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An Investigation on the Torsional Effect of Symmetric Moment Resisting Frame System Subjected To Eccentric Reinforced Concrete Lift Wall - A Finite Element Approach

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***Abstract** : The regular building structure consists of eccentric or unsymmetrical reinforced concrete lift walls made of shear walls leads to irregular Building in the plan due to uneven distribution of stiffness. Under the circumstance of such buildings located in the high seismic zone, the design engineer's responsibility becomes more challenging. Hence, the designer must understand the seismic response of irregular structures clearly. This research presents a comparative investigation on the lift wall structure located at the concentric and eccentric position, and it is subjected to lateral seismic load according to the Ethiopian building code. Here, a ground plus ten stories residential building is considered for the investigation, and linear static analysis is performed using the finite element method. In a nutshell, the eccentric lift wall is subjected to additional translation bending and rotational bending that produces an induced story deflection, leading to additional material requirement and is expensive compared to the concentric lift wall.*

Keywords — *Irregularity, seismic response, torsion, uneven distribution of stiffness, lift wall, and shear wall:*

I. INTRODUCTION

Buildings are primarily divided into two types: regular and irregular. Asymmetric-plan buildings, structures with asymmetric mass and strength distributions within them, are seismic systems that exhibit a coupled torsional - translational seismic response. Due to the variety of functional and architectural requirements in modern construction, asymmetrical building structures are almost unavoidable. Even in symmetric structures, the asymmetric arrangement of structural components (asymmetric mass and stiffness distributions) results in an effective asymmetric structure. Even a small amount of asymmetry can cause a torsional response in addition to a translational response [1, 2].

Observations of structures subjected to strong Earthquakes revealed that an excessive torsional response is a significant factor in causing severe damage to the structures, including collapse. Structural asymmetries frequently cause excessive torsional response codified, in most international standards, by a structural classification that distinguishes regular and irregular structures, compelling the designer to employ distinct structural analysis methods [3, 4].

This investigation focus on the typical structure consists of eccentric or unsymmetrical lift wall. These lift walls are made of the reinforced concrete shear wall, leading the system into the irregular structure in the plan due to the eccentric lift wall [5]. This is due to the enhanced strength and stiffness around the lift wall location. When such buildings are situated in a high seismic zone, the designer's responsibility is more challenging and critical against the seismic load design due to additional translation bending and rotational bending. Furthermore, To perform this research, a comparative investigation is conducted on the reinforced concrete lift wall structure whose length to width ratio is equal to 0.5 located at the concentric and eccentric position. It is subjected to lateral seismic load according to the Ethiopian building code. The difference between structural responses of both the cases of structural systems is carefully studied, and the effect of the elastic curve of the structure is also studied and compared. In addition, materials requirements of eccentric lift walls are estimated and compared with concentric lift walls. Here, a ground plus ten-story residential Building is considered for the investigation, and linear static analysis is performed using the finite element method [6, 7].

II. STRUCTURAL MODELING

A. Structural Arrangement

This study considers two structural layouts: case 1 represents the lift wall positioned symmetric/concentric about both horizontal axes, and case 2 deals with asymmetric/eccentric conditions as represented in figure 1. To perform the torsion analysis, a residential building structural layout consisting of ground plus ten stories considered with the measurements of 38.5m as the total structural height, 30m, and 16m as length and width, and approximately 0.5 as length to width ratio. Each floor measures a height of 3.5m, 2.5m foundation depth, and the floor layout follows a uniform pattern for the entire floor. Moreover, the linear static analysis is performed for both

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structural cases. The interior beams of each floor carry a 100mm thick partitioned wall whose calculated self-weight is 3.5kN/m, including plastering. Similarly, the exterior partitioned wall with a thickness of 200mm rests on the exterior beams of each floor, measuring 9.8kN/m as self-weight, including plastering. The exterior beams associated with the roof floor carry a parapet wall of 100mm thickness, 1m height, and measure 1kN/m self-weight.

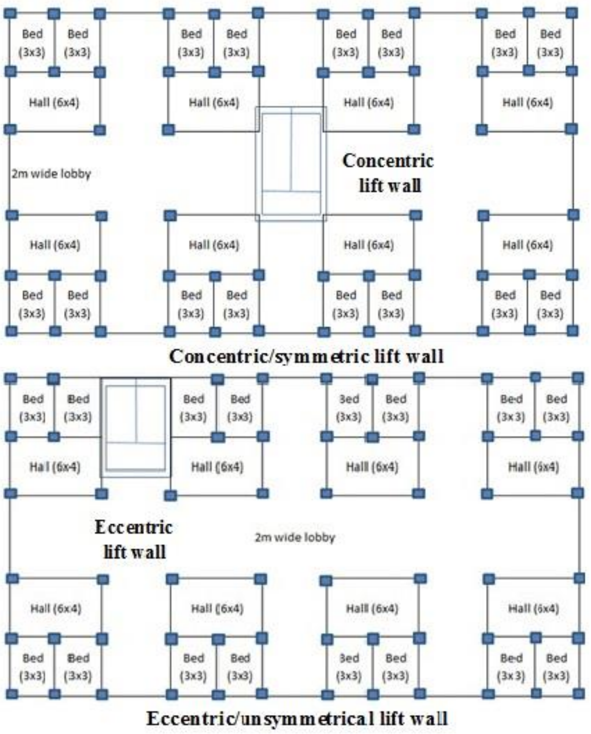

Fig 1 Structural layout of concentric and eccentric lift wall

B. Structural System

The structural system is the building framework that resists all the environmental forces acting on the Building, including the superimposed load due to non-structural elements[16]. In this study, the reinforced concrete beam-column arrangement called the moment-resisting frame system is considered for both the structural layout as presented in figure 2, and a reinforced concrete floor slab is cast monolithically with the beam. The beam-column framing system is designed in such a manner to support both the gravitational and lateral forces developed due to environmental actions. In the case of real-time building construction, the lateral resistance of the complete Building against the seismic is provided by the monolithic oneness of the floor slab, beam, and column arrangement. However, the consideration of floor slab for the modeling and analysis purpose is negated due to its minimal resisting capacity against the seismic load, whereas the beam and column framing constraint alone is considered. The slab panel dimensions significantly impact the one-way and two-way bending actions during the floor slab design procedure, and hence the structural load effect acting on the floor slab is calculated and applied to the beam-column framing. Both the gravitational and lateral loads acting on the floor slabs transfer through a load transferring mechanism and get distributed to the column through the network of beams [6].

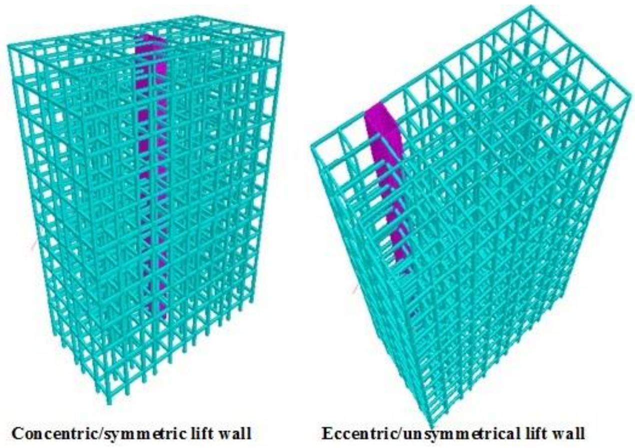

Fig 2 Modeling of the beam-column frame with concentric and eccentric lift wall

C. Material and cross-sectional properties

In general, the composite materials called reinforced concrete material are practiced for the moment-resisting high-rise buildings, and here C30 grade concrete and S400 material are used for the design of slab, beam, and column. As a result, the compressive design strength and tensile strength of concrete and steel are calculated as 13.6N/mm2 and 348N/mm2respectively. The economic and safe cross-sectional sizing of the slab, beams, and columns are derived from the strength limit and serviceability limit states [8]. To ensure the strength of the Building. Structure, it is mandatory to design the floor slab primarily with optimum specifications satisfying the limit states. Accordingly, the overall thickness of the floor slab is optimized as 140mm. The beamwidth is considered 300mm and is maintained constant for the entire floors, whereas the beam depth varies from 350mm to 650mm for both study cases. Similarly, on satisfying the limit state requirements, the optimum width and depth of the column vary at a range of 400x400mm to 800x800mm size. The longitudinal bar used for the design measures a varying diameter size from 12mm to 30mm, and the transverse reinforcement bars size varies from 8mm to 14mm diameter; in addition, the transparent cover considered for the slab, beam, and column is 25mm, 30mm and 40mm respectively.

Load cases and combinations

Three various loaded conditions such as dead, living, and seismic loads are considered for the analysis purpose[17]. The dead load includes both structural and non-structural loads and is calculated from the unit weight of the material. Based on the 140mm thickness of the structural slab, its self-weight is calculated as 3.68kN/m2and is applied to the beam elements along with a floor finish load of 1.5kN/m2. Moreover, the superimposed dead load of partition and parapet walls are also calculated and applied to the floor beams. A 200mm and 100mm thick hollow concrete block is considered as exterior and interior partition walls, in which their self-weight is calculated as 14kN/m3 and 10kN/m3respectively, based on its unit weight [9]. Concerning the code, the live loads are assumed as 2kN/m2 and 4kN/m2respectively for the room and lobby areas [9], and the same are applied to the floor slab for the static analysis purpose. The seismic load is estimated by considering the seismic zone 4 based on the EBCS code [10], wherein the bedrock acceleration ratio is 0.1, and the site coefficient is 1.5. In addition, the essential factor of the residential Building is one as per the code, and the behavior factor for the moment-resisting frame type is 0.3. The fundamental period of the building is calculated using the expression, where the factor C =0.075 for the frame type structure and H, the total height of the building frame is 36.5m. The design response factor is calculated using the expression. Based on these considered data is the horizontal seismic coefficient is calculated as 0.05. From this coefficient, the lateral earthquake load is calculated and applied along the longer and shorter direction of the structural layout, as shown in figure 3. According to the code [8,9,10], three separate load combinations are generated for strength and serviceability limit states such as dead plus live load, dead plus seismic load, and combination of dead, live, and seismic loads.

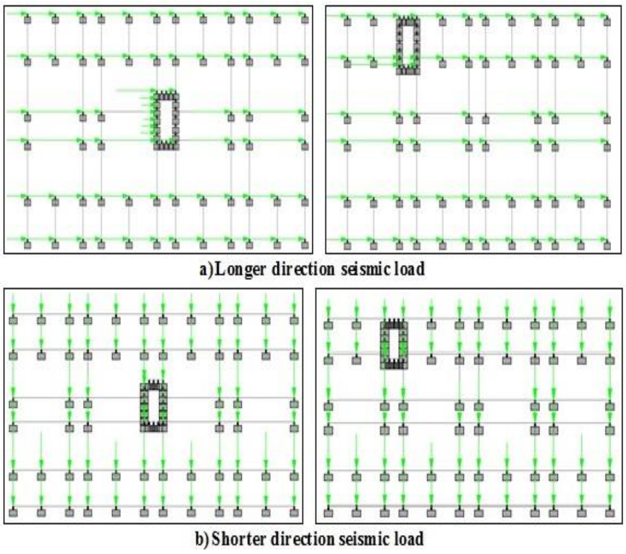

Fig 3 Seismic load on the structural layout along the long and shorted direction

D. Analysis and Design

A finite element tool named STAAD Pro is implemented to execute linear static analysis of both the considered building cases. As the number of variables involved is high for the design purpose, the inelastic behavior of unsymmetrical structures subjected to seismic is complex. The preliminary understanding of the issue is an essential criterion to generate a rational procedure of design for torsion, and subsequently, various aspects of the issues are investigated based on the outcome reports of the linear static analysis. The section output forces and displacements of various structural elements are recorded for the structural design.

Manual design calculations are derived according to the code for the purpose of structural designing of each element [8]. In the case of slab designing, the thickness of the slab is optimized to satisfy the bending and deflection criteria, whereas the slab tension reinforcement is calculated to resist tension due to bending. The depth of the slab required to resist compression and deflection due to bending is calculated using the expressions. $\sqrt{M_{max}/(0.29*f_{cd}*b)}$ And $(0.4+0.6\,f_{yk}/400)*L_e/\beta$ where, f_{cd} is the compressive design strength of concrete is the yield strength of steel, b width of slab, and β is the span to depth ratio. Furthermore, the required amount of percentage ratio of tension reinforcement due to bending is calculated using the formula $\left\{1\text{-}\sqrt{[1\text{-}2M/bd^2f_{cd}]}\right\}f_{cd}/f_{yd}$. In a similar way, The floor beams are also designed for bending and shear criteria. In favor of satisfying the diagonal compression due to shear, the provided depth of the concrete is checked and validated. In the case of diagonal tensile due to shear, the optimal transverse reinforcement is calculated. The slab and beam design calculations satisfy the minimum and maximum code provisions proficiently [8, 10]. Regarding the column, The uniaxial and biaxial bending factors are considered, and the corresponding interaction equations are calculated and validated as per the code. These bending factors are calculated from the first order, second-order, and additional eccentricities, in which the first order eccentricity is obtained from the frame analysis using the Finite element tool, the second-order and additional eccentricity is calculated manually [8]. The main longitudinal flexural reinforcement is calculated using the non-dimensional parameters for the combined axial force and moments, as well the transverse reinforcements are designed and provided to resist shear.

Result and Discussion

A. Torsion associated with non-uniform stiffness

The occurrence of structural irregularity has an unfavorable effect on the seismic response of the building, and hence the structural irregularity of plan and elevation in terms of symmetric and unsymmetrical lift wall is studied. In the case of symmetric lift wall structural layout, the distribution of structural element's stiffness is uniform [11]. As a result, negligible torsional effect on the beam-column is recorded due to the application of seismic load combination along the more robust and weaker axis as mentioned in Figures 4(a), 5(a), and 6. Therefore, this study recommends that the consideration of torsion can be neglected in the case of symmetric lift wall structure in which the lift wall is aligned at the center of mass of the Building

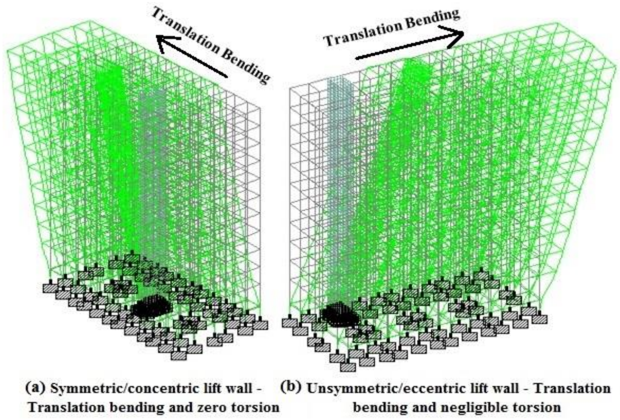

Fig 4 Seismic responses along longer direction

Whereas in the case of unsymmetrical lift wall building, a huge magnitude of torsion is recorded, as illustrated in Figures 5(b) and six, and this effect occurs due to variables such as seismic direction. Building length to width ratio and location of lift wall infers that the seismic corresponding to the shorter direction of Building produces higher torsion effect compared to the seismic along the longer direction of building Figure 5(b). Due to the uneven distribution of story stiffness [12, 13], a non-uniform torsion force distribution is recorded along with the height of the Building during the occurrence of longer direction seismic as pictured in figure 6. Moreover, the maximum torsion value reported along the longer direction seismic is 15% less than the maximum torsion force acting at the base of the Building due to seismic along the shorter direction. Hence the torsional force acting upon the unsymmetrical lift wall is critical along the weaker axis when the building plan ratio is equal to 0.5 and the severity increases concerning the increase of building plan ratio. It is inferred that there is an increase in lateral displacement due to accidental eccentricity, which is less than 5% for structural systems that are torsionally rigid. In the flexible structural system, there is a significant increase in response due to accidental eccentricity. The calculated accidental eccentricities are smaller than the code recommended value 0.05b, excluding the buildings with longer plan dimensions possessing width dimensions greater than or equal to 50m[14].

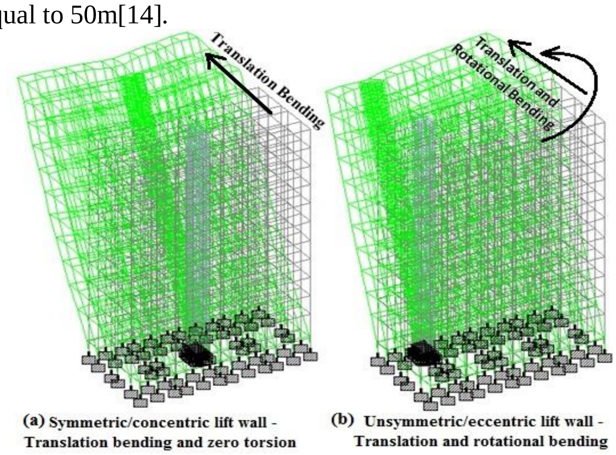

Fig 5 Seismic responses along the shorter direction

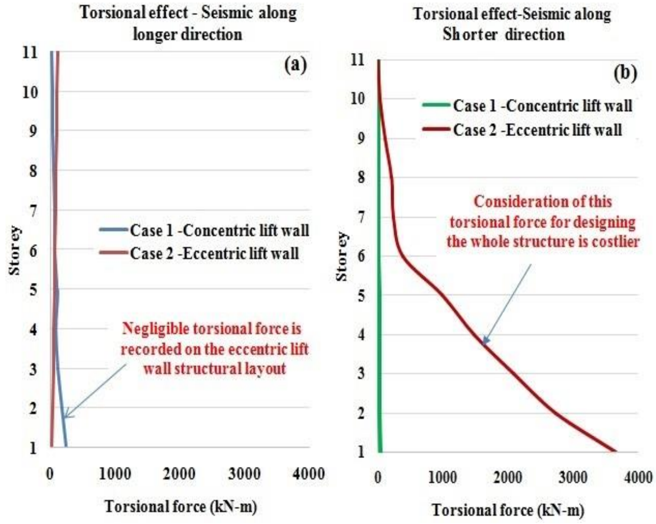

Figure 6 Effect of torsion with respect to the height of Building

B. Effect of torsion on the elastic curve

The elastic curve of both the symmetric and asymmetric lift wall is presented in figure 7, and it is observed that the torsional effect on the unsymmetrical lift wall greatly affects the deflection curve with respect to the building height. In the case of asymmetric lift walls, the deflection curve corresponds. Due to translation bending alone and zero rotational torsion is recorded due to the uniform distribution of stiffness and mass of the Building. Hence, it is clearly understood that the deflection on the symmetric lift wall building occurs because of the bending effect alone, and this recommends the designer to ensure the deflection criteria should be checked according to flexural theory [15].

In the case of an unsymmetrical lift wall, the longer direction seismic behavior is similar to the symmetric condition, whereas, in the shorter direction seismic, an increase of deflection is recorded due to the torsion bending. There is a rise in the translation bending along a length direction due to the eccentric position of the lift wall, which induces a higher deflection equal to 77% greater than the symmetric lift wall. On the contrary, along the shorter direction, the total deflection of the Building occurs due to both translation and rotational bending. The maximum deflection on the symmetric and unsymmetrical lift wall building is recorded as 104mm and 212mm, respectively. This represents that the eccentric location of the lift wall on the structural system doubles the deflection compared to the symmetrical lift wall structure. Hence, it is essential to additionally strengthen the eccentric lift wall beam and columns to overcome the enhanced deflection because of bending and torsion and the longer and shorter directions, respectively. This procedure consumes additional concrete and steel quantity which leads to uneconomic and expensive construction.

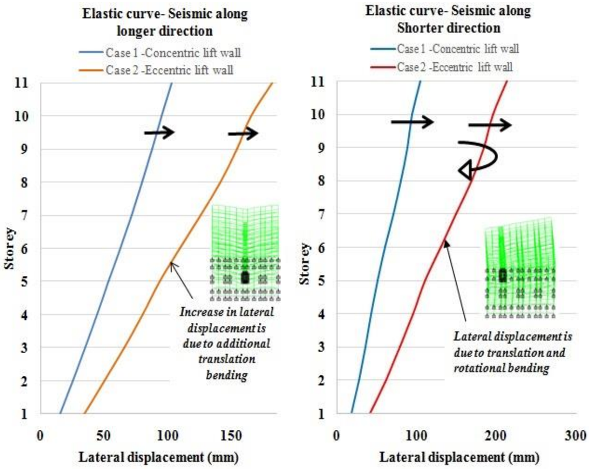

Fig 7 Effect of torsion and bending on the story displacement

C. Effect of torsion on the material necessity

This section presents the calculated concrete requirement of the structural frame belongs to both cases and is inferred that the eccentric lift wall frame demands 1% more substantial quantity than that of concentric lift wall position. This occurs because of the additional bending in the longer direction and torsional force in the shorter direction. In a similar way, the requirement of steel reinforcement is higher for eccentric lift walls and is equal to 1.3% higher than concentric lift wall structural layout. It is to be noted that the investigation is performed for the lift wall aligned asymmetrically about both axis and length-to-width ratio equal to 0.5. In summary, there is an additional demand for concrete and steel reinforcement to resist the bending and torsion that occurs due to the eccentric orientation of the lift wall on comparing with the concentric structure. Moreover, the material requirement for concrete and steel quantity is calculated for different length-to-width ratios of the Building, as shown in figure 8.

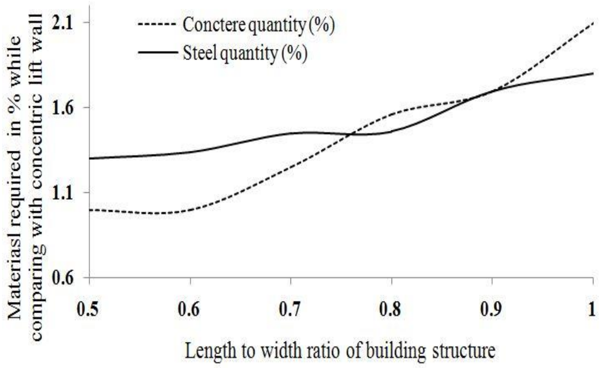

Fig 8 Material requirement of eccentric lift wall with different L/B ratio

III. CONCLUSION

The moment resisting frame with concentric and eccentric lift wall with the plan dimension ratio of 0.5is investigated under seismic loading. Eccentric location of lift wall buildings concludes that irregularity occurrence because of uneven distribution of strength and stiffness causes severe crack formation due to floor rotation and floor translation. The moment resisting frame subjects to translation bending along the longer direction seismic, whereas in the case of shorter direction and bending, the torsion is also induced due to eccentric positioning of lift wall. The torsional force develops along the longer direction seismic is estimated as 15% higher than, the shorter direction torsion, which causes a negligible impact to the structure during designing, and hence it can be neglected. Regarding the story deflection, an additional deflection of 77% is induced along the longer direction due to bending, whereas in the shorter direction, the total deflection is doubled due to both the bending and torsion effect compared to the concentric lift wall. It can be concluded that the additional torsion and story deflection demands higher material requirement, which leads to expensive as compared to concentric lift wall, and special care and attention is mandatory for the eccentric lift walls due to its enhanced element size.

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