Optımal shear wall heıght for lateral load resıstance ın wall-frame structures

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Abstract

Concrete shear walls are commonly used due to their advantages in reducing lateral displacement and enhancing seismic performance. These walls are subjected to gravity and lateral loads, as well as overturning moments and shear forces. They have a high stiffness that limits the lateral displacement of the building. The height and location of shear walls play a significant role in controlling the building response, reliability, and overall construction cost. Therefore, these walls need to be optimized. This study uses a continuous model to analyze the optimal height of the shear wall in long-walled frame buildings. The model is based on hyperbolic functions that require high computational accuracy for large values of variables. The optimal height is determined by minimizing the top deflection of the structure and avoiding negative moments and shear forces in the wall. The optimal height is always between the inflection point and the zero-wall cut-off point in the corresponding full-height wall structure. This result facilitates the search for the optimal height of the wall. The optimal height also corresponds to zero shear force at the top of the wall, which is a simpler criterion for finding the height of the shear wall.

Keywords: *Dual structural system, Optimal shear wall height, Continuum model.*

1. Introduction

Tall buildings have become increasingly popular in densely populated cities and have represented the symbol of urban development of nations in many countries of the world; this popularity is mainly due to the rapid growth of economic activities, the great demand for housing, and the limitation of the land. Even with the technological advances developed in computer analysis, such as increasingly powerful computers and sophisticated software packages, high computational and economic costs are required to perform the structural analysis of a tall building. Furthermore, its horizontal stiffness cannot be considered as simply the sum of the individual stiffnesses of the structural elements because its overall stiffness ensures that they work together and develop complex structural interactions. As a consequence, it is of great interest to develop structural analysis methodologies with a global approach where tall buildings can be idealized as a continuous beam and where their rigidities and kinematic fields associated with a continuous beam can represent the structural characteristics and the behavior of tall buildings.

Several researchers have proposed different methods for analyzing the structural behavior of tall buildings composed of shear walls and frames. Khan and Sbarounis [1] used the coupling of a shear beam and a bending beam and solved the interaction between them by a solution in which the shear wall is treated as the primary system and the framework as the secondary system, or vice versa. The deformations resulting from the primary system are imposed on the secondary system. The resistance forces induced in the secondary system are taken as the correction load in the primary system. This process is repeated successively until the convergence of equilibrium and compatibility of the deformations is achieved. Similarly, Glück [2] presented a three-dimensional continuous method for structures consisting of shear walls and frames arranged asymmetrically in the floor plane. He used the continuum approach and the theory of thin-walled sections of Vlasov. Based on the compatibility and equilibrium conditions, he derived a set of coupled differential equations with the translational and rotational displacement functions. However, this analysis did not include the effect of axial deformations of the shear walls and frames. In contrast, Glück and Gellert [3] developed a more complete three-dimensional analysis of a tall asymmetrical building and took into account the influence of axial deformations in them. They derived the second-order inhomogeneous differential equations of the cutting forces in the sheet system. Using the known basic functions, they established all the internal forces and displacements of the individual reinforcing elements. Additionally, Heidebrecht and Stafford [4] represented the shear wall by a bending beam and the frame by a shear beam and connected them by an axially rigid link medium distributed along the height of the building. The columns of the frames were considered axially rigid. From this continuous representation, they proposed the

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solution for the deflections of uniform shear wall structures-frames based on the differential equation that governs the system.
Nollet [5-6] provided a detailed exposition on the behavior of continuous and discontinuous structures, considering the influence of the horizontal interaction between them to stiffen the structure. He developed continuous solutions that allow generalizations about the behavior of a wide range of shear-frame wall structures. For such structures with structural variability in height, he found that the walls can be reduced without significantly modifying the overall horizontal interaction and lateral stiffness. Next, Stafford, Kuster, and Hoenderkamp [7] generalized the half-continuous technique that had previously been applied to coupled shear wall structures so that it could be applied to any type of bending and shear cantilevers. Then, Hoenderkamp [8], extending the continuous solution for asymmetric structures, proposed a generalized solution that included the axial deformations of the shear walls and frames. The coupled torsion-bending differential equations were decoupled using an orthogonal transformation. Finally, Miranda [9] used the continuum model to estimate the maximum lateral displacement demands in tall buildings that respond mainly in a fundamental mode when subjected to seismic movements. This method allows rapid estimation of the maximum displacement and maximum interstory drift for an acceleration history or for a displacement response spectrum. The procedure is based on a simplified model of multi-story buildings that consists of a combination of a bending cantilever beam and a shear cantilever beam. The simplified model is used to investigate the relationship between the spectral displacement, the maximum displacement, and the maximum mezzanine drift ratio to the building drift ratio. However, he neglected axial deformations, which are important to consider in the structural analysis of tall buildings.
The continuum method is a common technique for analyzing the structural behavior of tall buildings composed of shear walls and frames. Many researchers have applied and modified this method to address different aspects of the problem. First, Wang and Liu [10], based on the continuum method and the transfer matrix method, investigated the effect of shear wall height on the dynamic behavior of such systems. They showed that the height of the shear wall does not influence the dynamic behavior, except in very special cases and that it is not necessary to extend the shear wall over the entire height of the building. Next, Takabatake and Satoh [11] proposed an analytical method that replaces the building with a continuous equivalent rod for the dynamic analysis of high-rise buildings consisting of doubly symmetrical frame tubes with or without bracing. The solution of the differential equations was solved by the finite difference method; the suitability of the method was verified with four different types of buildings analyzed with the finite element method. Moreover, the effect of soil-structure interaction is discussed using the proposed method. Then, Espezúa [12] used a similar method based on the continuum technique to study the static and dynamic behavior of tall buildings against earthquakes. The approximation of the method was compared with the results of a finite element analysis with the SAP 2000 program, obtaining values with an acceptable approximation for engineering terms. Similarly, Jigorel [13] developed different continuous models using the discrete periodic media homogenization method to represent the dynamic behavior of buildings. He highlighted a new generic equation from which the other particular behaviors are derived, finding a new parameter that measures the influence of the local shear stiffness of the shear walls. In addition, Cammarano [14] proposed a synthetic three-dimensional approach based on the continuum method and Vlasov's theory of sectoral areas. This approximate approach is adaptable to static and dynamic analysis of tall buildings uniform or stepped in building height. Additionally, he conducted an experimental test to measure the effect of thin-walled beams subjected to torsion. Furthermore, Moghadasi [15] proposed two replacement beams based on the continuum method for the structural analysis of tall buildings. The first beam consists of the parallel coupling of two Timoshenko beams and takes into account the four characteristic rigidities of a tall building, and is applicable to all structural systems. The second beam consists of the parallel coupling of an tensile Timoshenko beam and a continuous core as a supporting rotational constraint. Due to the complexity of coupled differential equations, he developed a one-dimensional finite element formulation evaluating static and dynamic responses. He also used a discrete system of coupled shear walls to theoretically establish distributed internal viscous damping of the Kelvin-Voigt type with bending and shear mechanisms. Moreover, Lavan and Abecassis [16] studied the seismic behavior of a continuous shear wall - frame system in the context of the rehabilitation of existing frame structures. They first identified the non-dimensional control parameters of such systems. This is followed by a rigorous and extensive parametric study that reveals the pros and cons of the new system versus shear wall - frame systems. The effects of the control parameters on the behavior of the new system are analyzed and discussed. Finally, Zalka [17], based on the continuum approach, developed closed-form equations for two categories of analysis: a) An individual analysis and b) A three-dimensional analysis (global approach), where he developed closed-form equations for displacements presenting two methodologies: the

simple method and the precise method (using the interaction between bending and shear deformations), stability, frequency and critical load of entire buildings. He also introduced the global critical load ratio which acts as a generic characteristic with which the designer can monitor the overall performance of the entire building. Similarly, Gungor and Bozdogan [18], using the continuum method and the differential transformation method, adapted a Timoshenko-type replacement beam for the dynamic analysis of steel plate shear wall systems. They also performed a response spectrum analysis, finding the displacement, shear force and bending moments.

2. Continum Method for wall-frame structures

One of the structural systems used for tall buildings is the wall-frame system, which has some advantages and disadvantages. Wall-frame structures consist of a combination of shear walls and moment-resisting frames, which act jointly in resisting both gravity and horizontal loading. However, it is common in high-rise buildings to reduce in size and number, or to eliminate, the shear walls in the upper part of the building are required. This may affect the lateral stiffness and stability of the structure, especially under seismic or wind loads. Therefore, the design of wall-frame systems requires careful consideration of the interaction and distribution of forces between the walls and the frames (Figure 1).

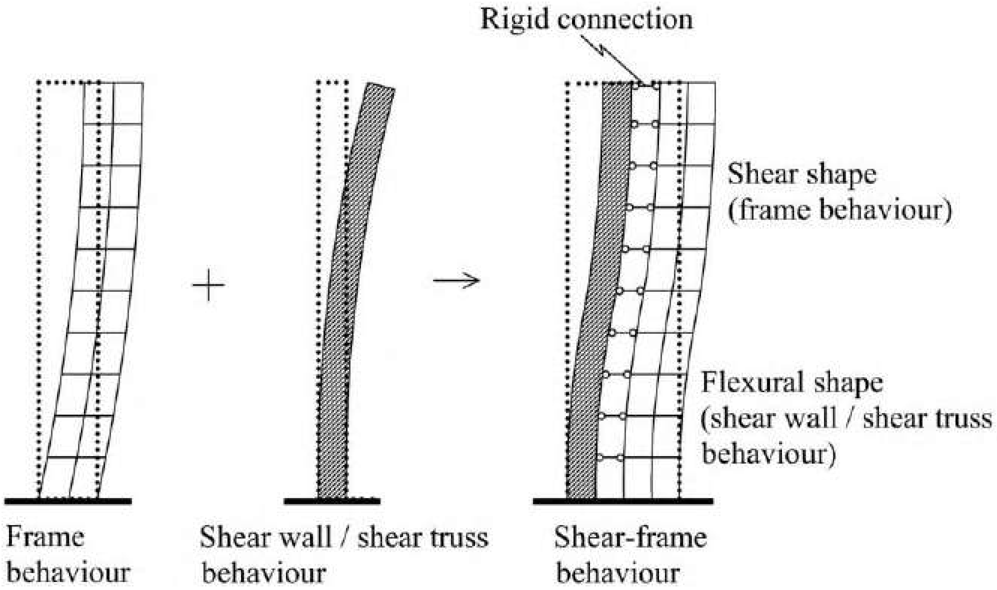

Figure 1. The Behavior of the wall-frame structures [14].

Using the continuum model and considering the axial deformation in the columns, Nollet and Smith [6] developed a generalized theory for the deflection of a curtailed wall-frame structure. The theory is that a curtailed wall-frame structure of total height H, subjected to a uniformly distributed horizontal load w is considered as a superposition of two substructures:

- The lower part (substructure I), is a wall-frame structure of height H_I
- The upper part (substructure II), is a moment-resisting frame of height H_{II}

Considering zero displacement/rotation boundary condition at the base, the top deflection of the substructure can be calculatted. To determine the optimum level of shear wall corresponding to the minimum top deflection, the aforementioned expression should be minimized. Therefore, its minimum corresponds to a first derivative equal zero.

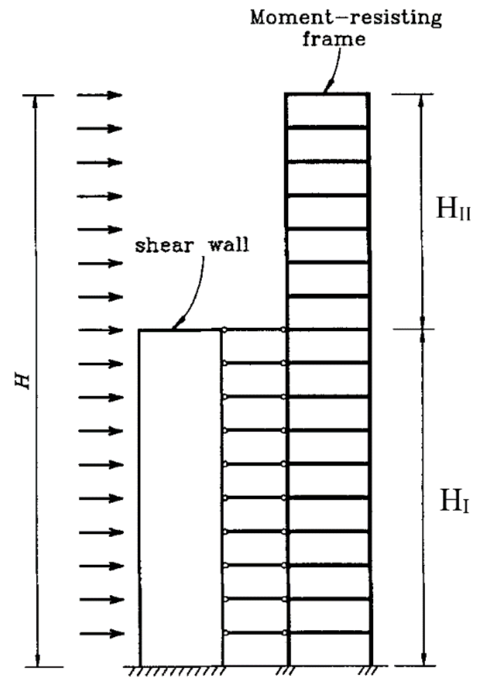

Figure 2. The Modaling of the wall-frame structures in proposed method.

On the other hand, Genetic algorithm is a heuristically probing algorithm famous in the evolutionary subjects of natural election. Genetic algorithm (GA) is a smart way to explore a specific search area and find solutions to problems. This algorithm uses a population of individuals that undergo mutation and crossover, which are factors that promote diversity. To evaluate individuals and ensure that the best ones survive, a fitness function is used to measure their reproductive success. Also for this algorithm, to check these parameters, we considered the sets for each parameter to obtain the most optimal possible state of each parameter so that for finding the optimal value of each parameter, other parameters were fixed. Fig. 3 depicts the location of optimum level for curtailment. The optimum level of curtailment always lies between the point of inflection and zero wall shear in the corresponding full-height wall structure.

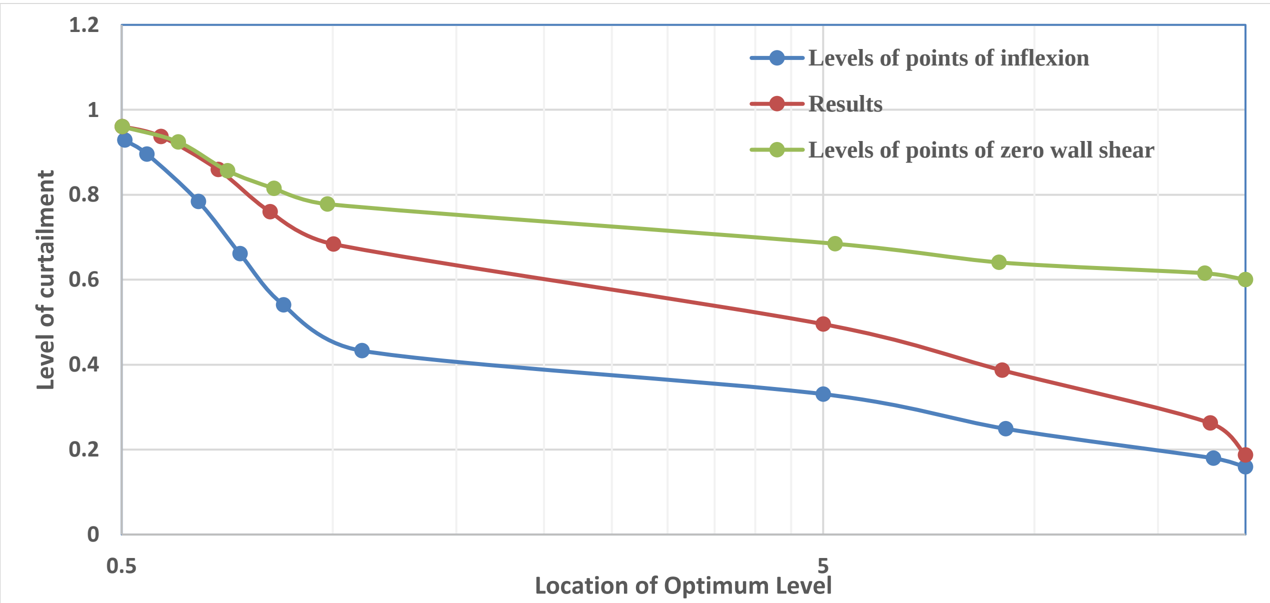

Figure 3. The Location of optimum level for curtailment.

3. Conclusion

The shear walls are commonly used due to their advantages in reducing lateral displacement and enhancing seismic performance. They have a high stiffness that limits the lateral displacement of the building. The height and location of shear walls play a significant role in controlling the building response, reliability, and overall construction cost. Therefore, these walls need to be optimized. This paper presents the optimum level of wall curtailment in wall-frame structures using the continuum model. The paper included a thorough analysis of the model, which is a simple and efficient tool but should be used carefully. It is highly sensitive to the calculation precision, because of the use of hyperbolic functions that need high calculation precision for high values of the variables. The results show that the method is very useful in the search for the optimum level of curtailment. Moreover, the method results in the minimum top deflection of the structure and eliminates, at the same time, the negative moments and negative shear forces in the wall.

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