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Realtime Floor Eccentricity Reduction: A Desktop Application for Mass and Stiffness Manipulation

Abel Haileselassie Beyene

Mekelle University Graduate, Email: helloabelu@gmail.com

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Abstract

In seismic design, building configuration (especially mass and stiffness distribution) is crucial for mitigating earthquake damage. When there is an eccentricity between the center of mass (CM) and the Center of Stiffness (CS) of a floor, a twisting moment occurs. This moment causes dangerous rotational motions during seismic events. To avoid this rotation, structural engineers must position structural elements to keep floor eccentricity within allowable limits. This process often involves lengthy trial and error process of rearranging structural elements. To address this, CMCS desktop application tool was developed by the author. Utilizing the original concept of center of stiffness that dates back to manual rigidity analysis techniques associated with the lateral analysis of single-story shear wall buildings and C++ programing language, CMCS enables engineers to visualize and adjust the centers of mass and stiffness in real-time while also providing methods for reducing eccentricity through the provision of precise shape of shear walls. CMCS's effectiveness is demonstrated with a highly eccentric multi-story reinforced concrete building. Initial eccentricities of 35% and 43% in the x and y directions on the ground floor and 33% and 41% on upper floors, were reduced to 0% in both directions for all floors by following CMCS shear wall recommendations. This highlights CMCS's potential in improving structural design and enhancing seismic resilience, offering a scientific solution to the twisting moment problem in building floors.

Keywords: Seismic Design, Structural Configuration, Irregular Buildings, Centre of Mass, Centre of Stiffness, Eccentricity, Shear Walls

1. Introduction

In seismic design, the configuration of a building plays a pivotal role in its ability to withstand earthquake forces effectively. Modern structural engineering practices categorize buildings into regular and irregular configurations, where irregularities can significantly influence a structure's response to seismic events. Planar irregularities, such as variations in mass and stiffness distribution across floors, pose specific challenges due to their potential to induce torsional effects during earthquakes (Wight & Macgregor, 2012).

One critical parameter affecting structural behaviour is eccentricity (the distance between the centre of mass and the centre of stiffness). High eccentricity can lead to uneven distribution of seismic forces, resulting in torsional moments that can compromise the structural integrity and performance of the building (Wight & Macgregor, 2012).

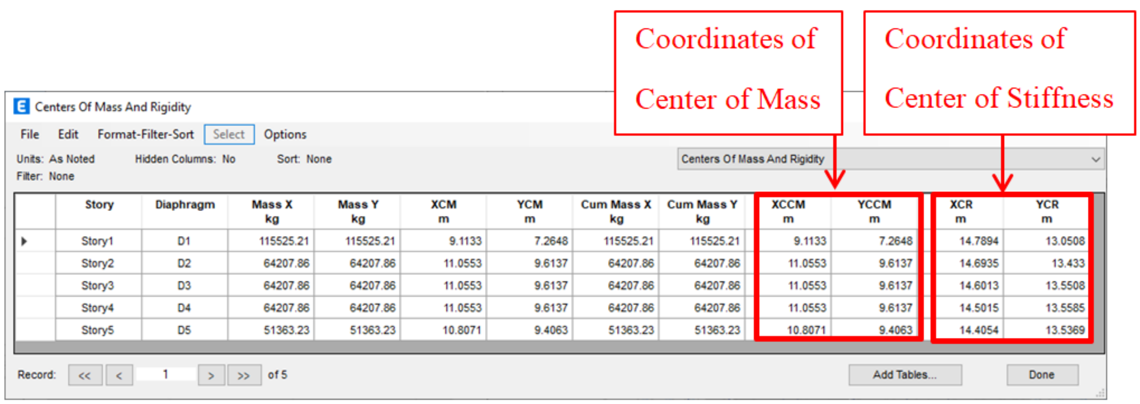
Traditionally, calculations for determining center of mass, center stiffness and ultimately eccentricity have been labour-intensive tasks for structural engineers and are conducted manually or partially with the help of structural analysis software. These labour-intensive calculations are even worsened for structures having irregular floor plans and numerous structural elements. In practical designs, not every floor has a symmetrical arrangement of mass and stiffness elements, leading to the existence of eccentricity almost always. To address this, structural engineers must go through a lengthy trial-and-error process that involves the rearrangement and/or recalculation of the mass and stiffness elements to avoid or at least keep the eccentricity within allowable limits. Even more than this is, practically this trial-and-error process could lead the structural engineer to get fed up with this work and not address the issue of eccentricity at all during design.

This paper introduces CMCS (Centre of Mass and Centre of Stiffness manipulation for seismic design), a novel software tool developed by the author to address these challenges. CMCS enables real-time visualization and manipulation of the centres of mass and stiffness for every floor within a building structure. By providing immediate feedback on the effects of structural element adjustments, CMCS facilitates efficient optimization of structural elements to enhance seismic performance. Moreover, through its semi-automatic method, CMCS is able to provide the precise dimensions for shear walls that are needed to reduce eccentricity to the desired value. Also, through its mandatory top to bottom approach of shear wall recommendation, CMCS is able to make eccentricity reduction a non-iterative process.

To illustrate its effectiveness, this paper presents a case study of a multi-story reinforced concrete building with significant eccentricity. Through CMCS, the study demonstrates how structural engineers can systematically reduce eccentricity and improve seismic resilience during the early stages of design meaning before detailed analysis of the structure are conducted, thereby highlighting the practical applicability and benefits of the software in contemporary structural engineering practices.

2. Literature Review (Related Tools)

ETABS is a widely used software for analysing and designing building structures, providing essential data such as the coordinates of the center of mass for floor diaphragms and the center of stiffness for lateral load-resisting systems. During analysis, ETABS automatically calculates the coordinates of centers of mass and stiffness once the diaphragm assignment is included in the model. Users can get this information by navigating to Display > Show Tables > Analysis Results > Structure Output > Other output items > Table: Centers of Mass and Rigidity (Diaphragm Centers of Mass and Rigidity).these data coordinates are presented in the form of table as displayed in Figure 1 for the structure used as case study.



Story	Diaphragm	Mass X kg	Mass Y kg	XCM m	YCM m	Cum Mass X kg	Cum Mass Y kg	XCCM m	YCCM m	XCR m	YCR m
Story1	D1	115525.21	115525.21	9.1133	7.2648	115525.21	115525.21	9.1133	7.2648	14.7894	13.0508
Story2	D2	64207.86	64207.86	11.0553	9.6137	64207.86	64207.86	11.0553	9.6137	14.6935	13.433
Story3	D3	64207.86	64207.86	11.0553	9.6137	64207.86	64207.86	11.0553	9.6137	14.6013	13.5508
Story4	D4	64207.86	64207.86	11.0553	9.6137	64207.86	64207.86	11.0553	9.6137	14.5015	13.5585
Story5	D5	51363.23	51363.23	10.8071	9.4063	51363.23	51363.23	10.8071	9.4063	14.4054	13.5369

Figure 1: Window Showing Center of Mass and Rigidity Results from ETABS

However, determining eccentricity necessitates manually extracting these coordinates and conducting additional calculations with help of calculator (usually spread-sheet program). ETABS computes the centers coordinates only after the initial analysis run, which may not be ideal for addressing eccentricity issues. Furthermore, users must repeatedly run the model, make modifications, rerun the analysis and do above stated calculations to observe changes in these coordinates and their effects on eccentricity.

Currently, no software tool allows structural engineers to visualize and manipulate the centers of mass and stiffness as effectively as CMCS does. By providing real-time updates and an intuitive interface, CMCS enhances the process of minimizing structural eccentricity and improves overall design efficiency.

3. Methodology, Assumptions and Scope

3.1 Method

The development of CMCS utilized a laptop computer running the Windows 10 operating system. The CMCS software was developed using the software development environment Qt Creator 4.7.1 (Enterprise), with programming conducted in C++. This environment provided the necessary tools for graphical user interface (GUI) development and real-time data manipulation capabilities (Qt Widgets Scribble Example).

When it comes to mathematical relations use by CMCS, the center of stiffness is calculated using original concept of center of stiffness that dates back to manual rigidity analysis techniques associated with the lateral analysis of single-story shear wall buildings (Diaphragm Centers of Mass and Rigidity). The center of mass is calculated by taking the floor diaphragms to be rigid in plan which makes the masses to be lumped at the center of gravity (Ministry of Works and Urban Development. *Ethiopian Building Code Standards 8: Design of Structures for Earthquake Resistance*, 1995). The shear wall recommendation is conducted by first calculating the additional moment of inertia to reduce eccentricity and determining the precise dimension of a rectangular section to achieve that additional moment of inertia.

The above core concepts are programmed in to CMCS with help of different subprograms and they are explained as follows:

3.1.1 Subprogram for Centre of Mass $(\boldsymbol{x_m}, \boldsymbol{y_m})$

The centre of mass of each floor is computed based on the explicit masses of structural elements such as slabs, beams and user-defined mass elements (e.g., point masses, line masses and area masses). The formulas used are:

$$\boldsymbol{x_m} = \sum_1^m m_i x_i / \sum_1^m m_i \quad , \quad \boldsymbol{y_m} = \sum_1^m m_i y_i / \sum_1^m m_i$$

Where (x_i, y_i) are the coordinates of the geometric centroid of element i and m_i is the mass of element i and m is the number of mass elements (Bhatt, P., MacGinley, T. J., & Choo, B. S., 2014).

3.1.2 Subprogram for Centre of Stiffness $(\boldsymbol{x_s}, \boldsymbol{y_s})$

The center of stiffness is determined by considering the moment of inertia of columns and shear walls in orthogonal x and y directions. The formulas used are:

$$\boldsymbol{x_s} = \sum_1^n I_{ixx} x_i / \sum_1^n I_{ixx} \quad , \quad \boldsymbol{y_s} = \sum_1^n I_{iyy} y_i / \sum_1^n I_{iyy}$$

Where (x_i, y_i) are the coordinates of the geometric centroid of element i. I_{ixx} and I_{iyy} are the moment of inertias of element i along x and y axes respectively , n is the number of stiffness elements (Bhatt, P., MacGinley, T. J., & Choo, B. S. , 2014).

3.1.3 Subprogram Eccentricities $(\boldsymbol{e_x}, \boldsymbol{e_y})$

The formulas used for calculating eccentricities of a floor are:

$$\boldsymbol{e_x} = \frac{|x_m - x_s|}{d_x} \times 100\% \quad , \quad \boldsymbol{e_y} = \frac{|y_m - y_s|}{d_y} \times 100\%$$

Where d_x and d_y are the maximum extension of the floor in the x and y directions respectively (Ministry of Works and Urban Development. *Ethiopian Building Code Standards 8: Design of Structures for Earthquake Resistance, 1995*).

3.1.4 Subprogram for Recommending Shear Wall Sizes

To reduce eccentricity, CMCS recommends additional rectangular shear walls required for a given floor plan configuration. It calculates the additional moment of inertia needed to relocate the center of stiffness from its original position $(\boldsymbol{x_s}, \boldsymbol{y_s})$ to a desired new position (x_{sd}, y_{sd}) and determines the number and dimensions of shear walls necessary to achieve this adjustment .

The moment of inertia needed to bring $(\boldsymbol{x_s}, \boldsymbol{y_s})$ to (x_{sd}, y_{sd}) are denoted by I_{xxc} and I_{yyc} and are obtained using:

$$I_{xxc} = I_{xx} \frac{x_a}{(x_c+x_b)} \quad , \quad I_{yyc} = I_{yy} \frac{y_a}{(y_c+y_b)}$$

where I_{xx} and I_{yy} are the total moments of inertia of original stiffness elements (elements that existed before any shear walls were recommended by CMCS) about the x and y axes respectively.
The number of $b \times t$ shear walls needed to bring $\boldsymbol{x_s}$ to x_{sd} and $\boldsymbol{y_s}$ to y_{sd} ,are calculated respectively as follows:

$$n_x = \frac{I_{xxc}}{tb^3/12} \quad , \quad n_y = \frac{I_{yyc}}{tb^3/12}$$

Where n_x and n_y are the integer numbers, disregarding any digits after decimal point. b and t are breadth and thickness of the single shear wall cross-section respectively and are given by user.

But there could be some moment of inertia that has to be provided by additional shear walls that don't have full size of $b \times t$, CMCS calculates the exact breadth of this shear walls assuming the same wall thickness t ,as follows:

$$b_{xo} = \sqrt[3]{\frac{12I_{xxo}}{t}} \quad , \quad b_{yo} = \sqrt[3]{\frac{12I_{yyo}}{t}}$$

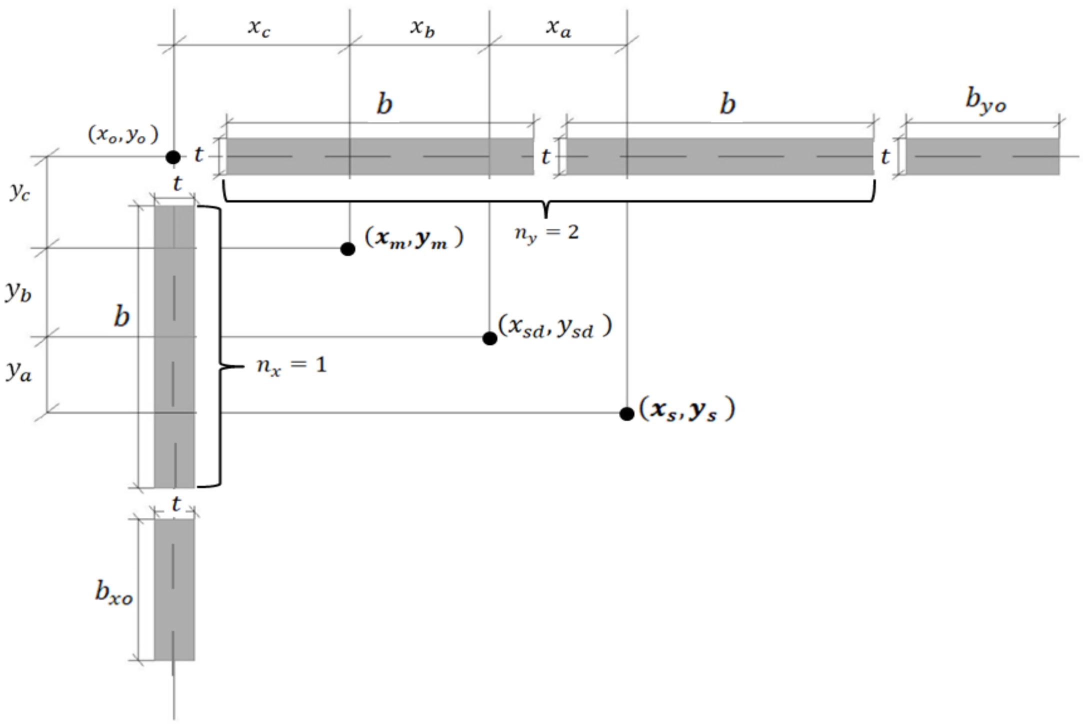


Figure 2: Random arrangement of center of mass and center of stiffness

Where b_{xo} and b_{yo} are the breadths of the shear wall that needed to bring from $(\boldsymbol{x_s}, \boldsymbol{y_s})$ to the desired position (x_{sd}, y_{sd}) in addition to n_x and n_y number of shear walls having $b \times t$ size. b_{xo} and b_{yo} are always less than b,also I_{xxo} and I_{yyo} are residual moments of inertias and are calculated as follows:

$$I_{xxo}=I_{xxc} -(n_x \, tb^3/12) \quad , \quad I_{yyo}=I_{yyc} -(n_y \, tb^3/12)$$

Therefore the total number of shear walls needed to bring $(\boldsymbol{x_s}, \boldsymbol{y_s})$ to (x_{sd}, y_{sd}) is n_x and n_y number of shear walls whose section sizes are $b \times t$ and two additional shear walls whose section size are $b_{xo} \times t$

and $b_{yo} \times t$. For the arrangement shown in Figure 2, $n_x = 1$ and $n_y = 2$. (x_o, y_o) is user given location through mouse cursor.

3.1.5 Subprogram for Real-Time Functionality

CMCS operates in real-time, continuously running the above subprograms at a rapid rate (more than 100 times per second) upon user interaction. This ensures immediate feedback on the effects of any modifications made to the structural elements, facilitating the design processes without the need for repeated analysis runs.

3.2 Assumptions and Scope

CMCS is tailored for Reinforced Concrete (RC) building structures that use shear walls and columns to resist lateral loads. The tool is intended for early design stages, where it helps minimize structural eccentricity by optimizing the arrangement of slabs, columns and shear walls.

CMCS operates under several key assumptions: (i) a rigid floor slab without in-plane deformation, (ii) non-coupled and slender shear walls with only flexural stiffness considered and (iii) lateral stiffness provided exclusively by columns and shear walls. The tool distributes lateral forces based on the moment of inertia of these elements.

However, CMCS has certain limitations: (i) it does not incorporate diagonal bracing, (ii) it restricts changes in cross-sectional sizes between floors and (iii) it calculates the center of stiffness solely based on moment of inertia, which may reduce its effectiveness in more complex structural scenarios.

4 User Interactions with CMCS

Before launching CMCS, users must organize the floor plans of the building structure. The functionality of CMCS is illustrated in the flowchart (vertical chevron list) shown in Figure 3.

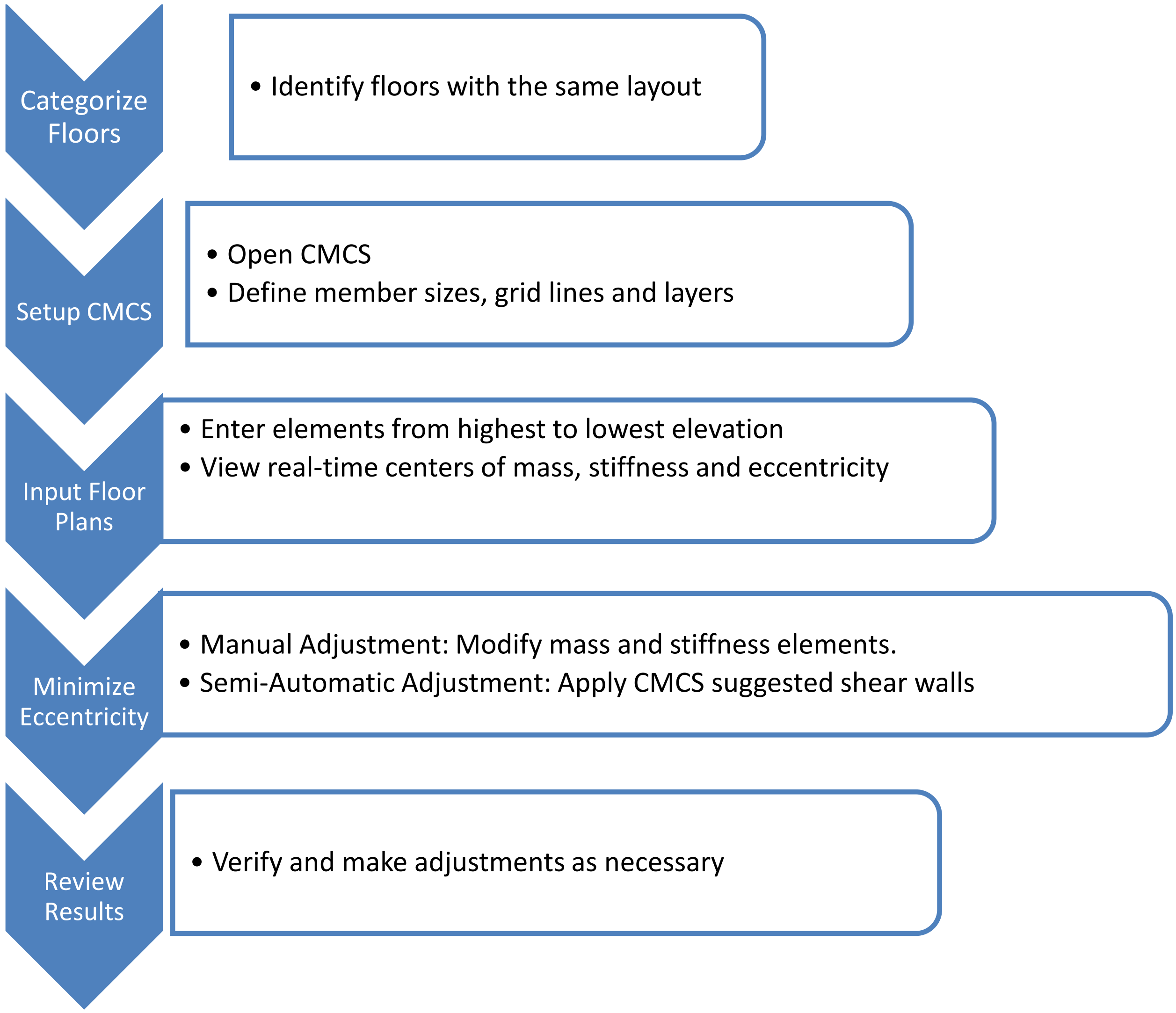


Figure 3: Flow-chart showing working of CMCS

Upon opening the application, users define mass elements, stiffness elements and grid lines. CMCS then presents a gridded platform for drawing and refining these plans.

As users input floor elements, CMCS dynamically calculates and displays the centers of mass, center of stiffness and eccentricity in real time. For instance, adding a slab immediately updates the center of mass, while introducing a column or shear wall recalibrates the center of stiffness.

Once all floor plan details are entered, users can reduce eccentricity either manually—by adjusting mass and stiffness elements—or semi-automatically, where CMCS recommends rectangular shear walls based on user-defined parameters, including allowable eccentricity, wall thickness and location.

An example illustrating how CMCS minimizes eccentricity through the use of shear walls is presented in the following section.

5 Studied Material (Case Study)

The case study involves a multi-story reinforced concrete building, specifically a Ground+4 commercial building structure as shown in the following Figure 4. This building is selected for its complex design, which includes substantial planar irregularities and significant eccentricity. Key characteristics of the structure include:

Asymmetrical Layout: Both the plan and elevation of the building exhibit pronounced asymmetries. This irregularity challenges traditional design approaches and necessitates advanced tools for accurate analysis and optimization.

Flat Slab System: The building employs a flat slab system, which simplifies the floor framing but introduces complexity in analysing lateral load resistance and eccentricity.

Variability in Mass and Stiffness: There is considerable variation in mass and stiffness distributions across different floors. This variability affects the overall structural performance and introduces additional considerations for managing eccentricity and ensuring stability.

The application of CMCS for minimising the building plan eccentricity of the building under consideration (Figure 4) is being illustrated step by step as follows:

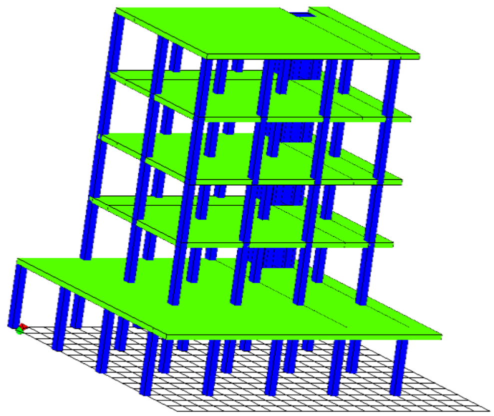


Figure 4: Showing Building Structure under Case Study

i. Categorize Floors

- *Identify Floors with the Same Layout*: Begin by categorizing the floors of the structure into categories based on their layout similarities.

For example the building structure has five floors that can be grouped under two categories – First category is named Ground Floor Plan and Second category is named First to Fourth Floor Plan as shown in the following Figure 5.

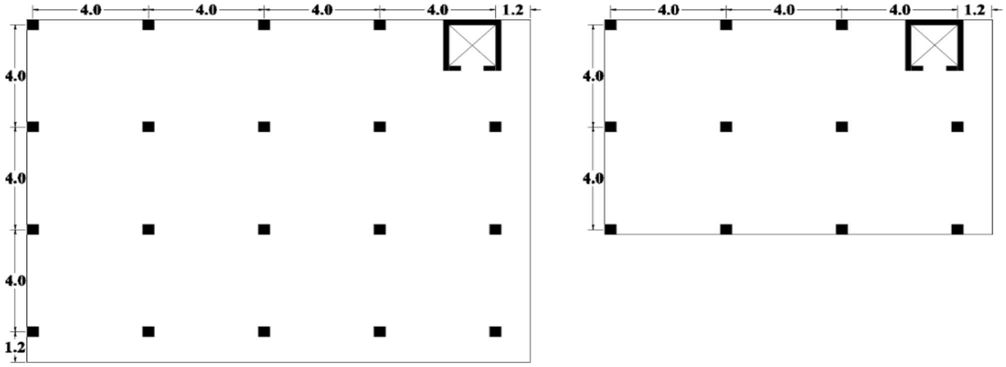


Figure 5: Showing Floor Grouping - Ground Floor Plan (Left Side) and First to Fourth Floor Plans (Right Side)

Note in Figure 5:
(i) Column Dimensions: $40\ cm \times 40\ cm$ (ii) Slab Thickness: $25\ cm$ (iii) Core (Wall Thickness): $20\ cm$ (iv) Span Lengths are in Meters

ii. Setup CMCS

- *Open CMCS*: Launch the CMCS tool to start the process.
- *Define Member Sizes, Grid Lines and Layers*:
    - Define sizes for floor plan elements such as slabs, columns and shear walls using Edit > Frame.
    - Create layers for each category of floor plans, entering them from highest to lowest elevation using Edit > Plan.
    - Adjust grid lines as necessary (Edit > Grid).

iii. Input Floor Plans

- *Enter Elements from Highest to Lowest Elevation*: Input floor plan elements starting from the highest elevation. As you do, CMCS will automatically display the centers of mass, stiffness and eccentricity in real-time. After modelling the entire building structure under consideration, the final positions of CM,CS , e_x and e_y for each category are shown in the following Figures 6(a) and 5(b).

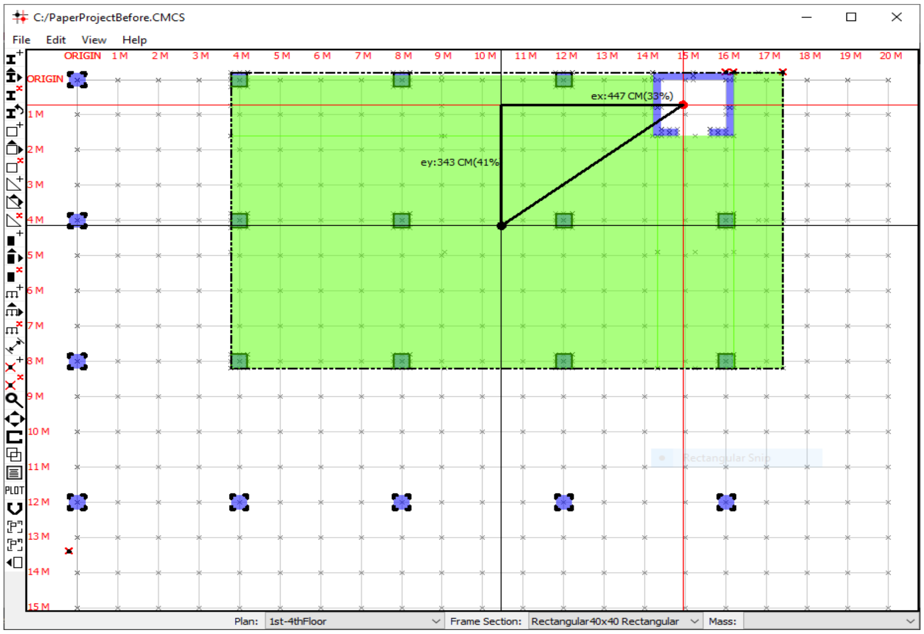


Figure 6 (a): Displayed CM, CS, e_x and e_y for First to Fourth Floor Plan

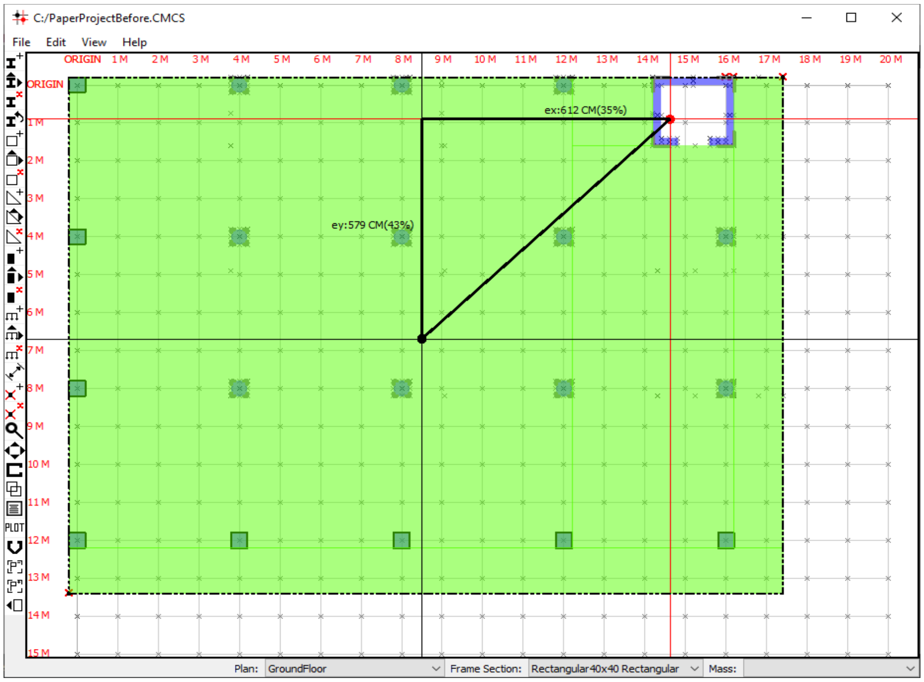


Figure 6 (b): Displayed CM, CS, e_x and e_y for Ground Floor Plan

In both categories the center of stiffness (red dot) is situated within the core due to its higher stiffness relative to the columns, which causes the center of stiffness to shift towards it. Similarly, the center of mass (black dot) is positioned near the geometric center of the slab. The eccentricity components (e_x , e_y) are clearly marked.

iv. Minimize Eccentricity

- *Manual Adjustment*: Modify mass and stiffness elements: Modify mass and stiffness elements as needed by adjusting mass and stiffness contributing elements through trial and error. This method provides the user with a very user friendly interface for moving, rotating, deleting and adding structural elements.
- *Semi-Automatic Adjustment*: Apply CMCS suggested shear walls: In this semi-automatic method, the user specifies shear wall locations using the mouse cursor, while CMCS calculates the required cross-sectional size of rectangular shear walls in real-time based on these positions. This approach highlights the user's active role in the recommendation process; without specified locations, the shear wall suggestions could result in multiple possible solutions. The following Figures 7(a) and 7(b) illustrate CMCS guiding the user on cursor placement.

The user can position the cursor within a hatched area defined by CMCS, based on the principle that shear walls should pull the center of stiffness toward the center of mass to reduce eccentricity. In this case, since the center of stiffness is located in the upper right quadrant relative to the center of mass, the hatched area appears in the lower left quadrant. The user is thus advised to place the cursor in the lower left corner of the slabs, ensuring that the recommended shear walls align with existing columns and do not compromise the structure's functionality.

The first shear walls recommended are for the topmost category of floors (first to fourth floors). This approach is intentional, as CMCS assumes each shear wall begins at the foundation and extends to the highest elevation of the selected layer (the top of the fourth floor). Placing shear walls for the lower layers before those for the upper layers could disturb the eccentricity of the lower floors, as CMCS does not account for upper-layer shear walls when calculating the lower layers. Therefore, it is mandatory to start the shear wall recommendation process from the topmost layer and proceed downward.

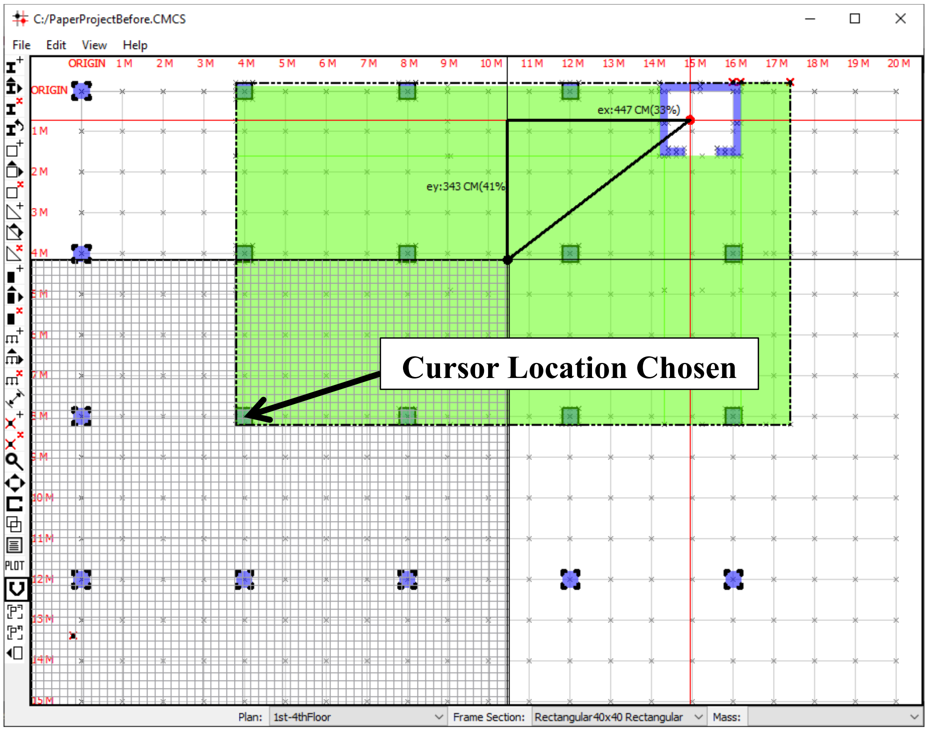


Figure 7(a): First- Fourth Floor Category - CMCS Showing Cursor Location

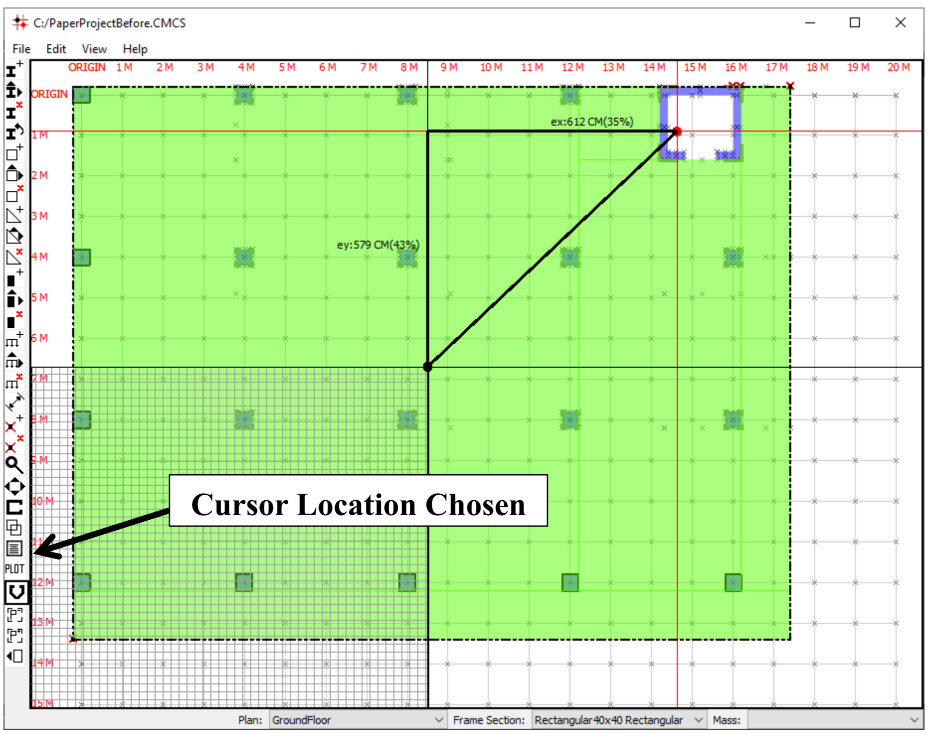


Figure 7(b): Ground Floor Category - CMCS showing cursor location

For the category first to fourth floors, the cursor is positioned at the bottom left corner of the slab, with the recommended shear walls (Shear Wall 1 and Shear Wall 2) illustrated in Figure 8(a). The existing columns in the locations of Shear Wall 1 and Shear Wall 2 have been manually deleted following CMCS's recommendations.

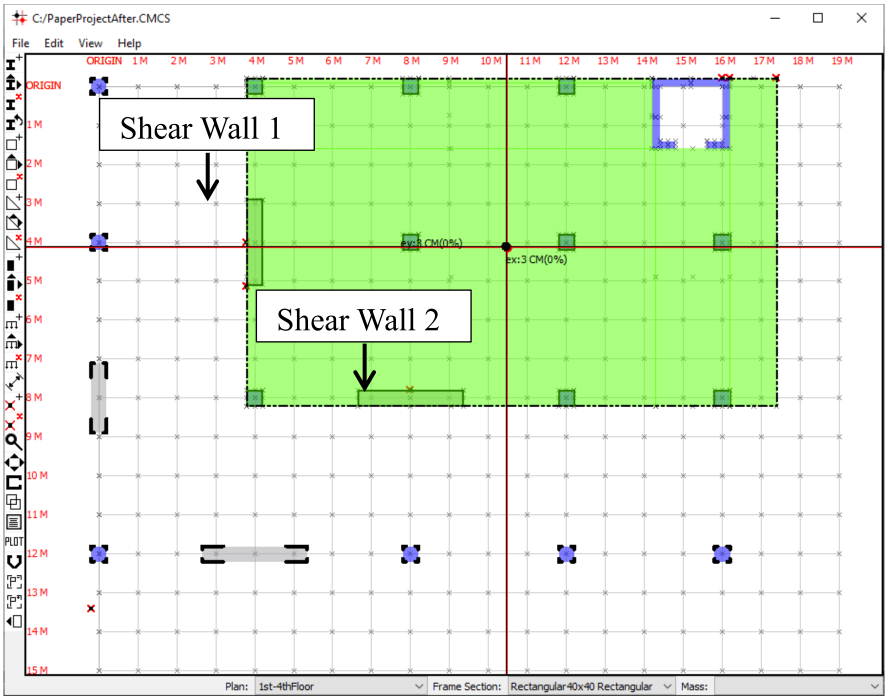


Figure 8(a): First-Fourth Floor Category CMCS Recommended Shear Walls are Placed

Figure 8(b): Ground Floor Category CMCS Recommended Shear Walls are Placed

Next, to reduce the eccentricity of the ground floor, the cursor is again placed at the bottom left corner of the of the slab, resulting in the recommended shear walls (Shear Wall 3 and Shear Wall 4), as shown in Figure 8(b).

These shear walls are calculated while considering the effects of the previously recommended shear walls (Shear Wall 1 and Shear Wall 2). The columns in the positions of Shear Wall 3 and Shear Wall 4 have also been manually deleted after CMCS's recommendations.

From Figs 8(a) and (b), it can be seen that the center of mass and center of stiffness have almost overlapped, which shows that eccentricity has been reduced drastically.

v. Review Results

- *Verify and make adjustments as necessary*: Review the final structure and make any necessary adjustments to further refine the eccentricity minimization. After incorporating the recommended shear walls into the structure, the eccentricity is reduced to 0% in both x and y directions for all floors, including the ground floor as well as the first to fourth floors. The recommended shear walls are shown incorporated in the following Figure 9.

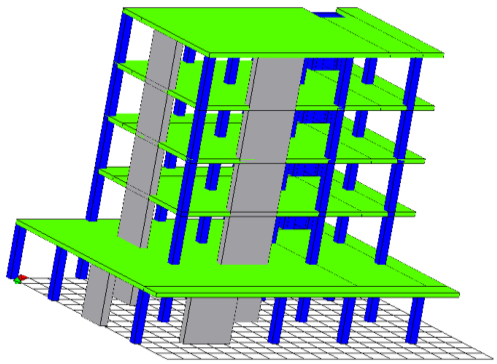


Figure 9: Showing incorporated CMCS Recommended Shear Walls

5 Results and Discussion

The effectiveness of the CMCS tool is demonstrated through a case study of a multi-story reinforced concrete building with high eccentricity. The building, a Ground+4 commercial building structure with an asymmetrical layout in both plan and elevation, utilizes a flat slab system.

Initial Eccentricity:
Ground Floor: Eccentricity was 35% in the x direction and 43% in the y direction.

First to Fourth Floors: Eccentricity was 33% in the x direction and 41% in the y direction.

Design Parameters:
Maximum Allowable Eccentricity: 1% in both x and y directions.

Shear Wall Specifications: Wall thickness of 40 cm and maximum width of 400 cm.

CMCS Recommendations:
CMCS suggested the following shear walls, presents in Table 1, to reduce eccentricity: the user can get these precise dimensions using the dimension tool of CMCS.

Table 1: Results from CMCS

Shear Wall No.	Shear Wall Size	Remarks
Shear Wall 1	$219\ cm \times 40\ cm\ (b_{xo} \times t)$	Extends from foundation to the fourth floor slab
Shear Wall 2	$270\ cm \times 40\ cm\ (b_{yo} \times t)$	
Shear Wall 3	$179\ cm \times 40\ cm\ (b_{xo} \times t)$	Extends from foundation to the ground floor slab
Shear Wall 4	$270\ cm \times 40\ cm\ (b_{yo} \times t)$	

For the case study building, both n_x and n_y were zero, indicating that none of the recommended shear walls exceeded the maximum width of 400 cm.

After incorporating the recommended shear walls into the structure, the eccentricity was reduced to 0% in both x and y directions for all floors, including the ground floor as well as the first to fourth floors.

The results confirm that CMCS effectively minimized structural eccentricity to within acceptable limits, demonstrating its practical utility in optimizing shear wall placement and enhancing building stability.

6 Conclusions

CMCS has demonstrated itself as a highly effective and precise tool for managing eccentricity in reinforced concrete building structures. Its real-time calculation capabilities allow structural engineers to instantly observe the impact of modifications to floor plan elements, eliminating the need to wait for lengthy analysis results. By vividly displaying the centers of mass and stiffness, CMCS facilitates the identification and resolution of eccentricity issues that might be overlooked with other tools.

Unlike tools based on specific building codes, CMCS is adaptable for global use. Its user-friendly interface enables architects to design floor plans with minimal eccentricity, potentially reducing conflicts between architects and structural engineers regarding shear wall placement. Future versions of CMCS could address its current limitations, enhancing its applicability to a wider range of structural types and further improving its utility in structural design.

7 Acknowledgments

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