assumption is not valid when shear walls are used as the vertical elements of the LFRS. In terms of dynamic behavior, Fleischmann and Farrow (2001) showed that increasing the flexibility of the diaphragm would begin to dominate the dynamic response of the entire structure instead of simply the localized response of the diaphragm. Sadashiva et al. (2012) states that assuming a rigid diaphragm where it should be flexible would underestimate the period of the structure and overestimate the seismic demand on it but would underestimate its displacements.

2.4 Diaphragm modelling

The most accurate way to analyze the load path in a diaphragm and associated building components is using the Finite Elements Method (FEM); however, this leads to more difficult and tedious work for design, leaving this method to special cases of analysis. The challenge in using FEM to model diaphragm results in the development of various analytical methods to simplify the design of diaphragms, with the assumption of a deep beam/girder analogy being the most common. It must be noted that the assumption of a deep beam analogy can be used in regular diaphragms, which was the subject of this project. However, irregular diaphragms may not respond in a manner consistent with the assumption. Using this method, the uniformly distributed unit shear is resisted by the plate elements whereas the tension and compression are resisted by the chord members (Moroder, 2016).

2.5 Conclusions

In this Chapter, the LFRS were presented. The purpose of these systems is to transfer the lateral loads from the superior stories of the building to its foundations. Then, the main elements (diaphragms and shear walls) of these systems were presented. The functions of diaphragms in the structure were explained and the purpose of each component of the diaphragm was described. Due to the lack of research on the design philosophy of diaphragms is that these elements are designed under assumptions and recommendations, being the most common the diaphragm flexibility which defines how the loads are distributed to the vertical elements (shear walls). Another assumption made in design is that the whole wall line will deflect uniformly, which implicitly assumes that the strut beam is stiff enough to transfer the load within the shear wall piers. However, the design of these elements is based in strength and it does not consider stiffness. These assumptions could lead to an inaccurate design overloading different elements of the structure which could produce the failure of the building under the design loads, failing the principal idea in the design philosophy which is to not put at risk the life of its occupants. Hence, it is required to analyze if the common assumptions are conservative obtaining overdesigned elements in the LFRS. Finally, the deep beam analogy to model diaphragms was presented. In this research, the common assumptions will be compared to a more complete computational analysis, where the properties of the components of the LFRS can be modelled and analyze if the common assumptions and recommendations in the design of the LFRS are conservative enough.

CHAPTER 3 PROCEDURE OF ANALYSIS

3.1 Introduction

In this chapter the procedure of analysis is presented. First, the general considerations like the geometrical and the material properties are presented. Then, the conditions to analyze the effect of the diaphragm flexibility on the load distribution are presented. Finally, the different simulation procedures to analyze the effect of the strut axial stiffness on the load distribution are presented. Comparisons with the common assumptions are presented.

3.2 General considerations

Elastic analyses were performed using the software SAP2000 (CSI, 2017). In these models, only diaphragms, walls and strut beams were modelled. Diaphragms and walls were modelled using shell elements with 30.5 cm thickness and linear properties. Non-linear analyses were not included, as this research was scoped based on the design provisions given in the codes, and the load path for analysis of the entire building was the topic of interest. The strut beams had a cross section area of 20 x 30 cm. All the elements were initially modelled using the concrete properties given by the software, with an MOE of 2.53 x 10^5 kg/cm^2 (24.8 GPa). The general steel reinforcement details of the diaphragms were not included as their effect was assumed to be averaged over the entire diaphragm and the effect on the distribution of the lateral force was considered to be. The chosen geometrical properties represent the common values for a regular building.

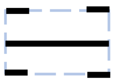
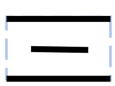
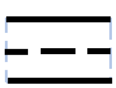
A building footprint of 44 m x 14.7 m (aspect ratio of 1:0.33) was analyzed. The supporting wall configurations were modeled as having three lines of resistance in the diaphragm longitudinal direction, one wall line in the center and the other two wall lines at the extremes of the building. The footprint represents a common building with a long corridor. The building had only one story. However, the results can be expanded to multi-story buildings.

3.3 Procedure to analyze the effect of the diaphragm flexibility on the load distribution in the Lateral Force-Resisting System

Six different wall configurations were created to analyze the distribution of a constant horizontal load applied to the diaphragm. Each configuration is presented in Table 3.1. Illustrations of these configurations can be found in Appendix 3.1.

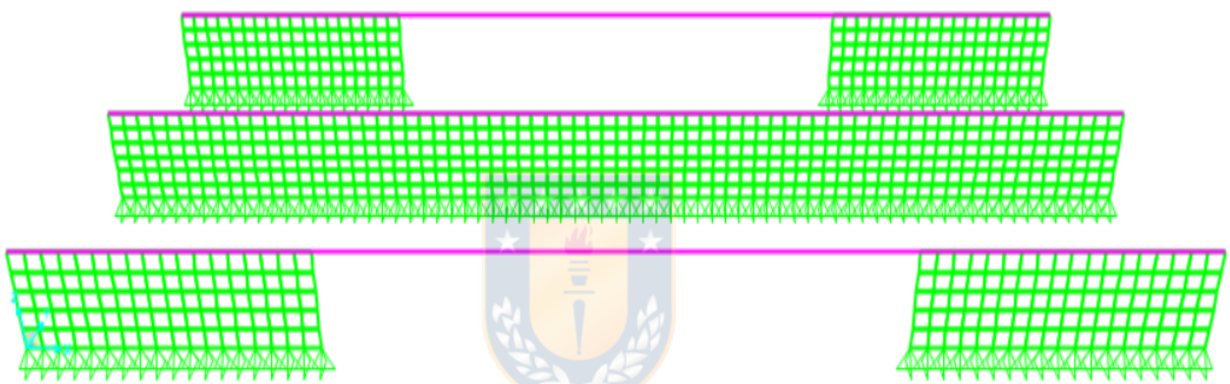
For each configuration, the effect of the wall proportion on the load distribution was analyzed. As shown in the first column of Table 3.1, the length of the interior wall (or exterior walls) remained constant while the wall length in the other line(s) of resistance (exterior or interior wall lines) was increased by increments of 10% until all three walls reached the same length. Three different classes of diaphragms were analyzed: flexible, rigid, and semi-rigid (with elastic behavior). Each diaphragm was modelled by varying the MOE of the material: to obtain a flexible diaphragm this value was drastically reduced to 0.0253 kg/cm^2 (2.48 kPa), whereas to model a rigid behavior the property was significantly increased to 2.53×10^9 kg/cm^2 (248.1 TPa). The flexibility of the semi-rigid diaphragm was modeled using the material properties of concrete. All the cases were modelled with and without the frame element (strut). Also, the effect of the out-of-plane bending of the diaphragm and shear walls was investigated. Out-of-plane deformations are flexural deformations of either the shear walls or diaphragms due to forces perpendicular to the plane of the element. First, the structures were analyzed considering only in-plane deflection parallel to the loading and then all the degrees of freedom were considered. Finally, for the flexible diaphragm, the effect of the diaphragm aspect ratio was analyzed, varying the aspect ratio (width-to-depth) from 1:0.33 to 1:1 and 2:1 in some configurations.

Table 3.1: Distribution of walls per configuration

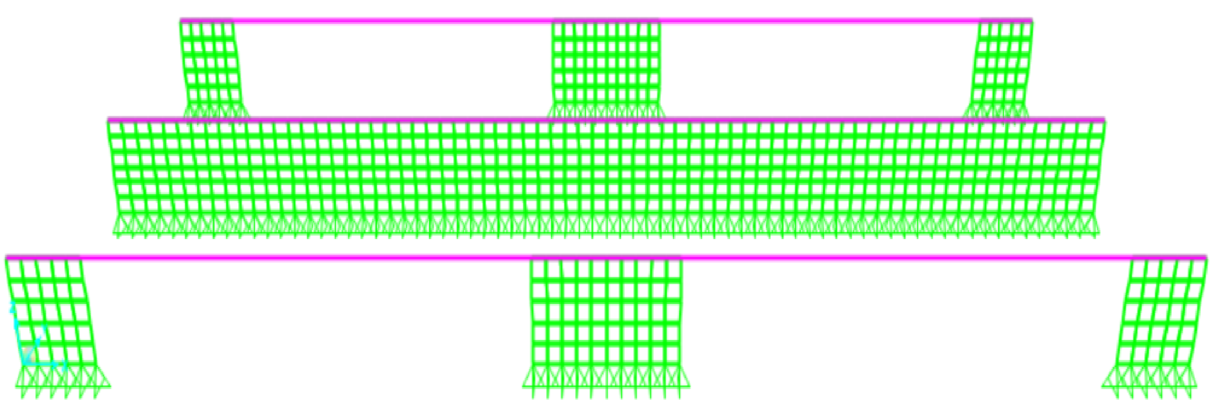
Configuration	Exterior Axes	Interior Wall Line
1 	Symmetric, composed of 2 piers, each one at the ends of the wall line. The length of piers in each line varies from 0% to 100% of the interior wall length.	Full length (44 m)
2 	Symmetric, composed of 3 piers: 1 pier in the middle and 2 at the ends of the wall line. The length of piers in each line varies from 0% to 100% of the interior wall length.	Full length (44 m)
3 	Symmetric, composed of 1 pier in the middle of the wall line. The length of pier in each line varies from 0% to 100% of the interior wall length.	Half length (22 m)
4 	Asymmetric, one wall line composed of a wall in the middle, the other axis composed of 2 piers, each one at the ends of the wall line. The length of piers in each line varies from 0% to 100% of the interior wall length.	Half length (22 m)
5 	Full length (44 m)	Composed of 1 pier in the middle. The length of the pier varies from 0% to 100% of the exterior wall length.
6 	Full length (44 m)	Composed of 3 piers, 1 pier in the middle and 1 at each end of the wall line. The length of piers varies from 0% to 100% of the exterior wall length.

3.4 Procedure to analyze the effect of the strut axial stiffness on the load distribution in the Lateral Force-Resisting System

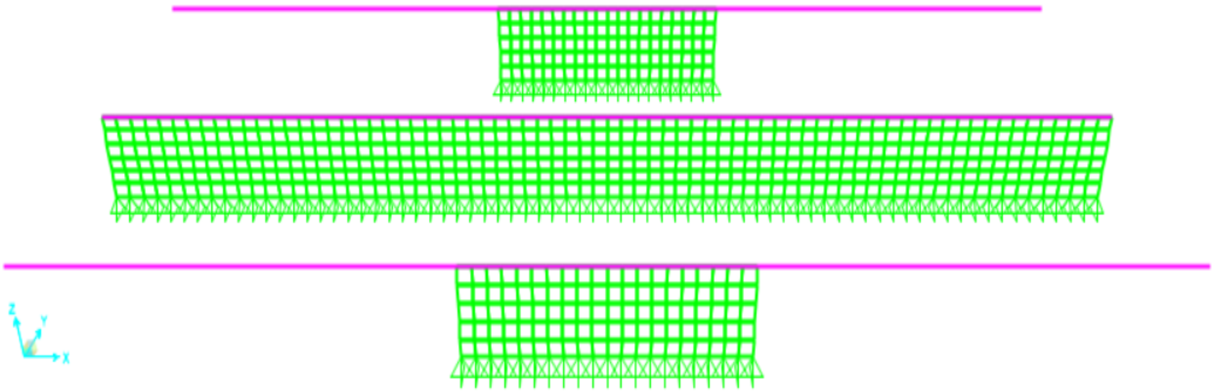
Three shear wall distributions were compared, all of them with an interior wall of 44 m. In the three configurations, the two exterior wall lines were symmetrical about the center wall line. Configurations 1 and 3 were already defined in Table 3.1. Configuration 7 had only one wall pier located at the center of the wall line of the exterior axis. These three configurations are illustrated in Figure 3.1.



a) Configuration 1



b) Configuration 2



c) Configuration 7

Figure 3.1: Analyzed configurations.

All the results presented use the stiffness ratio of the axial stiffness of the strut element to the in-plane lateral stiffness of the longest pier in the wall line. The stiffness of the pier was obtained directly from the software applying a unit load to the pier and then the axial stiffness of the frame element was changed using modifiers.

The effects of the shear wall distribution and strut axial stiffness were analyzed. To do this a uniform lateral traction load distributed across the entire the diaphragm in the longitudinal direction was applied. A comparison between the three configurations was made using total of the three shear wall pier lengths (11, 16.5 and 22 m). The stiffness of the longest pier and the strut of each case were obtained directly from the software. Elastic analyses were performed increasing the stiffness of the strut until it had the same value than the longest pier, stiffness ratios of 1%, 10%, 20%, 40%, 60%, 80% and 100% were analyzed. The total force induced in each wall line was compared. Configuration 1 was also modelled using asymmetric piers, the long wall pier in the wall lines remained a constant length of 11 m whereas the length of the short piers was increased from 0 to 11 m by 10% increments (1.1 m). The total force per wall line was obtained. Furthermore, the resisted load and average displacement ratios among asymmetric piers were compared.

3.5 Conclusion

In this chapter, the procedure of analysis was presented. The selected footprint was presented and the properties of the finite elements used to model it were described. Then, the different simulation conditions were described. In order to analyze the effect of the diaphragm flexibility on the load distribution to the shear walls, six different shear wall distributions were analyzed. To simulate the diaphragm flexibility, the Modulus of Elasticity of the diaphragm material was highly increased or decreased, depending the case. The parameters to include the effect of the out-of-plane bending and the diaphragm aspect ratio were presented. Then, the simulation procedure to analyze the effect of the strut axial stiffness on the load distribution in the LFRS were presented. Three shear wall distributions were analyzed using a semi-rigid diaphragm. The stiffness of the strut element was varied using modifiers in the models. The load distribution as the average displacement ratio within one resistant line were analyzed.

CHAPTER 4 Results

4.1 Introduction

In this chapter, the principal results of the investigation are presented. First, the load distribution modelling the theoretical diaphragm flexibilities are compared against the semi-rigid analyses. The effect of the out-of-plane bending of the diaphragm and shear walls and the effect of the strut element are presented. Then, the effect of the strut axial stiffness in the load distribution is presented, showing the influence of the stiffness in the load distribution and the average displacement ratio within a resistant line.

4.2 Effect of the diaphragm flexibility on the load distribution in the LFRS

4.2.1 Results for flexible diaphragm considering only in-plane deflection

The load distribution for the exterior and interior walls of the first four configurations with a flexible diaphragm assumption is shown in Figure 4.1. The aspect ratio of the diaphragm is 1:0.33 and only in-plane deflections of shell elements are considered. As can be seen, the distribution of shear wall stiffness affects the load distribution, where the tributary area estimate is conservative for the exterior walls. On the other hand, the interior wall line is overloaded until the stiffness ratio between the interior and exterior walls reaches approximately 80%. Configuration 1 appears the most sensitive to the uneven load distribution with an error as high as 64% when the length of the exterior wall is 10% of the interior wall. Configuration 2 is the least sensitive with an error of 47% at the same shear wall relative length (i.e, 10%).

The results for the other two configurations are presented in Figure 4.2. Below stiffness ratios of 20% and 40% for Configurations 5 and 6 respectively, most of the load is resisted by the exterior walls. In this case, the exterior wall curve is decreasing, while the interior wall curve is increasing. However, as these relative stiffness ratios increase, the behavior of the structure changes. As can be seen, the diaphragm begins to respond in a similar manner to those presented in Figure 4.1 when the exterior and interior walls have the same wall length. Below the relative stiffness ratio of 80%, the tributary area distribution is not accurate leading to an overload of the interior shear walls, and nonconservative estimate of the tributary area of the exterior walls. The error in estimating the loads in the shear wall lines is about 64% for Configuration 5 and 46% for Configuration 6 when the length of the interior wall is 10% of the exterior wall.

It can also be seen that if the collector (strut) frame element is included for a flexible diaphragm, the load path of all wall configurations follows the assumed simplified tributary area assumption. However, the calculated deflection of the diaphragm is unrealistically large, because of the unrealistically low (near zero) modulus of elasticity used to simulate this behavior. For this reason, a small stiffness is required in the strut element. However, the analysis shows that the strut element is required to obtain a “perfect” tributary area load distribution.

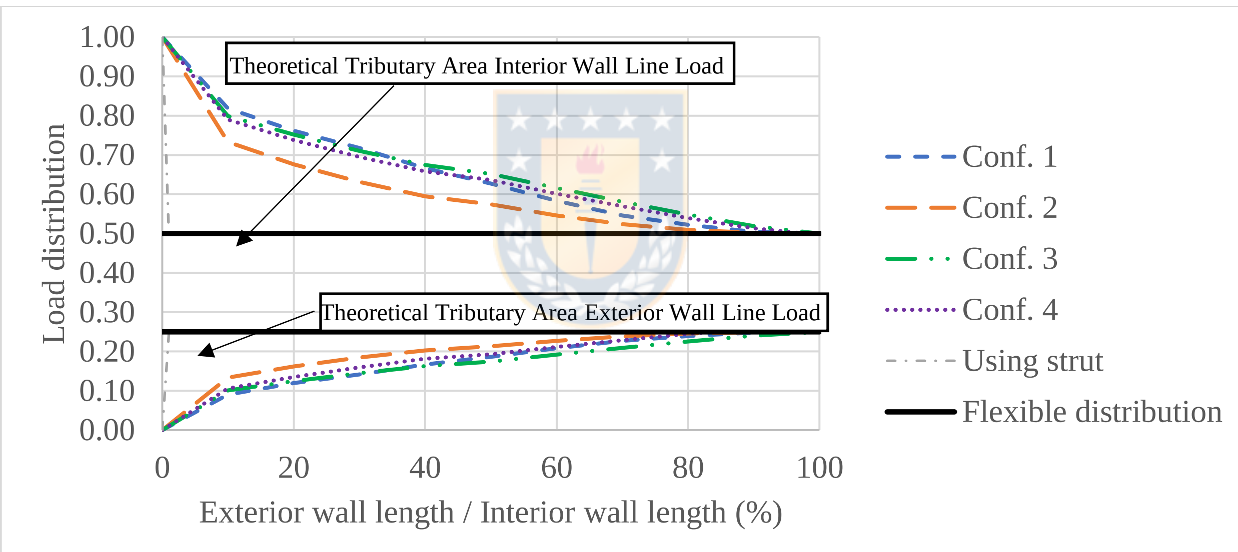


Figure 4.1: Load distribution for Configurations 1, 2, 3 and 4 with flexible diaphragm and aspect ratio of 1:0.33

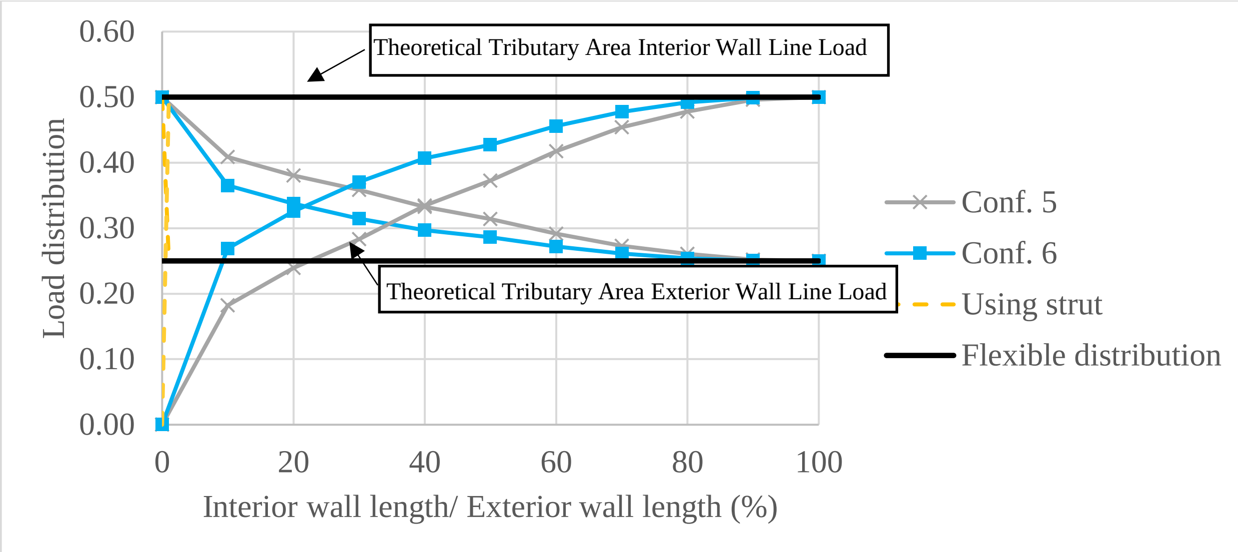


Figure 4.2: Load distribution for Configurations 5 and 6 with flexible diaphragm and aspect ratio of 1:0.33

4.2.2 Load distribution for 1:1 flexible diaphragm considering only in-plane deflections

The results for the same configurations with increasing the aspect ratio (width to depth) of the diaphragm from 1:0.33 to 1:1 and considering only in-plane deflections of shell elements parallel to the load, are presented in Figures 4.3 and 4.4. It can be appreciated that the response is closer to the theory for flexible diaphragms. However, as can be seen, the analysis is still unconservative. For Configurations 1, 5 and 6, the behavior of the structure is similar to that of diaphragms with the aspect ratio 1:0.33 shown in 2.3.4 but is amplified. For Configurations 2, 3 and 4 the behavior of the structure changes significantly. This can be appreciated in Figure 4.5, where the three different flexural diaphragms are illustrated for Configuration 2. To avoid boundary effects, the stresses were obtained from the averaged lower quarter of the diaphragm thickness. In the first step (shear wall length relationship from 0 to 49%), the bending is resisted at the location of each shear wall, then the diaphragm can be idealized as two smaller diaphragms. However, the second step (shear wall length relationship from 50 to 99%) shows that part of the bending is resisted in the openings between shear walls, breaking the diaphragm in 6 smaller elements. Finally, when the walls along the three axes have the same length (100%), the diaphragm behaves as one element.

For Configurations 3 and 4 the behaviors are different. In Configuration 3, the first step is a double diaphragm from a flexural aspect which increases to four effective diaphragms at the second step and finishes with 3 diaphragms at 100%. For Configuration 4, due to the asymmetry of the wall lines, the behavior of the diaphragm is different on each side of the wall located in the central portion of the wall line. The diaphragm behavior on the side with the middle wall is the same as in Configuration 3. The side with the two wall piers at the ends of the wall line starts as a simple diaphragm and then transitions to behaving as three diaphragms. These results can be appreciated in Appendix 4.1. If the strut element is included, then the tributary area distribution is achieved. As expected, increasing the diaphragm aspect ratio also leads to a flexible distribution even if the strut element is not considered. For the first four configurations, the maximum error of 43% (at wall line stiffness ratio of 10%) is shown for Configurations 3 and 4. The minimum error of 29% is observed for Configuration 1. The maximum observed error is 29% for Configuration 5 and 46% for Configuration 6.

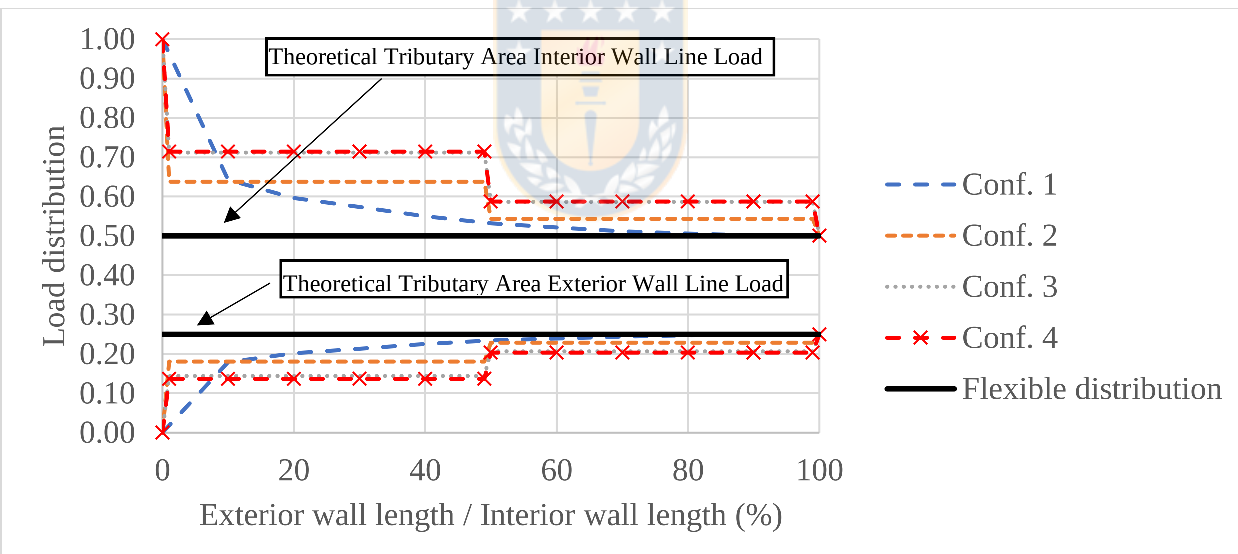


Figure 4.3: Load distribution for Configurations 1, 2, 3 and 4 with flexible diaphragm and aspect ratio of 1:1

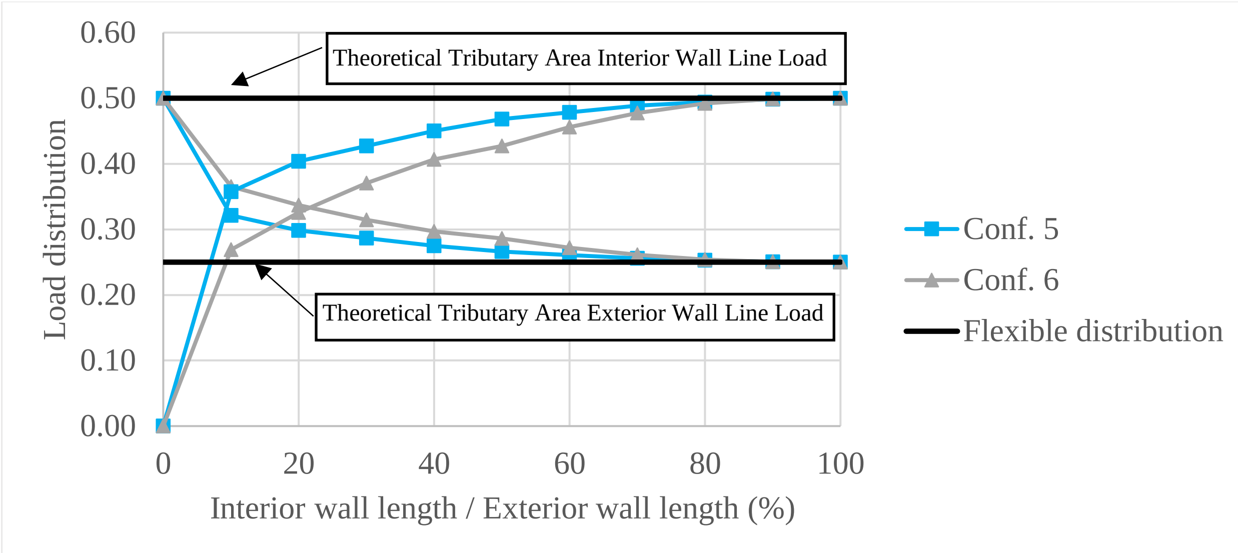


Figure 4.4: Load distribution for Configurations 5 and 6 with flexible diaphragm and aspect ratio of 1:1

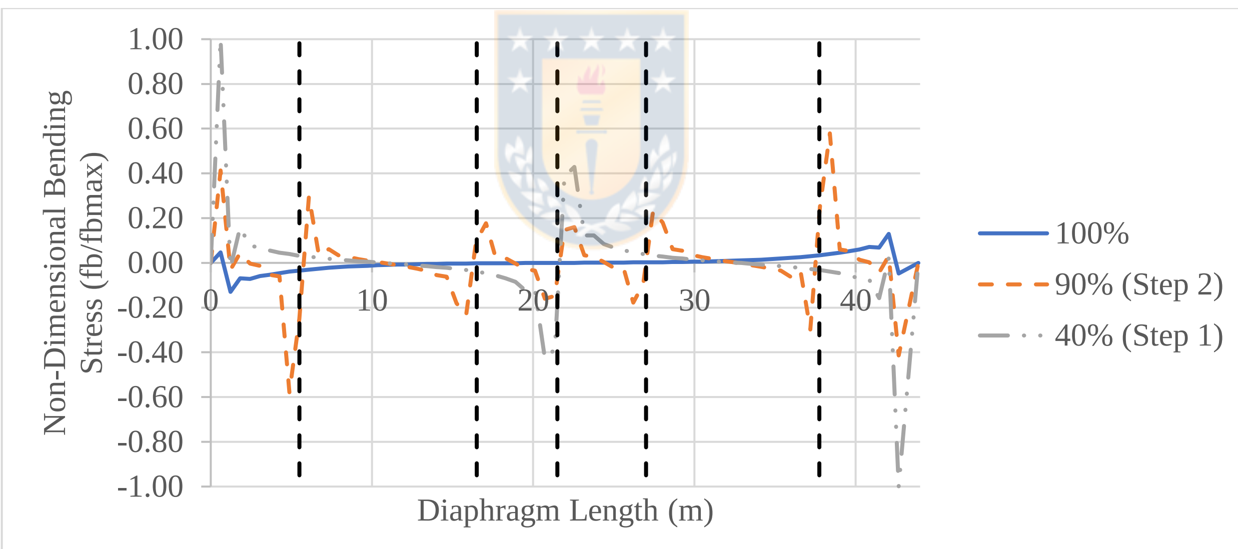
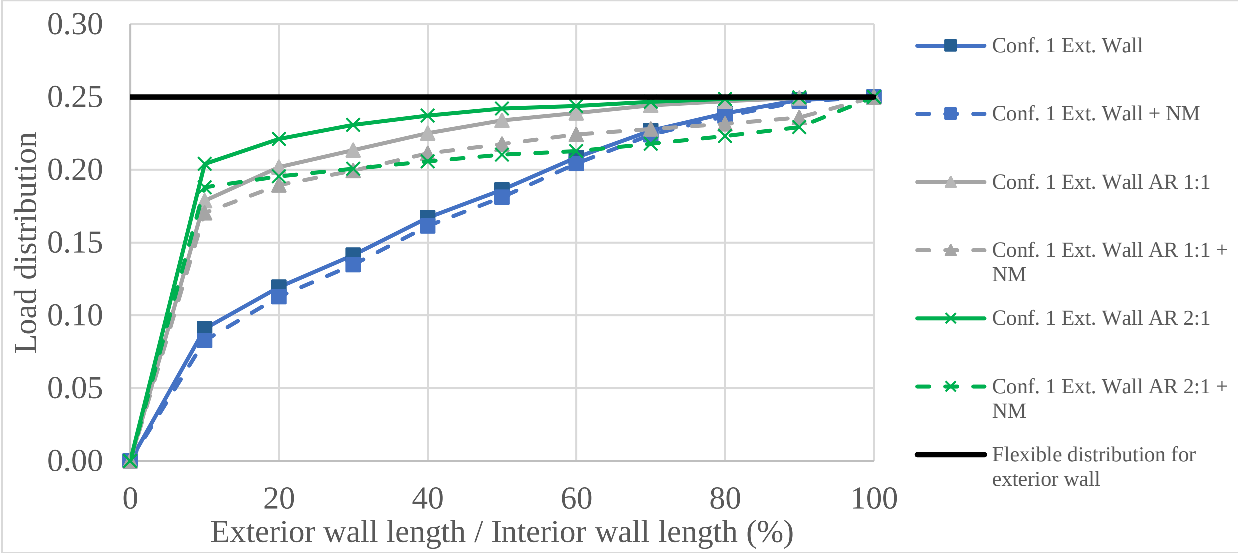


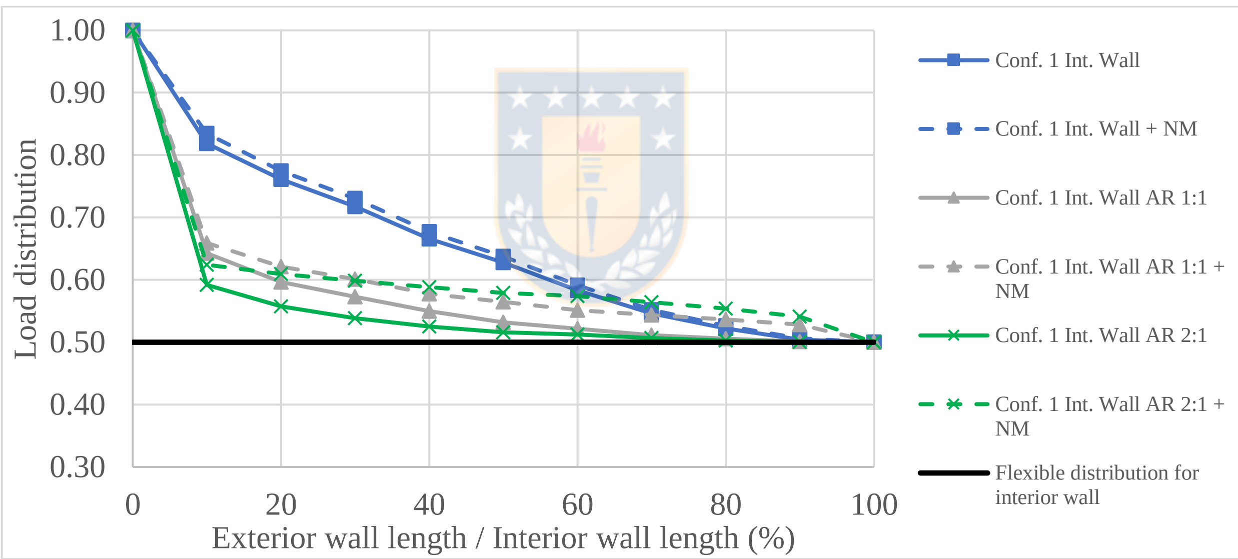
Figure 4.5: Change in the diaphragm behavior for Configuration 2 and aspect ratio of 1:1

4.2.3 Out-of-plane effects in flexible diaphragm

The results presented earlier are based on in-plane deflections parallel to the load, which is the standard method for design of diaphragms. The following analysis was made to investigate the effect of including the out-of-plane stiffness of the supporting walls. The analysis considered the out-of-plane bending stiffness of the shear walls and diaphragms by releasing these degrees-of-freedom for the model mesh. For the initial building footprint, if these boundary conditions are included in the models, the results are almost the same, except for Configuration 4, where a maximum difference of around 27% is shown in the exterior resistance wall line, consisting of 2 wall piers. This type of distribution produces a cantilever diaphragm condition in sections of the diaphragm, which increases the out-of-plane deflections. However, if the strut element is included, the tributary area load distribution is achieved as shown in Figures 4.1 and 4.2. If the aspect ratio of the diaphragm is increased, then the out-of-plane effects also increase, as it can be seen in Figures 4.6 and 4.7, where this effect is presented for Configurations 1 and 5 (with the name "+ NM", which means that the out-of-plane bending of shear walls and diaphragms is included). These results show that the exterior walls resist a lower proportion of the load than the initial configuration, and hence, the interior wall becomes overloaded. For Configuration 1, the maximum error between the analysis and the tributary area theory due to the out-of-plane effect are seen in the exterior walls, with values of error of 15% for the 2:1 aspect ratio, 8% for the 1:1 aspect ratio and 10% for 1:0.33 aspect ratio. For Configuration 5, the errors for these same aspect ratios are of 13%, 9% and 9% respectively. It must be noted that this error is in addition to the previous differences with the theoretical distribution value. However, if the strut element out-of-plane bending stiffness is high the theoretical flexible diaphragm load path is achieved.

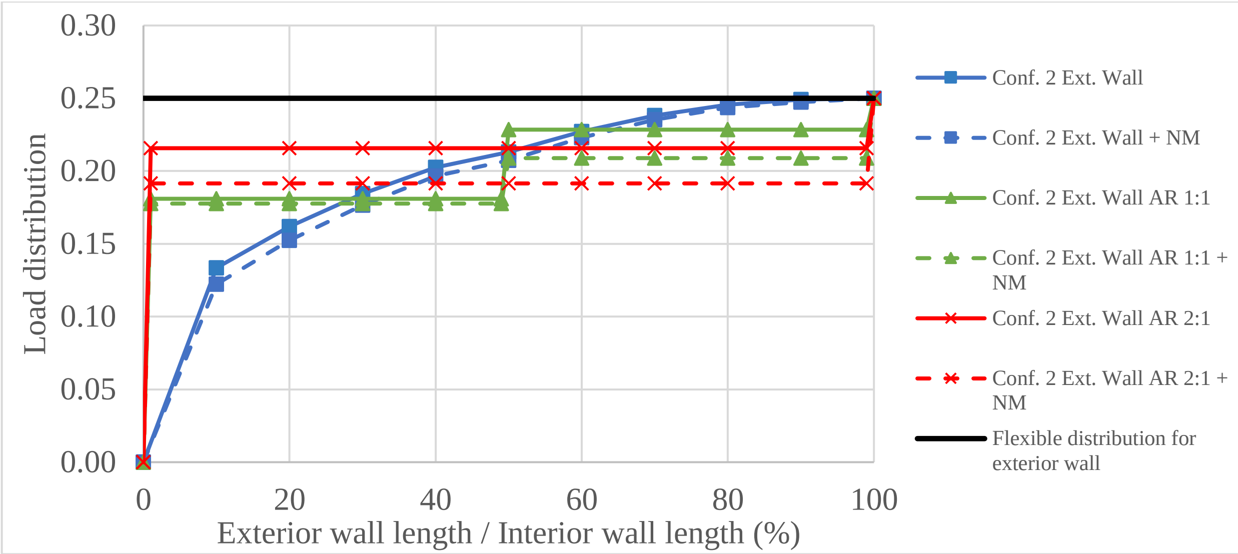


a) Exterior wall line

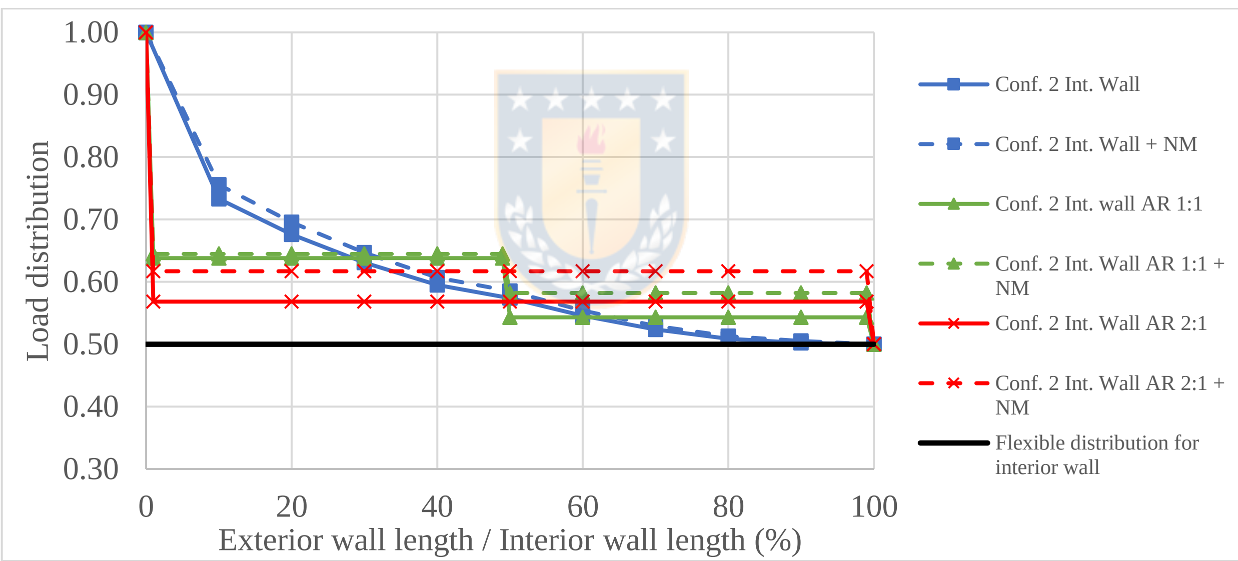


b) Interior wall line

Figure 4.6: Out-of-plane bending effect in Configuration 1.



a) Exterior wall line

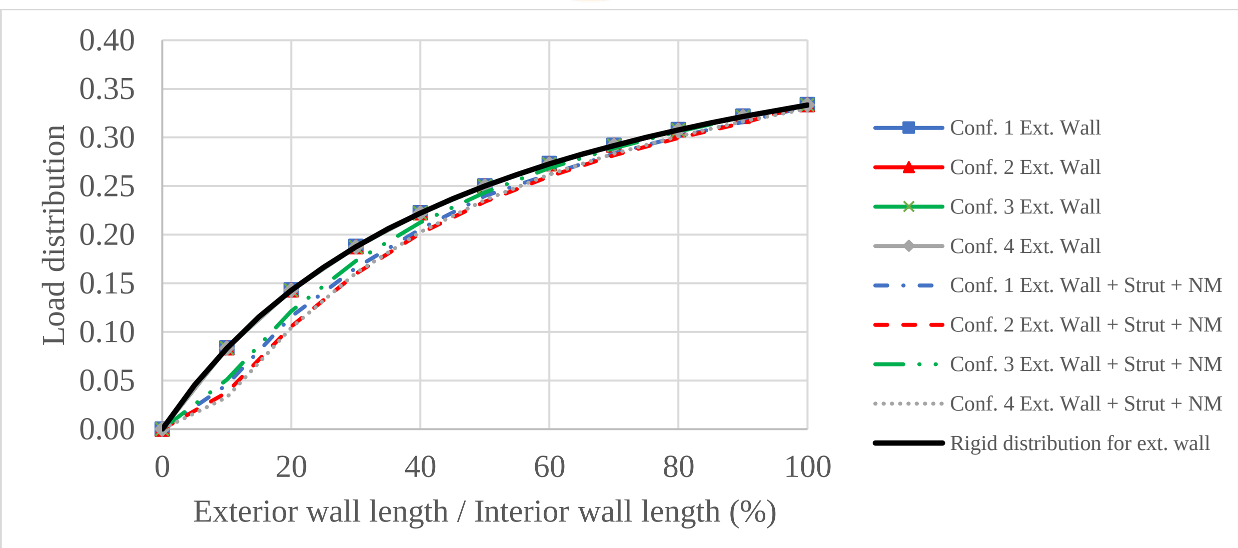


b) Interior wall line

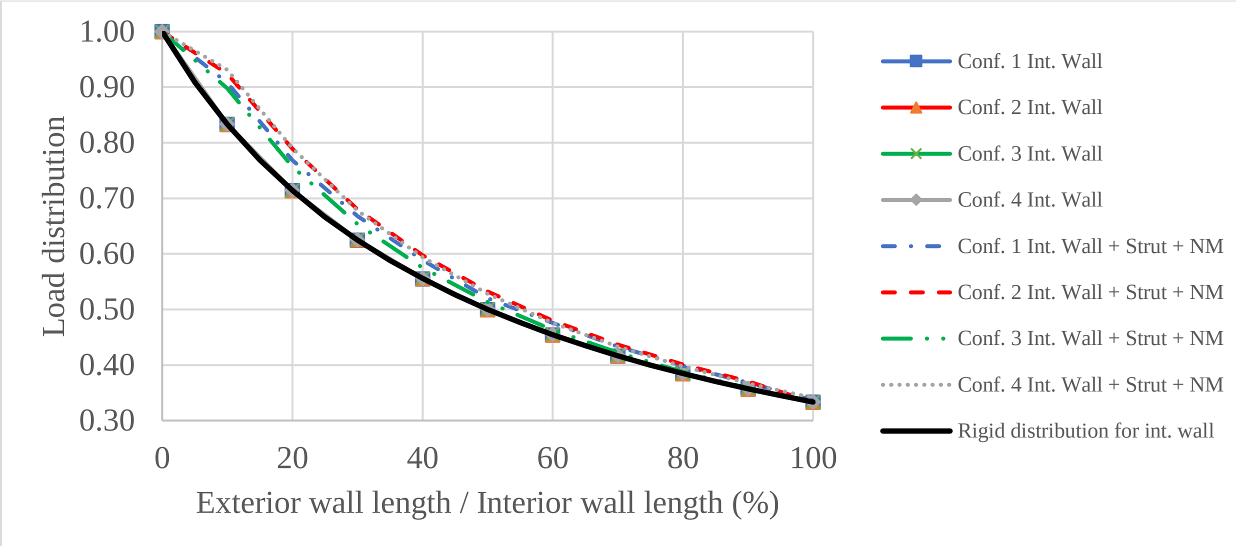
Figure 4.7: Out-of-plane bending effect in Configuration 2.

4.2.4 Rigid diaphragm results considering out-of-plane deflections

When a rigid diaphragm is modelled and only in-plane deflections are considered, the results follow the theory of force proportional to the wall line stiffness. The same behavior is observed in all studied configurations and is independent of whether the strut element is present or not. The diaphragm is stiff enough to act as the strut itself. However, if the out-of-plane deflections are included, the results vary from the theoretical distribution, with different behaviors for each configuration. For Configurations 1, 2, 3 and 4, the interior wall is overloaded, and the exterior walls resist a lower amount of load. The maximum error for the force resisted by the exterior walls of 60% was observed for Configuration 4 and the minimum error of 39% was observed for Configuration 3. When the interior wall line is considered, the maximum error of 12% and the minimum of 8% was observed for the same configurations. These results are presented in Figure 4.8. For Configurations 5 and 6 the errors in the distribution of load are reversed, with the interior walls being more affected, and the maximum error of 58% is observed for Configuration 6 for the exterior wall and 3% for the interior wall. These results are illustrated in Figure 4.9. These results make sense considering that the inclusion of out-of-plane movement decreases the effective stiffness of the supporting exterior wall line.

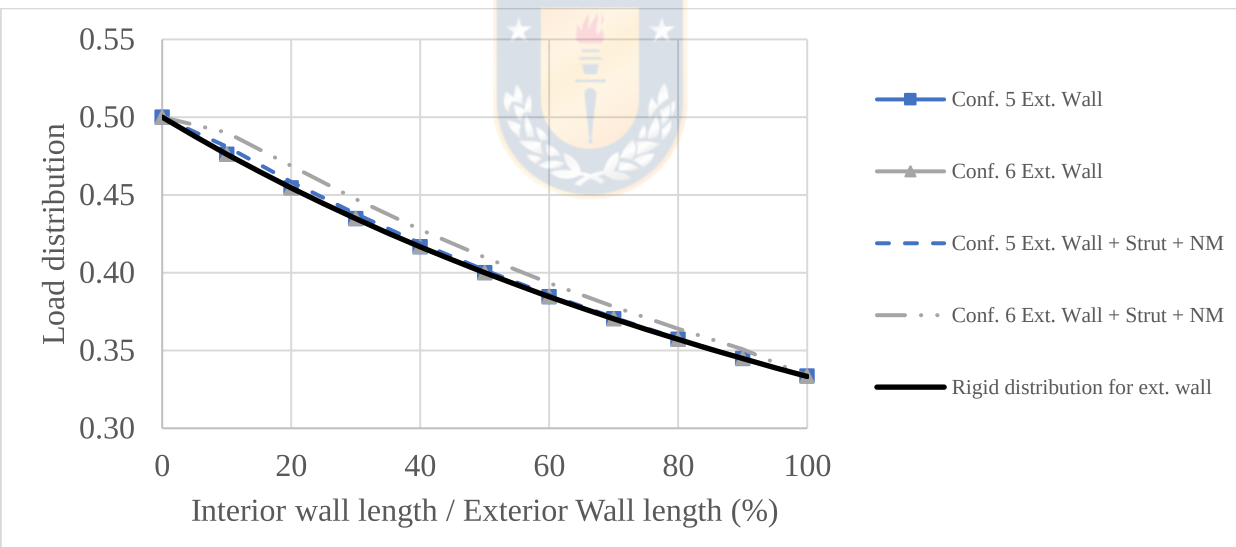


a) Exterior wall line

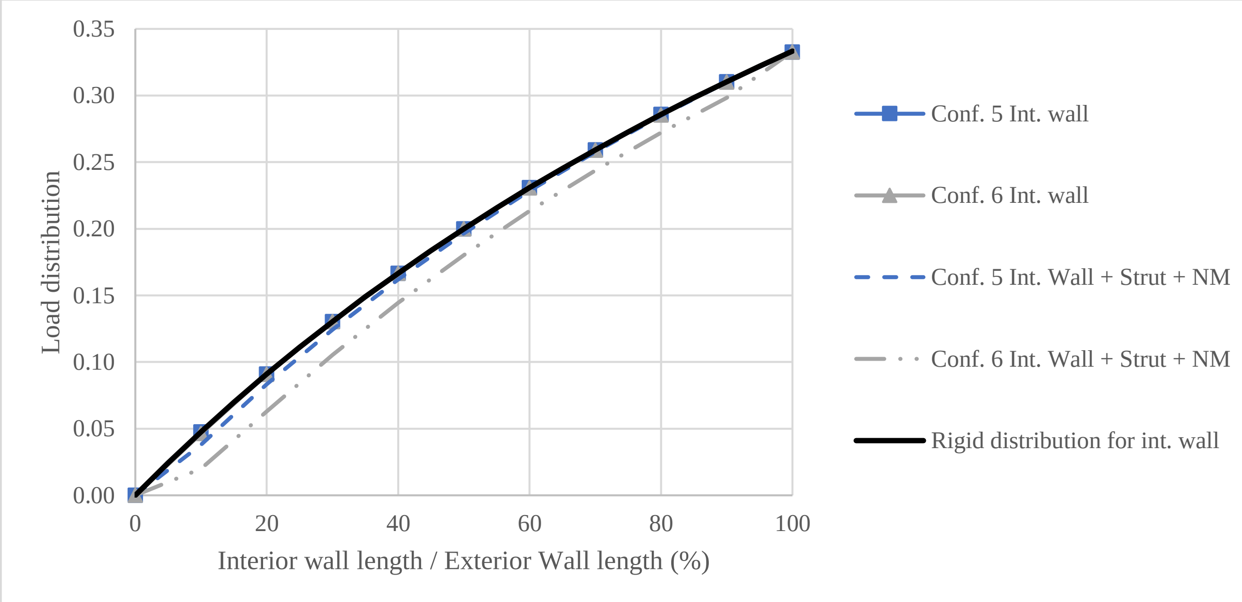


b) Interior wall line

Figure 4.8: Load distribution for Configurations 1, 2, 3 and 4 modelled as rigid diaphragms.



a) Exterior wall line

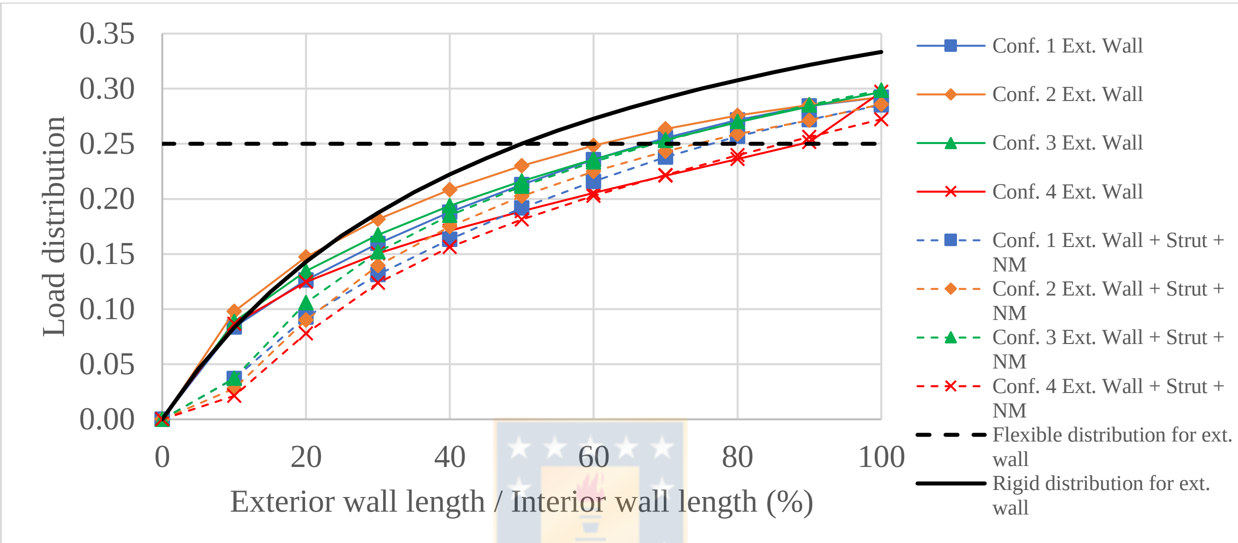


b) Interior wall line

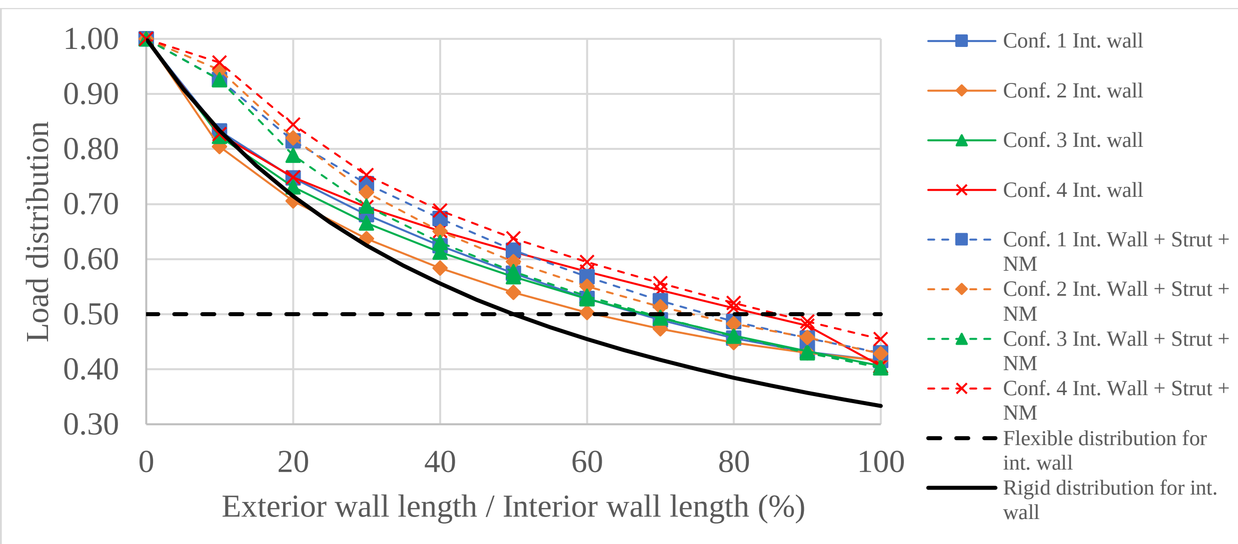
Figure 4.9: Load distribution for Configurations 5 and 6 modelled as rigid diaphragms.

4.2.5 Elastic diaphragm results considering out-of-plane deflections

The load distributions for all the configurations using an elastic diaphragm analysis are presented in Figures 4.10 and 4.11. As expected, each configuration behaves in a different manner than either the flexible or rigid diaphragm theory would predict. Like in the case of the rigid diaphragm results, the effect of the strut is negligible in these cases, and only the out-of-plane bending of the supporting walls and the diaphragm increase the error in the load distribution between the analysis and the theory. This indicates that ignoring the real out-of-plane flexural stiffness of the supporting wall elements can be a non-conservative assumption. The load distribution curves for Configurations 5 and 6 are in between the two simplified theoretical values; hence, an envelope design method might be considered for simplicity, but there would be significant errors between the two theoretical extremes and the actual load distribution. Similar results are presented in Figure 4.10 a) for the exterior walls. However, if the wall length ratio is below 80%, the interior wall would be under designed if an envelope method is employed, as shown in Figure 4.10 b). At a 10% wall length ratio, the maximum error observed in Configuration 4 is 74%. The minimum error at the same wall length ratio is obtained for Configuration 3 with a value of 55%. These errors are for the configurations including the out-of-plane bending effects. If these errors are in the form where the simplification assumptions result in an overestimation of the actual load in the wall line, it implies that the adjacent wall (either interior or exterior) will be overloaded, and vice versa if the plot indicates that the simplification is under-estimating the load in a given wall line.

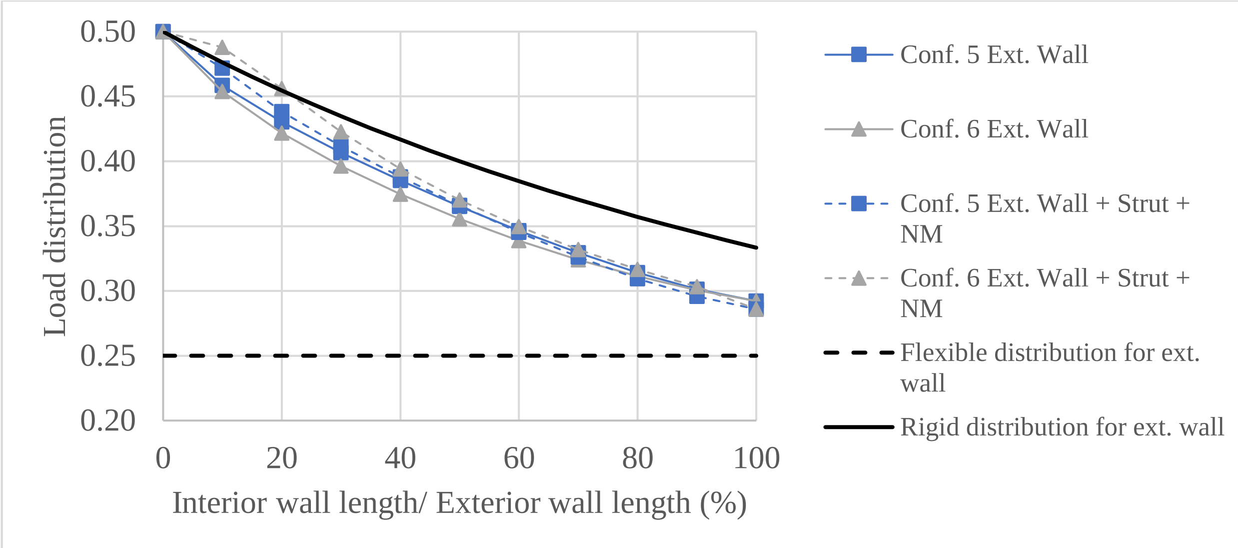


a) Exterior wall line

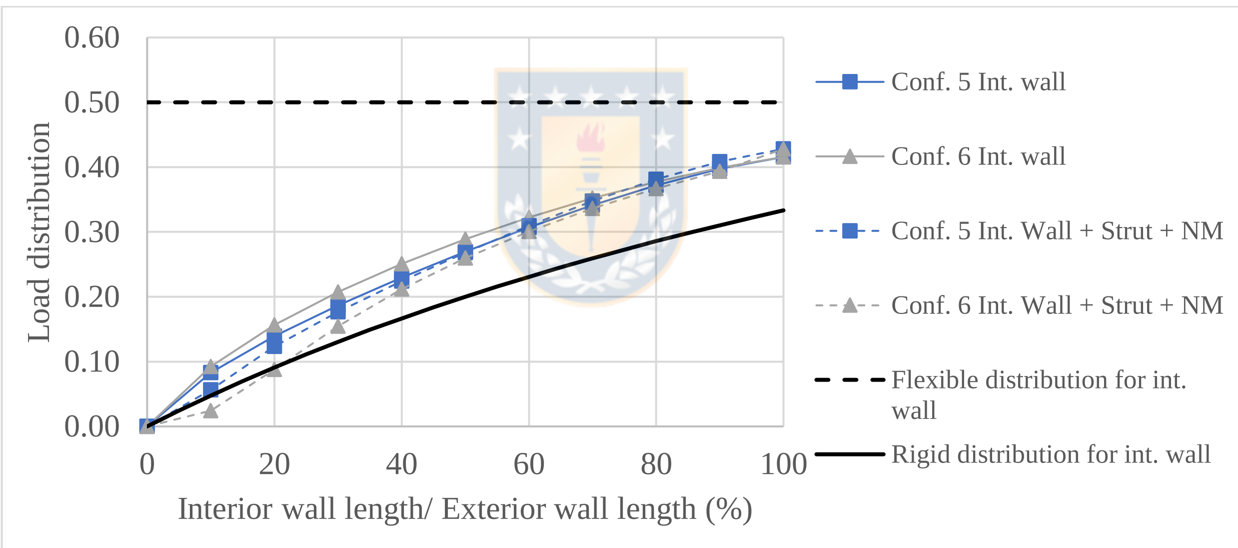


b) Interior wall line

Figure 4.10: Load distribution for Configurations 1, 2, 3 and 4 modelling an elastic diaphragm.



a) Exterior wall line



b) Interior wall line

Figure 4.11: Load distribution for Configurations 5 and 6 modelling an elastic diaphragm.

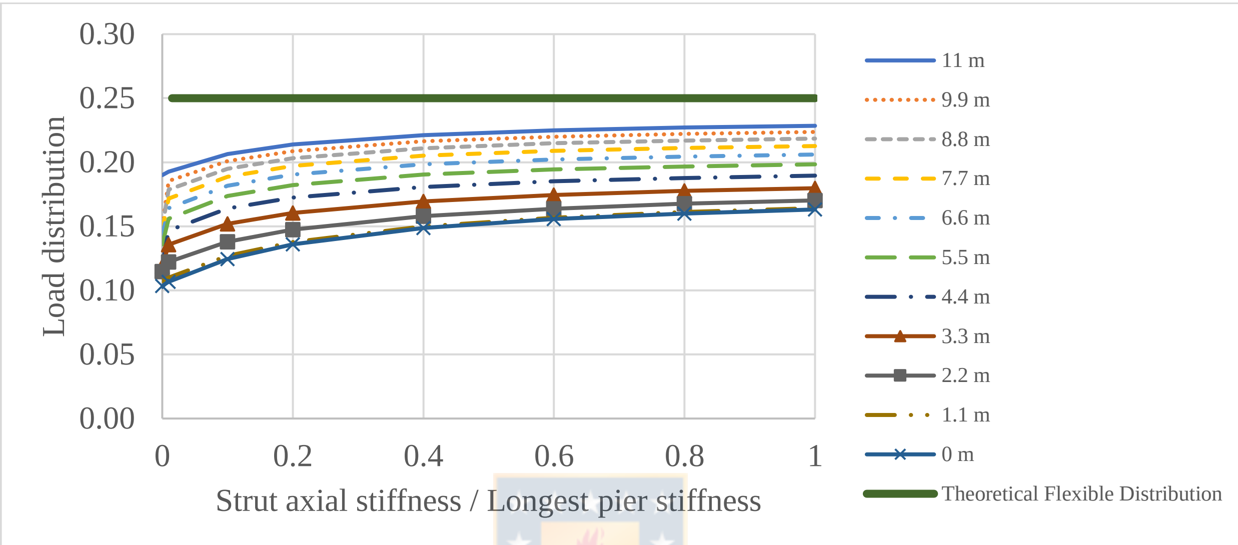
4.3 Effect of the strut axial stiffness in the load distribution of the LFRS.

4.3.1 Effect of the shear wall length in the load distribution

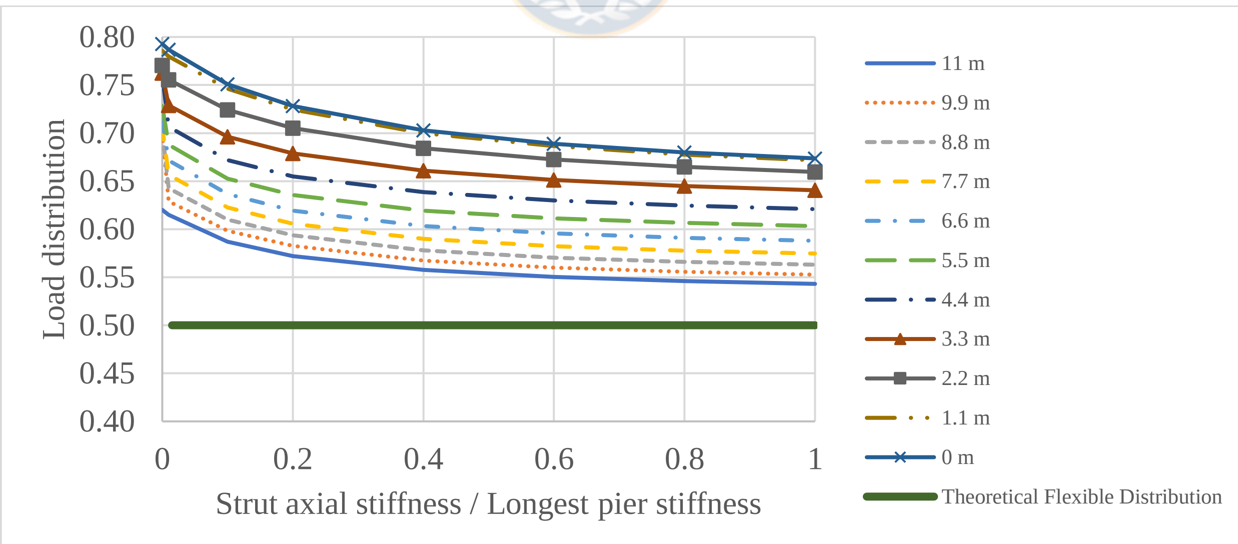
The lateral load distributions from the diaphragm to the individual wall lines for Configuration 1 are presented in Figure 4.12 for the exterior and interior walls, respectively (graph axes have different scales). As shown, even the stiffest strut element does not increase the stiffness of the exterior wall line sufficiently to meet the assumptions of the flexible diaphragm theory of loads being proportions to the wall lines according to the tributary area of the wall lines, where each exterior wall receives 25% of the load and the interior wall 50% of it. As shown, the minimum error in this assumption is about 10%. The exterior wall line resists only 90% of the theoretical load that is should and the interior is overloaded by a minimum of 10%. All of the error in load estimation in the following discussion will be additional error in the quantification of load resisted.

Each curve is labeled according to the length of the shorter pier length. It can be appreciated that the load distribution follows the same trend in all cases, and the effect of the total shear wall length is also seen. When the strut axial stiffness is equal to the longest pier stiffness (stiffness ratio = 1.0) and the short wall pier is at the longest length considered, the additional error in the load estimated for the wall line compared to the simplifying tributary area theory is 8.8% for the exterior wall and 8.6% for the interior wall. The exterior wall in over designed by 8.8% and the interior wall is under-designed by 8.6%. Also, if the short pier is at the shortest length considered and the strut stiffness is also at the minimum considered (stiffness ratio = 0, i.e., there is no strut element), the additional error in load estimation is 58.4% in the exterior wall (underestimated) and 58.6% in the interior wall line (underestimated). This results in the exterior wall being overdesigned by 58.4% and the interior wall be under designed by 58.6%. This is almost a sure failure condition for the interior wall line.

This illustrates that the effect of the strut stiffness essentially dictates the effective stiffness of the wall line, and it also dictates whether the assumed reaction in the beam analogy used for diaphragm design is valid or not. As the strut is increased in stiffness, the wall line begins to act more as would be required to be compatible with the tributary area load analysis used to distribute the loads to the wall lines. This analysis shows that for an elastic diaphragm assumption, the strut axial stiffness will have significant influence on whether or not the diaphragm will distribute the loads to the wall line according to the assumed theory of the wall line stiffness being equivalent to the sum of the wall pier stiffnesses in that wall line.



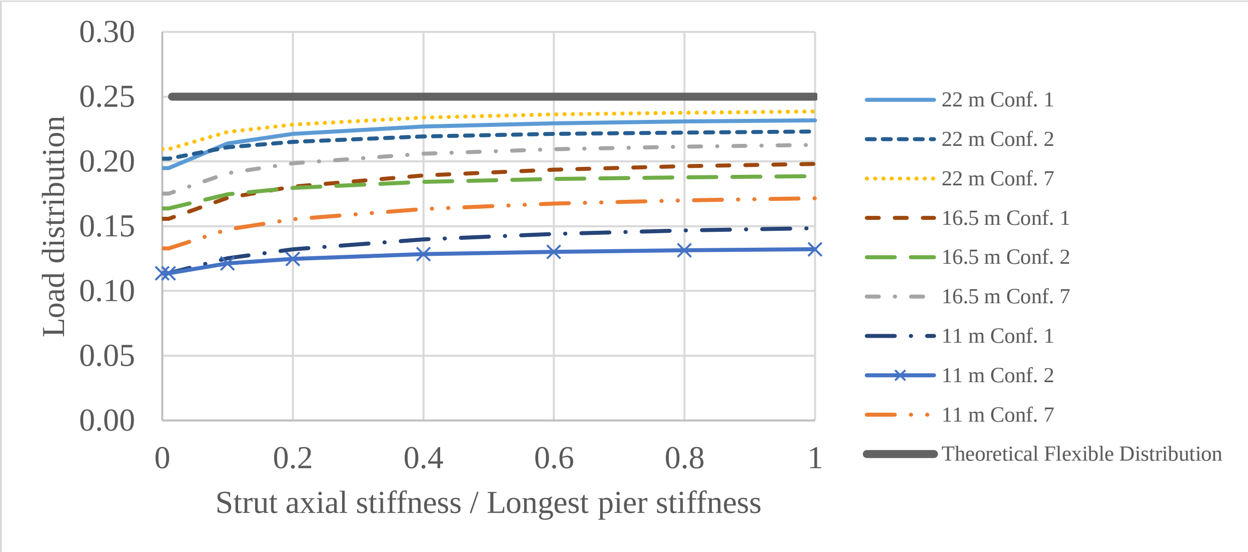
a) Exterior wall line



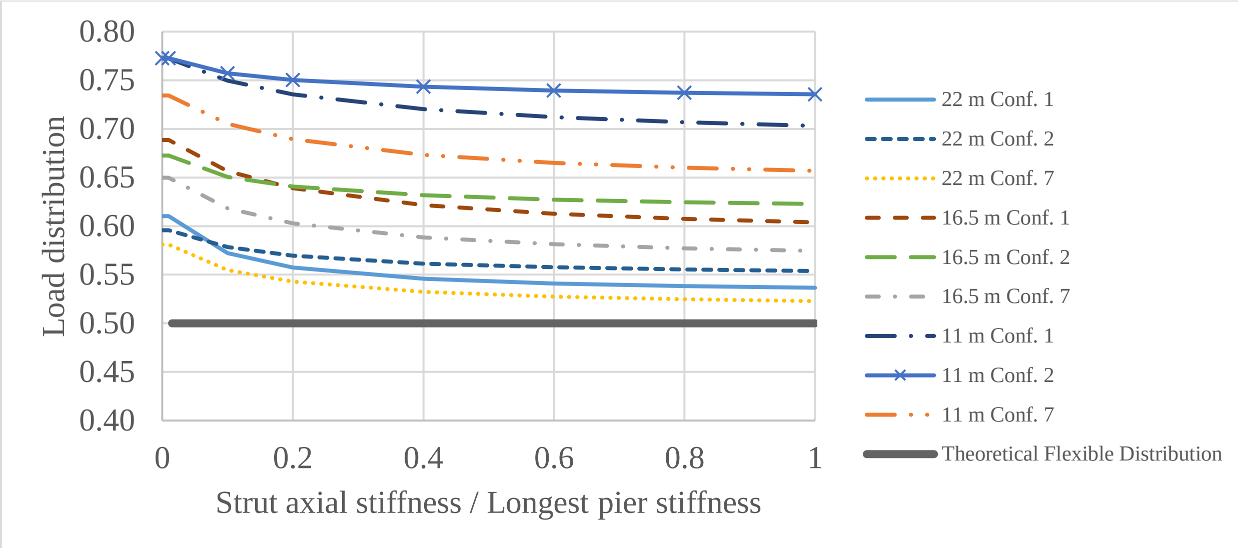
b) Interior wall line

Figure 4.12: Load resisted by the wall lines for Configuration 1 using asymmetrical piers with varying strut stiffnesses in the wall lines.

In Chapter 4.2, the effect of the shear wall pier distribution along the line of resistance was discussed. However only one strut stiffness was analyzed. The effect of the strut stiffness is presented in Figure 4.13 for Configurations 1,2 and 7. In order to make comparisons, three different exterior shear wall line total pier lengths were used; 11 m, 16.5 m and 22 m. It can be seen that all the configurations have different behaviors. The highest load is resisted by the exterior wall line for Configuration 7, which results in the minimum load being resisted by the interior wall line. The minimum load resisted by the exterior wall is for Configuration 2 when it has a length of 11 m. This also results in the interior wall line resisting the maximum magnitude of load in this configuration. However, for the 16.5 and 22 m wall pier lengths, if the stiffness ratio between the axial stiffness of the strut and the lateral stiffness of longest wall pier in the exterior wall line is lower than 0.2 and 0.075 respectively, Configuration 1 presents the lowest resistance for the exterior wall (and the maximum for the interior). This is due to the total length of opening in the exterior wall changing between the configurations. However, the errors between the estimated load to the theory used for design ranges from 4.4% to 54.4% for the exterior wall line and 4.6% to 54.6% for the interior wall line. This results in the interior wall line being overdesigned by as much as 54% and the interior wall line being under designed by as much as 54%. Again, this results in a high probability of failure of the interior wall if the building experiences the design level loading event.



a) Exterior wall line



b) Interior wall line

Figure 4.13: Load distribution for Configurations 1, 2 and 7.

4.3.2 Displacement results for different piers

In design, a common assumption is to assume that the entire shear wall axis will deflect the same amount along the wall line when subjected to the lateral load. However, this is often not achieved due to the design not addressing the strut axial stiffness issue. The average displacement ratio (displacement of the short wall pier or the displacement of the long wall pier) of both short piers of the exterior wall is presented in Figure 4.14 for the different shear wall lengths for Configuration 1. Only the symmetrical distribution results in the same average displacement in both piers. The displacements among the individual pier lengths are never constant because of phenomena like the Saint Venant's effect, the different shear lag effect along the wall pier, and the rotation of the wall top due to flexural response. It can be seen that when the short pier has a length of 1.1 m, its displacement is around 3.2 times the displacement of the long pier in the same wall line when the stiffness of the strut is zero (i.e., no strut present), which leads to the small pier displacing 3.2 times as much as the long pier in the wall line. When the stiffness of the strut is equal to the stiffness of the long pier, the short pier displacement is only 1.4 times the displacement of the long pier, but this still results in a difference of 40% when compared to the wall configuration with two equal length piers. It must be noted that in a real building, it is not usual to have a strut with the same stiffness as a wall. The stiffness of the strut will depend on the cross-sectional dimensions of the strut element and the length of the opening between the piers. However, this analogy was used to demonstrate the inaccuracy of assuming that the line entire of resistance displaces the same amount. Increasing the length of the short pier reduces the inconsistency between reality and the design assumption of a constant displacement, but the displacements are still significantly different than the configuration with equal length piers. When the short pier has a length of 9.9 m (90% of the long pier), the difference in pier displacements is 3.5%, which could be considered as neglectable. If the short pier length is 80% of the long pier (8.8 m), the difference in displacement increases to 10%, which is becoming significant and many designers would consider unacceptable. Hence, assuming a uniform displacement within the shear wall line may not be conservative and each pier should be analyzed independently, and the strut should be designed with as high of axial stiffness as possible.

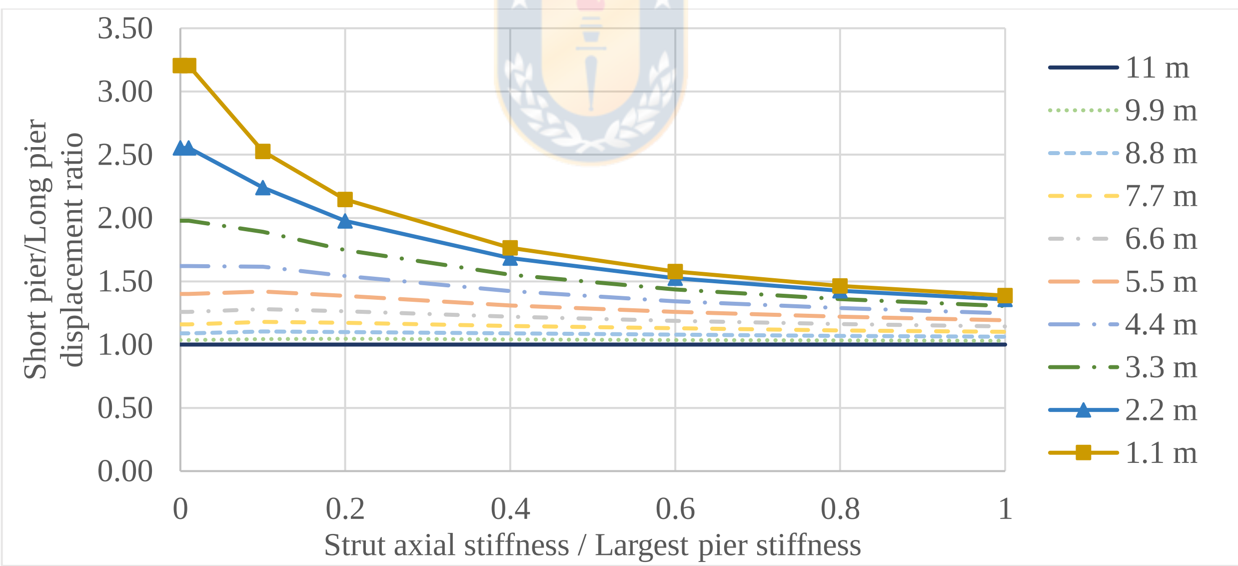


Figure 4.14: Displacement per pier ratio (short pier/long pier) of exterior wall in Configuration 1.

4.3.3 Load distribution per pier

The ratio of load resisted by the short pier to the load resisted by the long pier of the exterior wall line in Configuration 1 is presented in Figure 4.15. It can be seen that similar to displacements, an equal distribution of load is only achieved in a configuration with equal length wall piers. When the ratio between the strut axial stiffness and the stiffness of the longest pier is above 60%, the curves tend to stabilize, this because the shear deformation behavior of the pier starts to dominate over the flexural deformation behavior. Above this percentage, when the short pier length is 50% or longer when compared to the long pier length, the percentage of load resisted is the constant. For example, if the short pier has a length equal to 80% of the long pier length (8.8 m), then the total load resisted by the pier will be 80% compared to the load resisted by the long pier. The axial load in the strut will be higher as the differences in pier length increase. Hence, assuming a uniform load distribution in a wall line for design may not be conservative, and a more advanced analysis should be used to obtain the force distribution with in the wall line. If a design software is not used, distribute the load according to the relative stiffnesses of the piers, determining the wall pier stiffness using the length of the piers will be the most accurate.

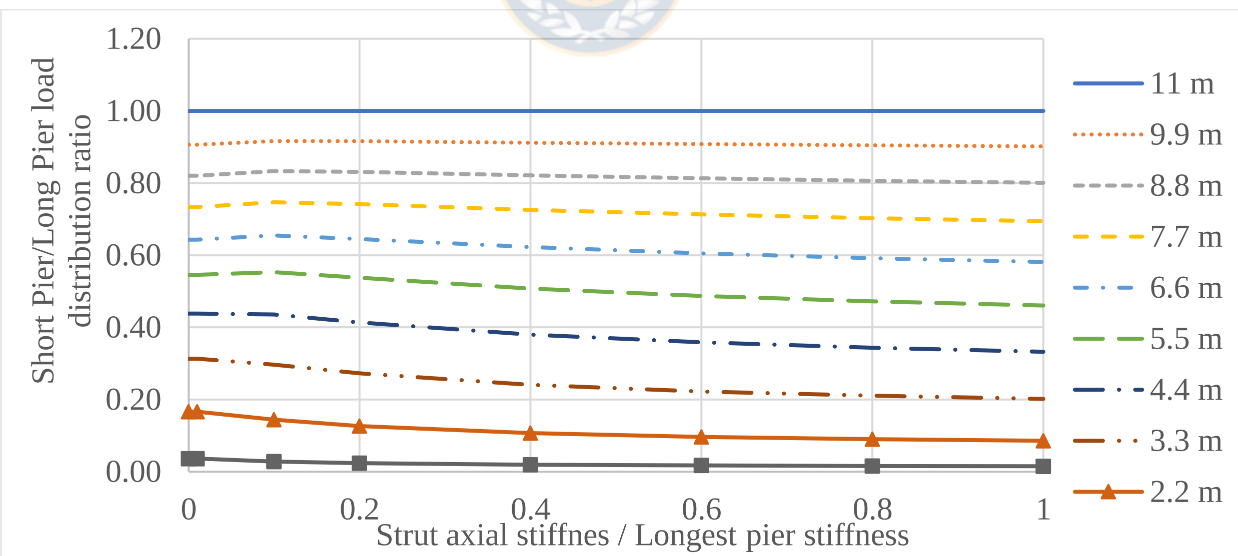


Figure 4.15: Load per pier ratio of exterior wall in Configuration 1.

So, for design, the current methods of analyzing the strut element have been overly simplified and result in potential under designed members. For the design of the collectors, is it recommended to assume a uniform axial traction load representing the unit shear load from the diaphragm and the strut itself should be designed as an continuous axial member with elastic reactions representing the wall piers with relative stiffnesses proportional to the wall pier lengths, in addition to the imposed bending actions.

4.4 Conclusions

In this Chapter, six different shear wall configurations were modelled, simulating different diaphragm behaviors from perfectly flexible to perfectly rigid. The results of this study showed that these simplifications are not always conservative. From the presented results it can be concluded that:

To model a structure with a flexible diaphragm it is necessary to include the strut element of the diaphragm to drag the forces over the openings to the wall piers. If this element is not included in the models, the load distribution depends on parameters like the shear wall pier distribution, and wall pier and diaphragm aspect ratios. Differences in load distribution of up to 64% are obtained at the original diaphragm aspect ratio of 1:0.33, and 46% when the aspect ratio is increased to 1:1. This error is only considering the in-plane deflections parallel to the load; when the out-of-plane bending of the supporting walls is included, the error increases further. It was found that the bending effect has a larger effect on the response as the diaphragm aspect ratio is increased.

The structures modelled with a rigid diaphragm considering only in-plane deflections parallel to the load followed the simplification theoretical behavior, distributing the loads according to the shear wall length. However, when the out-of-plane bending response of the supporting shear walls and diaphragm was included, the error in the estimated load path increased to approximately 60%.

Elastic diaphragm analysis showed that for configurations where the exterior walls remained with a constant length while the interior wall length was changing (Configurations 5 and 6), using an envelope design would provide a conservative estimate of the load distribution since the estimated loads were in between the theoretical results for a flexible and rigid diaphragm. However, for configurations where the interior wall remained with a constant length while the exterior wall length was changing (Configurations 1 to 4) the actual loads in the wall lines were non-conservative. The envelope design would be conservative for the exterior wall line but non-conservative for the interior wall line, with the interior wall line being overloaded by as much as 75%. These errors demonstrate that the assumptions of the diaphragm flexibility are not conservative and that the properties of diaphragms should be considered explicitly in the models.

Then, three different shear wall configurations were analyzed using an elastic diaphragm in order to analyze the effect of the strut axial stiffness on the load distribution from the diaphragm itself and within the wall line. Initially, it was shown that the minimum error in the analysis made by assuming a flexible diaphragm for design and using simple tributary area to distribute the loads to the wall lines is 10%.

The error depending on the relative wall pier lengths within the exterior wall line can result in underestimating the magnitude of the load resisted by the interior wall line as high as 58.6% and overestimating the load resisted by the exterior wall line by 58.4%. This results in a condition that almost ensures a failure of the interior wall line if the structure is exposed to the design load.

The effect of the strut element axial stiffness was shown to have an additional effect on the load distribution to the wall line. If the axial stiffness in not at least 20% of the long wall pier lateral stiffness, the load error increases.

The effect of the stiffness of the strut element relative to the longest wall pier in the wall line showed that the assumption that all the wall piers displace the same amount is false. If the strut axial stiffness, which depends on the strut cross-section and length of opening it spans, is at least 80% of the lateral stiffness of the longest wall pier, the error between the assumed distribution of loads in the wall line being proportional to the relative wall pier lengths is acceptable. However, it the strut axial stiffness is less than 80% of the longest wall pier lateral stiffness, the displacements of the short piers can be underestimated by as much as a factor of 3.2.

If the axial stiffness of the strut element is at least 60% of the lateral stiffness of the longest wall pier in the wall line, the load distribution within the wall line stabilizes and approaches that assumed by most designers that the relative load resisted by each wall pier is proportional to the wall pier lateral stiffness. If the axial stiffness of the strut element is less than 60% of the lateral stiffness of the long wall pier, then a more advanced analysis is required to distribute the load within the wall line.

CHAPTER 5 GENERAL CONCLUSIONS AND COMMENTARIES

This document presented the effects of the diaphragm flexibility, relative to the supporting wall lines and the strut axial stiffness relative to the lateral stiffness of the stiffest wall pier on the distribution of the loads within the LFRS composed of diaphragms and shear walls. The inaccuracy of the common assumptions in design was presented, showing that these simplifications can lead to the overload of some elements of the structure, which could lead to a possible failure of the structure if the design loads are imposed.

Historically, research on the LFRS mainly focused on the shear wall behavior and the little investigation in diaphragms has focused only its flexibility, ignoring the effects of the supporting structure or the elements required to transfer the forces from the diaphragm to the supporting shear walls. This has led the design of the systems being governed by assumptions, simplifications and recommendations, which are not necessarily conservative. One of the most common assumption is to assume a rigid or flexible diaphragm response, depending on its material as a simplification for the design process, and the assumption is made thinking that the resulting design will be conservatively over-designed by a slight margin to compensate for the simplification. Furthermore, many design codes actively allow the designer to assume one of the theoretical behaviors depending on the relationship between the relative deflections of the diaphragm and supporting shear walls. However, this limit is not further explained in the codes.

It was demonstrated that using an envelope design methodology can lead to an over-design of some axes while the others are under-designed. This means that the structure could fail under an event that subjects the structure to the actual design loads. Furthermore, it was shown that if the designer wants to model a theoretical diaphragm, which is allowed by the codes, different parameters have to be included. In the case of a flexible diaphragm, if the strut element is not included in the analysis, the tributary area load distribution is not achieved except if the building is composed by diaphragms with high aspect ratios (length/width). However, this is only true when only the in-plane deflection (or parallel to the load deflection) is considered, if the out-of-plane bending of the shear walls and diaphragms is included, then the behavior of the structure moves further away from the theory as the aspect ratio of the diaphragm increases. In the case of a rigid and elastic diaphragms, it was shown that the selected strut frame element did not affect the behavior of the overall structural load path. Rather, the out-of-plane bending of the shell elements (diaphragm and shear walls) influenced the load path the most.

It was also shown that assuming a uniform displacement within a shear wall line composed of unequal length wall piers is highly inaccurate, even when the strut is as stiff as the longest pier, the displacement is uniform only when the piers have the same length. The results showed that if a pier is only 20% shorter than the longest pier, the displacement ratio error already 10% which is not neglectable for stiff materials. Furthermore, the common assumption for design of the strut element is that it is stiff enough to distribute the loads to the piers according to their relative length (stiffness). However, it was shown that this approximation can only be made when the strut stiffness is at least 60% of the longest pier stiffness. The design of the collectors should include the elastic reactions representing the wall piers in addition to the imposed bending actions produced by the diaphragm and gravity loads.

Finally, it is strongly recommended that for the design of the structure, the elastic properties of the diaphragm be included, in order to avoid all the possible inaccuracies that the theoretical assumptions pertaining to diaphragm response can produce. The evolution of the computational technology is making this easier every day and reducing the associated delay time in the design models.

All the analyses were performed for structures with shear walls parallel to the loads, the effect of the perpendicular walls and the associated chord elements should be investigated in the future to fully define the behavior of the complete structure. Also, the accuracy of the displacement ratio between diaphragms and the supporting shear walls given in the codes to allow simplified analysis should be verified for different materials as a future research.

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Appendix 3.1 ANALYZED CONFIGURATIONS

In this section, the six different shear wall configurations are presented in Figures A.3.1 to A.3.6. It should be noted that the diaphragm is not shown in the figures.

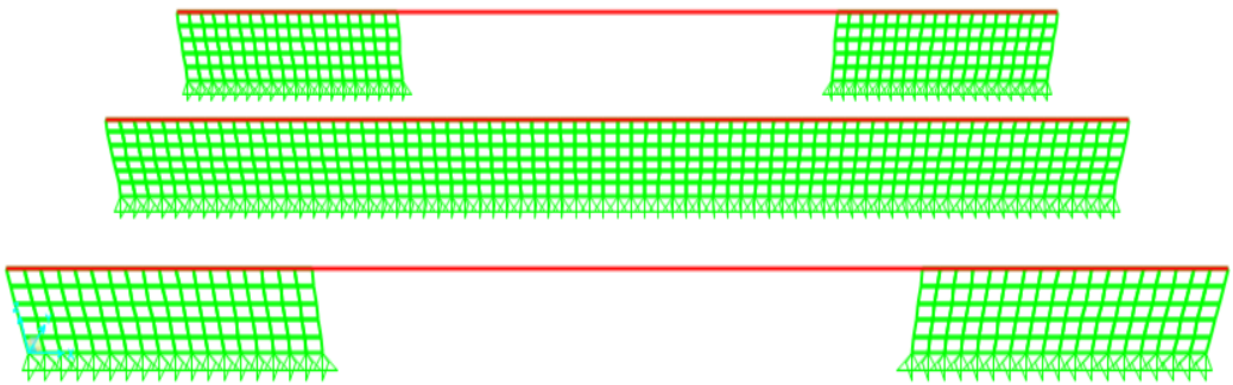

Figure A.3.1: Wall Configuration 1

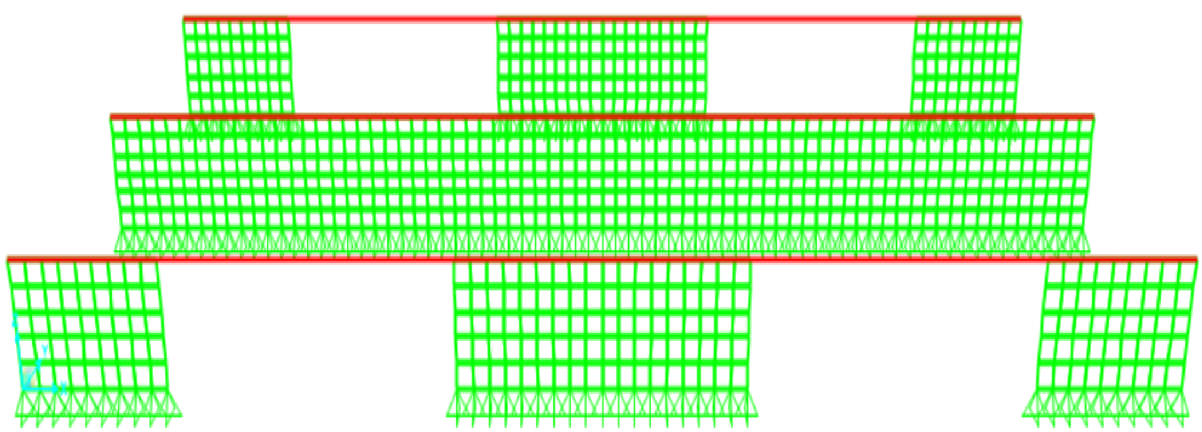

Figure A.3.2: Wall Configuration 2

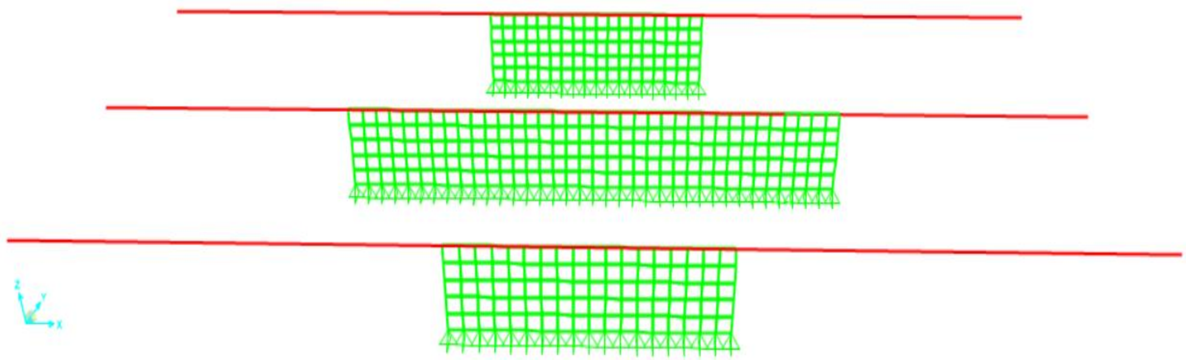

Figure A.3.3: Wall Configuration 3

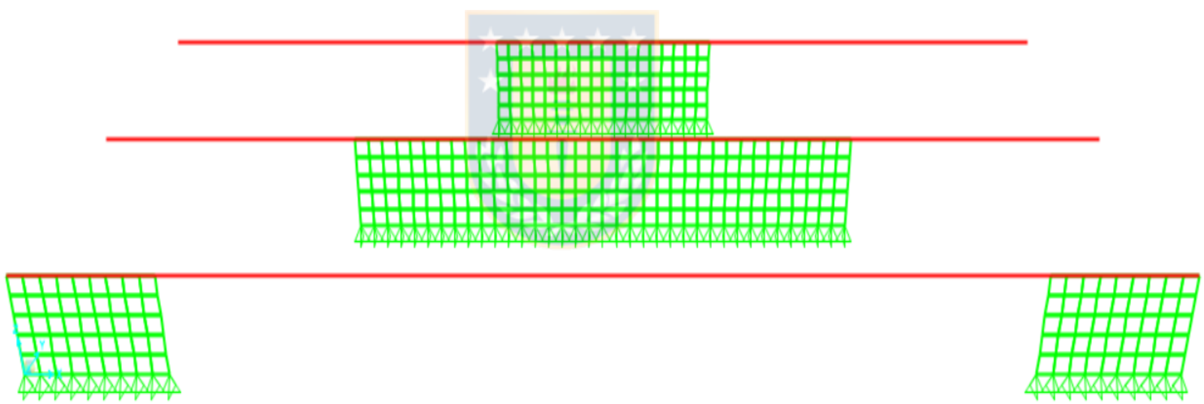

Figure A.3.4: Wall Configuration 4

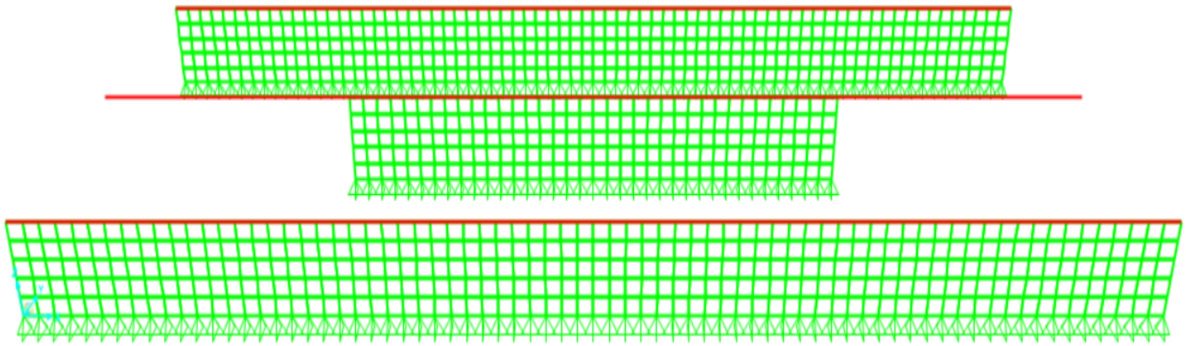

Figure A.3.5: Wall Configuration 5

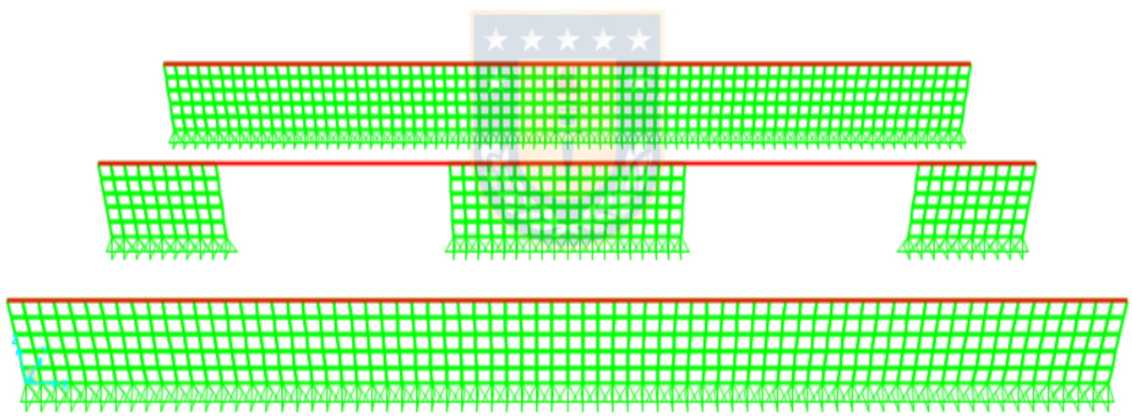

Figure A.3.6: Wall Configuration 6

Appendix 4.1 CHANGE IN THE DIAPHRAGM BEHAVIOR FOR CONFIGURATIONS 3 AND 4

In Chapter 4, the change in the bending stress distribution of the step functions was presented only for Configuration 2. In this chapter, the results for Configurations 3 and 4 are presented from Figures A.4.1 to A.4.3. For Configuration 4, two different plots are presented as the exterior wall lines have different shear wall distributions.

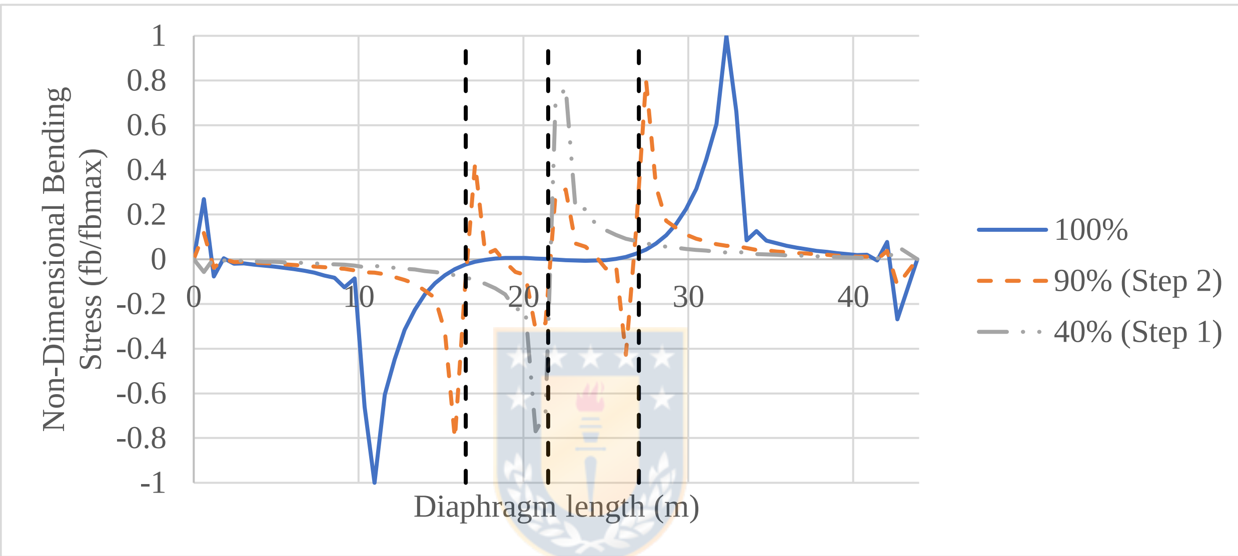

Figure A.4.1: Change in the diaphragm behavior for Configuration 3 and aspect ratio of 1:1

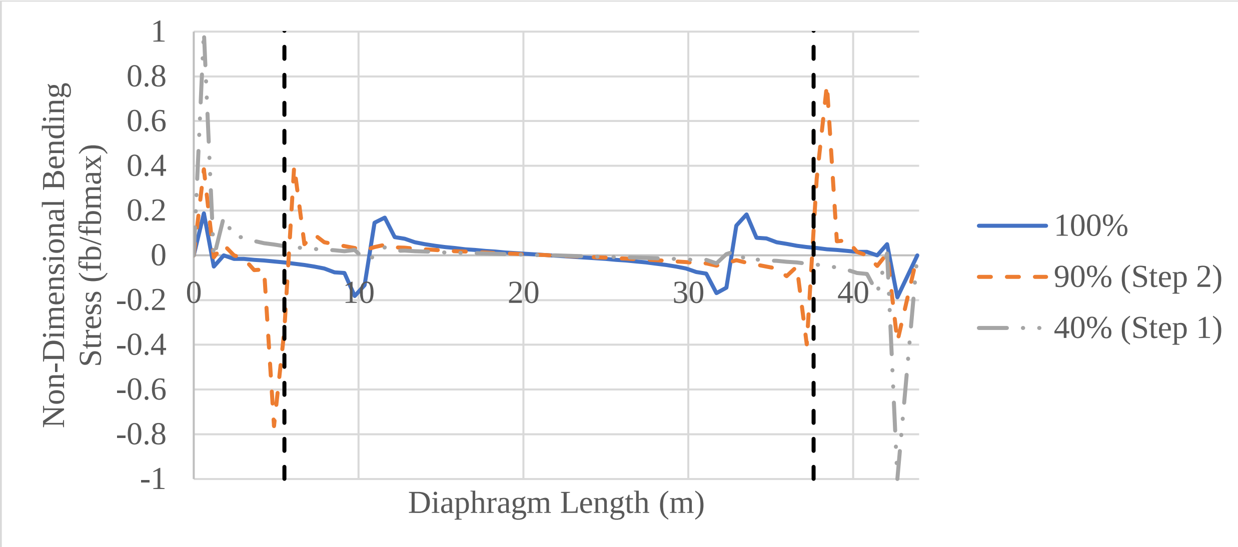

Figure A.4.2: Change in the diaphragm behavior for bottom diaphragm of Configuration 4 and aspect ratio of 1:1

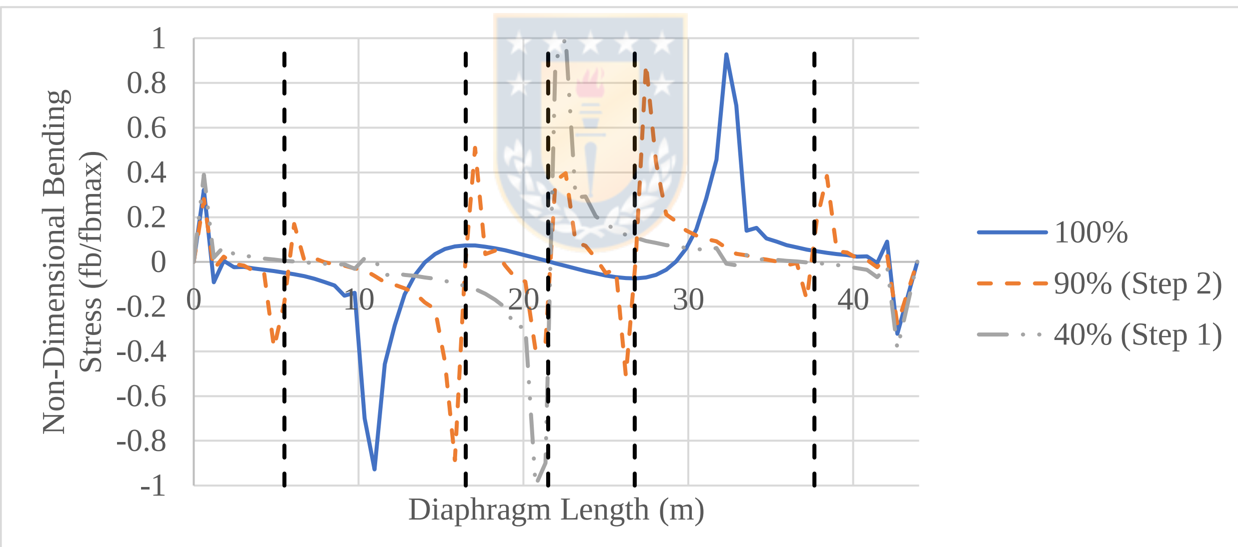

Figure A.4.3: Change in the diaphragm behavior for top diaphragm of Configuration 4 and aspect ratio of 1:1