Investigation of the Dynamic Behavior of Coupled Shear Wall Systems

Hamdy El-Gohary

College of Engineering, Umm Al-Qura University, Makkah, Saudi Arabia

gohary_h@yahoo.com

And

Ayed Eid Alluqmani**

Faculty of Engineering, Islamic University of Madinah, Madinah, Saudi Arabia

dr.ayed@iu.edu.sa**;** eng.ayed@hotmail.com

**** Corresponding Author**

Abstract: Coupled shear walls are vertical shear walls or elevator cores with openings connected together by beams or slabs. In the present work, the behavior of the reinforced concrete coupled elevator cores of multistory building has been investigated under the seismic loads. The system consists of two U-shaped in the plan monolithic walls, connected at slab levels by beams. Seismic loads were determined according to the International Building Code, IBC-2015. The elastic analysis of the models, was carried out using finite element method (FEM) and the results were compared with the results obtained using the closed form solution (analytical method). Results show that the rigidity of coupling beams has significant effect on the dynamic behavior of the coupled wall system. The presence of connecting beams and the increase of their rigidity resulted in valuable decrease in the period of vibration and deformations of the coupled wall system in all models. Shear stresses in the cross sections of the connecting beams were calculated in accordance to the American ACI Code and Eurocode. It was observed that in some beams it is possible to use only the minimum required reinforcements, whereas in the majority of the cases, designed shear reinforcement must be provided for the connecting beams.

Keywords: Coupled Shear Walls; Dynamic Behavior; Lateral Loads; Elevator Cores, Finite Element Method; Analytical Method; Shear Stresses.

التحري في السلوك الديناميكي لأنظمة جدران القص المزدوجة

الملخص: جدران القص المزدوجة هي جدران قص عمودية أو نوى المصاعد مع فتحات متصلة فيما بينها بواسطة أعمدة أو بلاطات. في العمل الحالي، تمت دراسة سلوك نوى المصاعد المزدوجة من الخرسانة المسلحة في عمائر من عدة طوابق تحت الأحمال الزلزالية. يتكون النظام من جدارين متجانسين بشكل (و) في المخطط متصلين على مستوى البلاطات بواسطة أعمدة. تم تحديد الأحمال الزلزالية وفقا لمعايير البناء العالمي (إ. ب. س) 2015. تم إجراء التحليل المرن للنماذج باستخدام طريقة العناصر النهائية (ف. إ. م) وتمت مقارنة النتائج بالنتائج المتحصل عليها بمساعدة الحل ذو الشكل المغلق (الطريقة التحليلية). توضح النتائج أن صلابة أعمدة الربط المزدوجة لها تأثير كبير على السلوك الديناميكي لنظام الجدران المزدوجة. أسفر وجود أعمدة الربط وزيادة صلابتها عن انخفاض معتبر في مدة اهتزاز وتشوهات نظام الجدران المزدوجة في جميع النماذج. تم حساب ضغوط القص في المقاطع العرضية لأعمدة الربط وفقا للمعيار الأمريكي والمعيار الأوروبي. لوحظ أنه في بعض الأعمدة من غير الممكن الإكتفاء بإستخدام الحد الأدنى من التسليح المطلوب، في حين أنه في معظم الحالات، فإن التسليحات المقصية يجب توفيرها لأعمدة الربط.

1. Introduction:

The special feature of the systems in question is the substantial difference between the flexural rigidity of each separate wall and entire system as a whole. In this case, this difference significantly depends on the degree of fixing the beams, which connects the walls. For the case of hinged connection of beams to the mating walls, the flexural rigidity of entire system is equal to the sum of the flexural rigidities of all walls, which forms the system. In the hinged connected beams, the shear does not appear in this case, but they only redistribute the general horizontal loads on the system between its vertical elements proportional to their rigidity.

In the case of rigid connection for beams with the walls, beams contribute to the system by resisting shear forces, which is generated between the coupled walls, and the entire system is deformed as a frame.

Investigation of dynamic behavior of the coupled shear wall system is the focus of interest of many researchers at the present time [1, 2, and 3]

In the present paper the effect of the connecting beam rigidity on the dynamic behavior of the coupled shear wall system under seismic loads was investigated.

2. Structural Action of Coupled Shear Wall System

2.1 Coupled Shear Wall:

The ratio of the sum of the flexural rigidities of the separate walls of composite system to the horizontal rigidity, which substitutes the composite system of frame, is called the degree of the coupling of walls or the degree of fixing the beams to walls.

The degree of the coupling of walls can be defined just as the ratio of the moment of internal forces in the walls to the moment of the external action:

$$C = \frac{P \cdot L_w}{M} \qquad (1)$$

Where,

$M = \sum F_i \cdot h_i$

F_i = Value of the concentrated load on system at the level “i”,

L_w = Distance between centers of gravity of the sections of walls,

h_i = Distance from the base to the level “i”, and

P = Axial force in the walls.

The value of pair of internal axial forces in the walls depends on the shear, resisted by the connecting beams. Therefore, the beams which connect the walls substantially influence the systemic reaction of the system, and this influence increases with the increase of the stiffness of the connecting beams. At the same time, in the case of flexible beam connection, the behavior of the system approaches the behavior of separate free walls. Short-span beam connection is more effective, since this increases the shear capacity of the beams. It is considered that in the flexible concrete plates, the steep gradient of the diagram of the bending moments takes place.

In some works, the behavior of systems, which consist of the coupled shear walls, was investigated analytically and numerically [4, 5, and 6]. On the basis of these studies, the conclusion is that the displacements of the connecting beams obtained analytically are frequently more than those ones measured experimentally for the same beams. It was also noted, that in practice, rigidity of connecting beams frequently exceeds required values compared to the design [7, 8, and 9]. Studies show clear contrary [10, and 11].

The high degree of coupling in the majority of the practical cases causes bending at the supporting zones of the beams. It was found that one characteristic of the degree of coupling does not always satisfy the requirements of the parameter for predicting the spectrum of reactions or determination of the expected behavior of coupled walls [8]. The additional parameters of the rotation at the top of walls, flexibility or relative rigidity of walls and beams, are required for the accurate estimation of the reaction of the coupled shear walls.

The investigations of the enumerated parameters include:

1. Evaluating of the role of the critical geometric parameters in the determining characteristics of the coupled shear walls, with the focusing of attention to the requirements of the arrangement of connecting beams;

2. Determining the collection of the characteristic prototypes of constructions for further nonlinear analysis;

3. Determining the additional parameters, which are effectively shown in the coupled structural systems.

The purpose of this study consisted of the development of the parameters, which allows to accurately estimation the initial data, the global behavior of the composite systems, the local behavior of coupling beams and the relation between the global and local behavior.

3. Parametric Study:

Aim is to investigate the effect of the enumerated parameters, a core in the form of two monolithic reinforced concrete walls of u-shape, coupled by beams at the opening portion in the lateral wings of walls. Both walls have identical shape and dimensions in the plan and thickness of 400 mm throughout the entire height of the building. The height of floors is considered constant and equals 3.0 m. The coupling beams, in all models, have a span of 1.0 m, a width of 0.40 m and thickness of 0.5, 0.6, 0.7, 0.8, 0.9 and 1.0 m. A row of models of these coupled shear wall systems with number of stories of 10, 15, 20 and 25 is examined. It is considered that because of the symmetry of the models, torsional moment will not take place. Figure 1 shows coupled shear walls model. Shear walls are considered fixed at base and modeled using shell elements with mesh 1.0 x 1.0 m. The coupling beams are modeled as frame elements.

The weight of the structures at each floor is taken as 15000 KN. The compressive strength of concrete was considered equal to 30 MPa and the concrete modulus of elasticity (E_c) was assumed to be 26000 MPa.

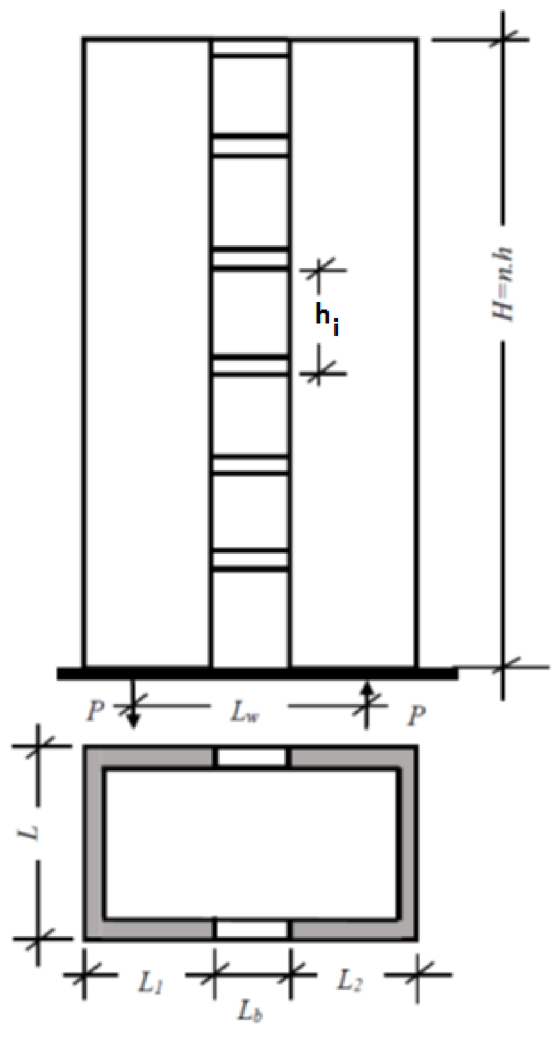

Figure 1. Coupled Shear Walls Model

4. Analysis of Models:

The elastic analysis of the models was carried out by FEM and is compared with the calculation by closed form solution (analytical method) [5]. The analytical calculations of continuous systems give the final form of formula for calculating internal forces and displacements. Horizontal seismic load acting on the models is considered in accordance with the IBC [8].

The used values of the period of vibration were determined by the FEM using SAP2000 [12]. All internal forces, reactions and lateral displacements of the models have been determined from SAP2000 models as well.

For the analysis of the behavior of systems, the parameters α, k and H, were used [9, 10 and 11]:

$$\alpha = \sqrt{\frac{12 I_c L_w^2}{L_b^3 \cdot h \cdot I}} \qquad (2)$$

$$K = \sqrt{1 + \frac{(A_1 + A_2) \cdot I}{A_1 \cdot A_2 \cdot L_w^2}} \qquad (3)$$

$$I_c = \frac{I_b}{1 + \frac{12 E I_b}{L_b^2 G A_b} \times 1.2} \qquad (4)$$

Where α and k are analytical parameters which are constant;

I_b = Moment of inertia of the connecting beams;

I_c = Moment of inertia of the walls sections, equal to I_1+I_2;

A_1 and A_2 = Cross-sectional areas of the walls.

The parameter 'α' depends on the relation of the rigidity of connecting beams and walls. Low value of α indicates a relative flexibility of the connecting beams of system. In this case, the general behavior of the system of walls will be characterized in essence by the bend of each wall. Higher value of α leads to larger interaction of the walls with each other.

The parameter 'K' characterizes the relation of the bending of the walls of system. This parameter has the lower limit, equal to 1, and it varies in this study from approximately up to 1.2. This parameter usually has a value, which is equal to 1.1, in real structures.

The parameter (degree of coupling) D is defined as:

$$D = K \cdot \alpha \cdot H = \sqrt{\left(1 + \frac{(A_1 + A_2) \cdot I}{A_1 \cdot A_2 \cdot L_w^2}\right) \cdot \frac{12 \cdot I_c \cdot L_w^2}{L_b^3 \cdot h \cdot I} \cdot H^2} \quad (5)$$

Where, H is the total height of the structure.

The parameter 'D' can be interpreted as a criterion for the stiffness of connecting beams, which is substantially depending on their lengths. If the connecting beams have zero rigidity (D = 0), then external moment bends only walls. In this case, the construction behaves as a pair of walls, connected by beams with hinged ends. If the connecting beams are absolutely rigid (D = ∞), then the behavior of the system approaches a bend of the simple cantilever, fixed at base. Figure 2 shows the increase of degree of coupling with the increase of connecting beam height.

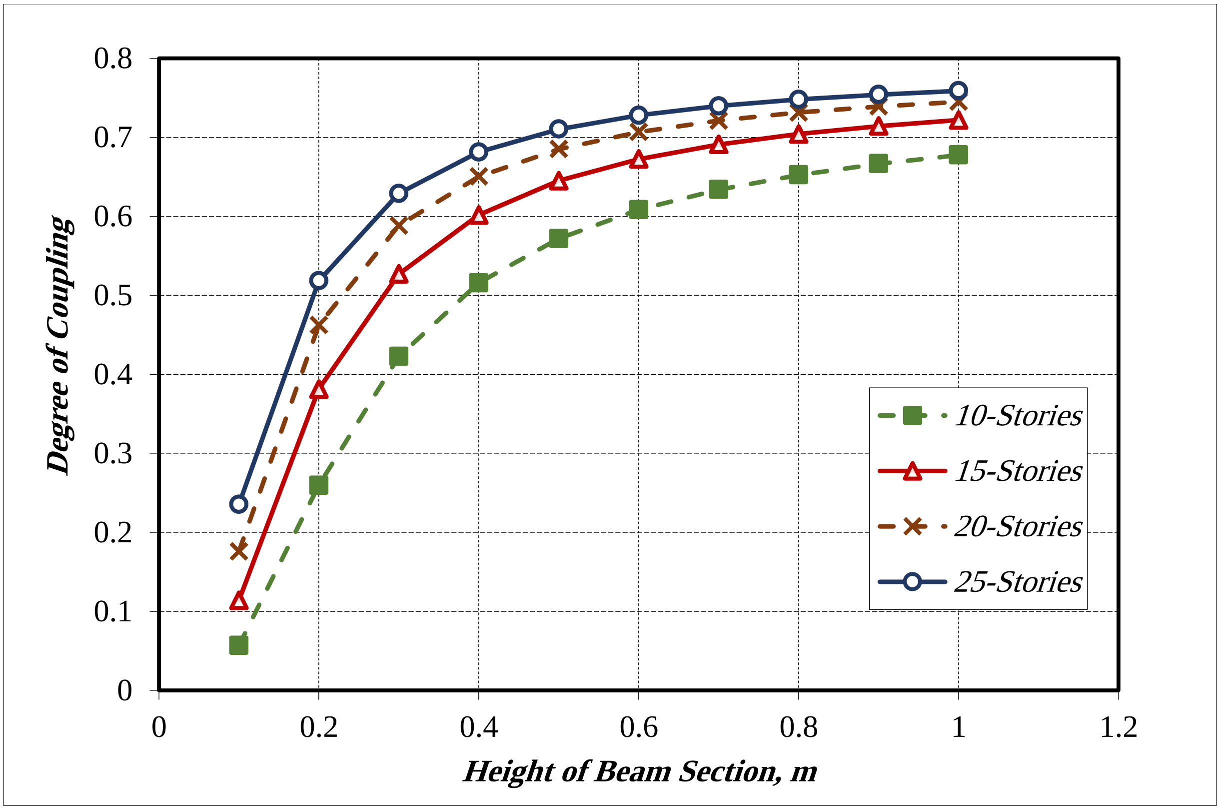

Figure 2. Relation between Degree of Coupling and Height of Connecting Beam

It is obtained that, with an increase in the thickness of the connecting beams (a measure of rigidity), the degree of the coupling "C" increases up to 0.45 in the case of 5-story model and to 0.73 for the 25-story model with the section thickness of 0.6 m as shown later in Figure 5. The increase in connecting beam thickness of more than 0.6 m has small influence on the degree of the coupling "C".

It is acceptable that for $D < 1$, the structure is considered to have negligible influence on the connecting beams and it will behave as a system of coupled shear walls with hinged connecting beams ($C < 20\%$). With an increase in D up to 8, the connecting beams are considered rigid, and the system responds to domination of one of the walls in accordance with the coefficient ‘k’.

The advantage of the coupled shear walls is mainly in the fact that in such systems, a decrease of the period of vibration takes place and it is possible to optimize the horizontal displacements of the system.

5. Discussion of Results:

Figure 3 shows the effect of connecting beam rigidity on the fundamental period of vibration of the considered models. It can be observed that, the period of vibration decreases in comparison with case of coupled shear walls connected by hinged beams. This decrease approximately reaches 50% in the case of 10-story model, while it is 60% for the case of 25-story model. The effect of connecting beams rigidity on the fundamental period of vibration of the system increases with the increase of system height.

The relation between top displacement of the coupled shear wall models and the connecting beam rigidity (as indicated by beam section height) is shown in Figure 4. It can be noticed that the top displacement drops more than 50% for the cases of models height 10-stories and more, once the beam thickness is 0.2 m. In most cases the lateral displacement dropped by 70 % from the case of hinged connection. The presence of connecting beams has significant effect on the system lateral rigidity.

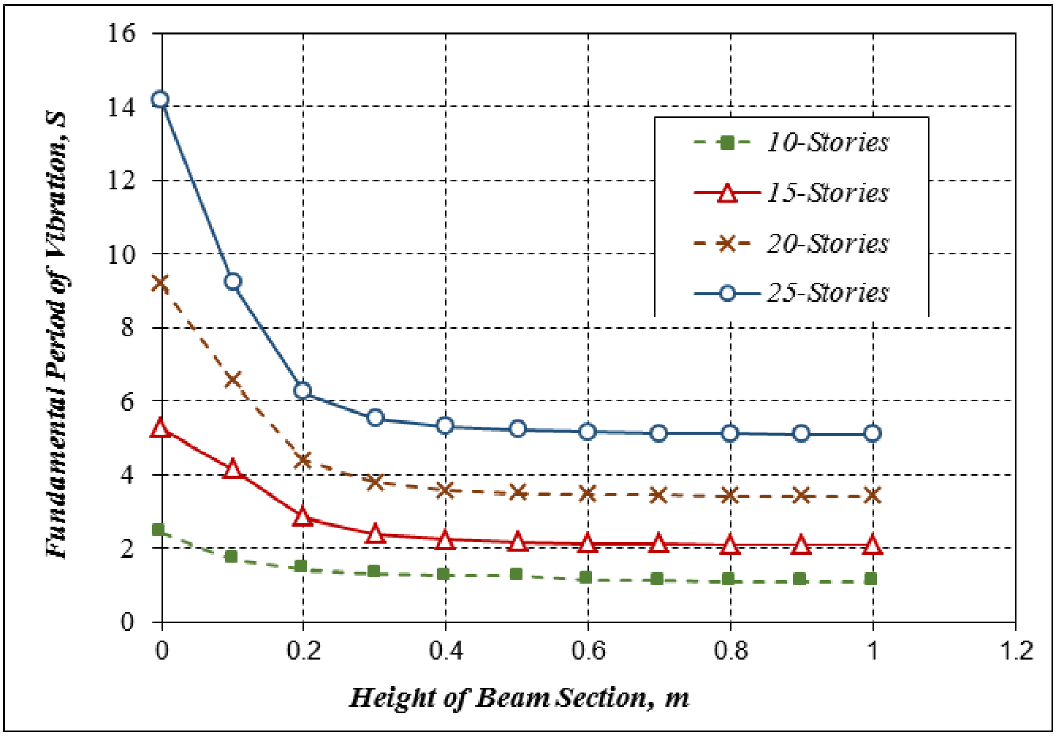

Figure 3. Fundamental Period-Beam Height Relationship

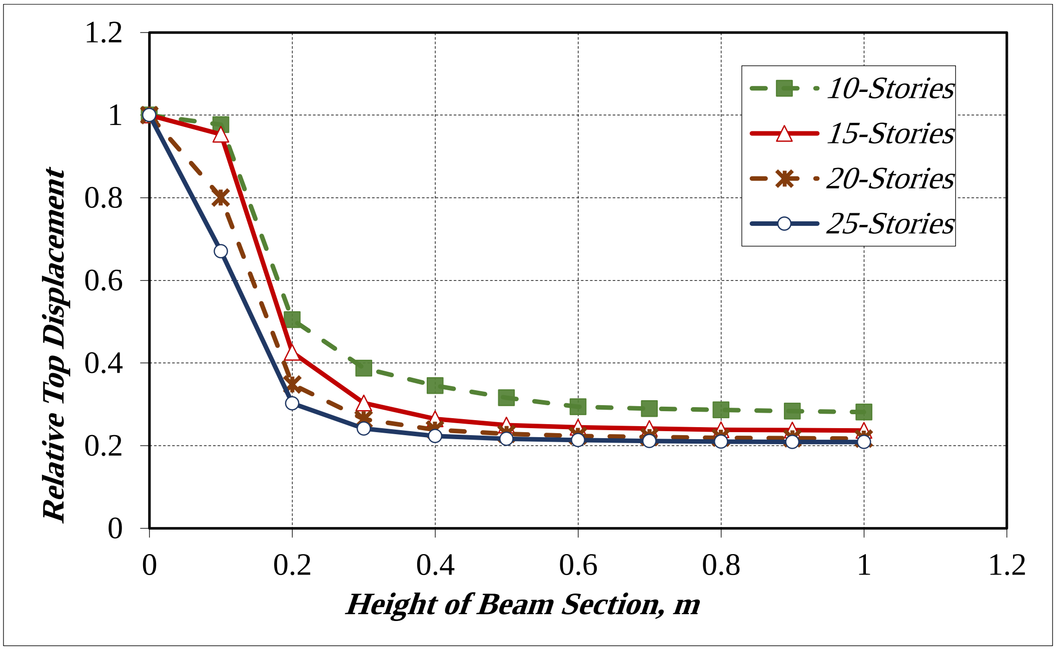

Figure 4. Relative Top Displacement-Connecting Beam Rigidity Relationship

Shear stresses in the cross sections of the connecting beams were calculated and compared with the limiting values of the following Codes: Egyptian Concrete Code (ECC-203), Eurocode for concrete structures (EC-2), American Concrete Institute (ACI-318-14), and Saudi Building Code for reinforced concrete structures (SBC-304) [4, 13, 14, 15 & 16]. The shear design provisions in ACI and SBC-304 are the same, which is the same case for ECC-203 and EC-2. It is clear that in some beams it is possible to use only the minimum required reinforcements, whereas in the majority of the cases designed shear reinforcement must be provided for the connecting beams (Figure 5).

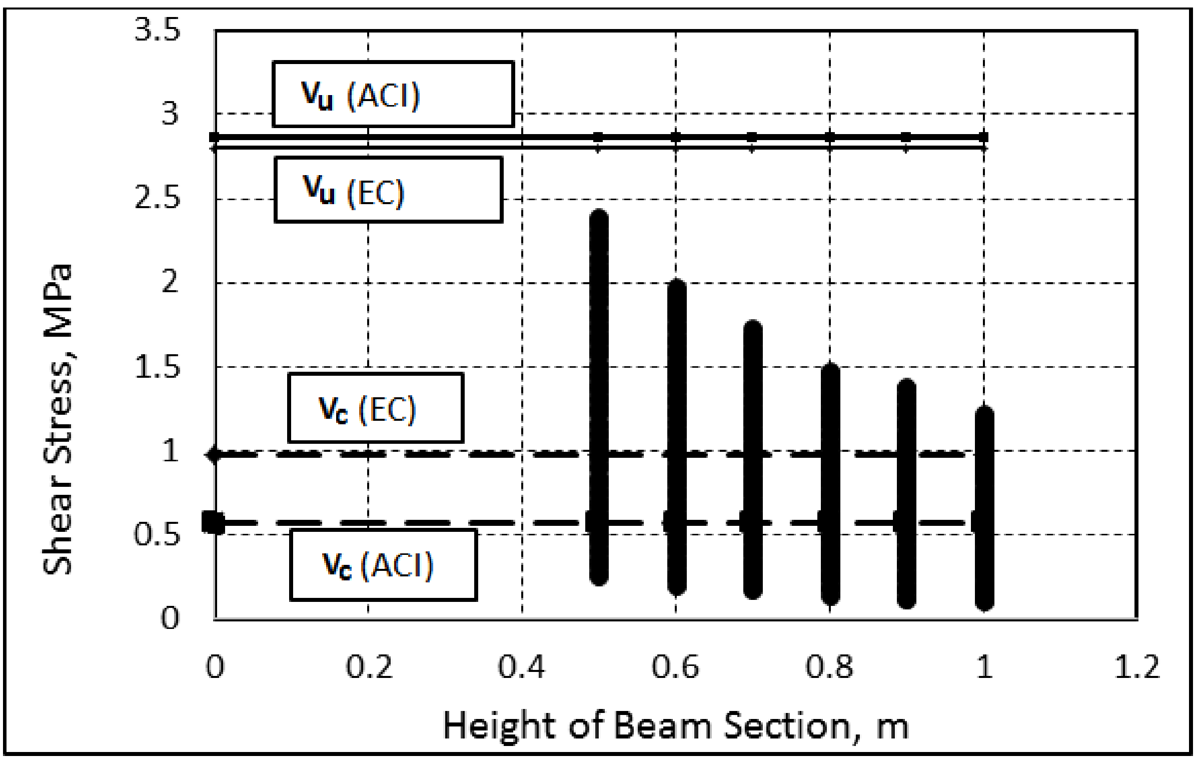

Figure 5. Shear Stresses in Connecting Beams and Codes' Limits

Figure 6 shows the distribution of shear forces in the connecting beams along the height of all models for the case of beams section thickness 0.7 m. Maximum shear force generated in connecting beams at 0.2 to 0.4 of the model height from base. Connecting beams at levels from 0.2 to 0.6 of the total height, carry more than 80% of total shear forces generated in all connecting beams. With the increase of the height of the model, shear forces in the beams of the lower stories increase and they decrease for the upper stories. This is due to the decrease in shear deformations with the increase of the building height.

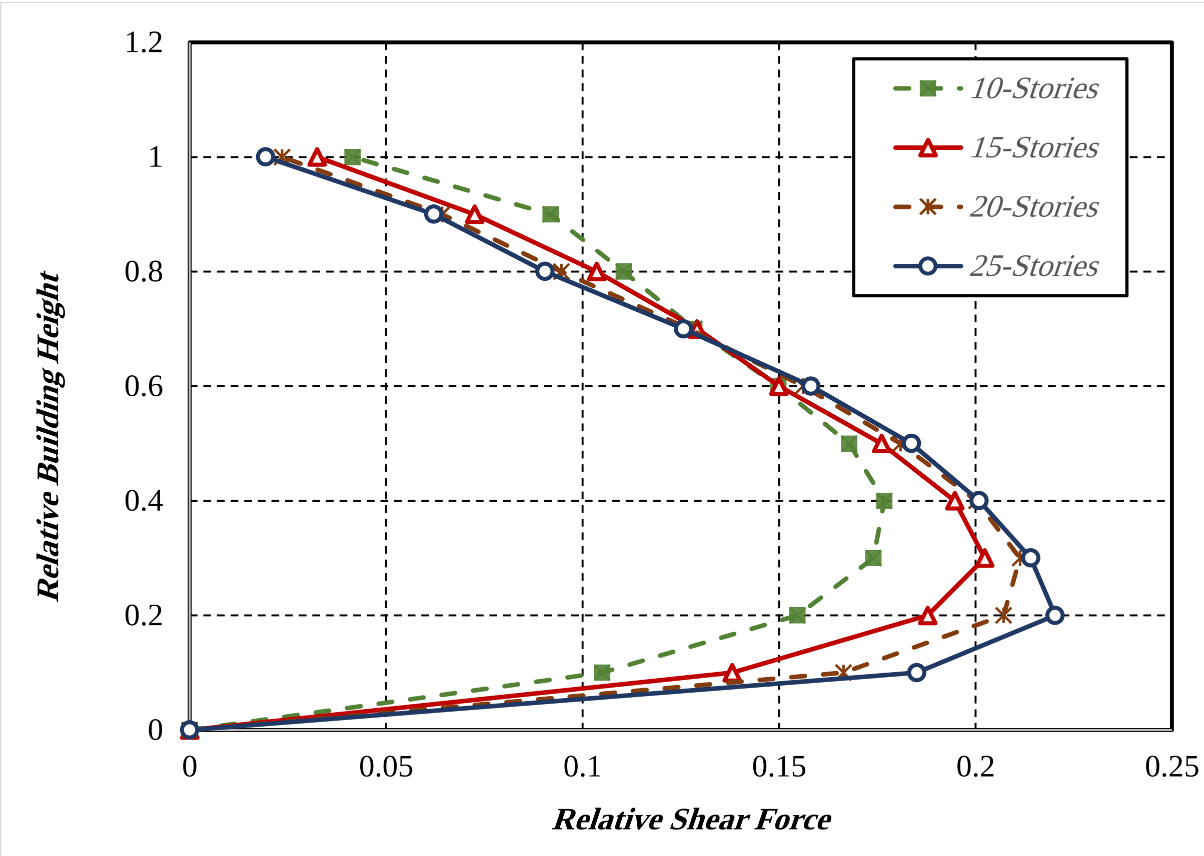

Figure 6: Distribution of Shear Forces in Connecting Beams

6. Conclusion

Dynamic behavior of coupled shear wall system has been investigated under seismic loads. The analysis shows that the connecting beam rigidity has great influence on the coupled wall system behavior. The dynamic properties of the system (period of vibration and top displacements) decrease significantly with the increase of the connecting beam rigidity. The shear stresses in connecting beams in all investigated models are within the current Codes' limits. The maximum shear forces generated in connecting beams are located at 0.2 to 0.6 of the coupled wall system height. The design of connecting beams at these levels need more attention.

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