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StructuralComponents 6: An early-stage design tool for flexible topologies of mid-rise concrete buildings

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Abstract

This paper discusses the project StructuralComponents 6, a continuation of the ongoing project StructuralComponents which focuses on the development of computational tools for conceptual building design beginning with Breider [1]. The goal of StructuralComponents 6 is to develop a tool for the conceptual design of mid-rise concrete buildings laterally supported by shear walls. The tool allows a user to digitally construct a prismatic, rectangular building design with a custom number and arrangement of shear walls and performs structural validation of any given design in terms of stiffness, strength and stability. The project in split into two main phases. 1) A calculation method is developed that can be applied to a flexible number and arrangement of shear walls, assuming the shear walls are connected by infinitely rigid floors. 2) The tool is implemented using Python and Grasshopper. A case study is performed to determine the applicability of the tool to real-life building design. It is concluded that the rigid-floor calculation method is adequate for the design of buildings with minimal out-of-plane floor effects (i.e. buildings with pre-cast floors) and minimal torsional effects. Through the case study, it is shown that the tool can be successfully applied to a building with a complex arrangement of shear walls.

Keywords: parametric design, conceptual design, Grasshopper, structural analysis, computational design, concrete structures.

1. Introduction

The building industry has historically been inefficient and wasteful. Not enough planning is put into early stages of the building design, leading to an uncoordinated process wherein much time and effort is spent in later stages of the building design resolving problems caused by a lack of communication and poor planning in early stages (MacLeamy [8]). Resolving problems in the later stages of building design can be very costly, because at this stage, many features of the building are set in place and not easy to change (MacLeamy [8]).

To create a more efficient and less wasteful building design process, the bulk of the effort should be shifted earlier in time, to the conceptual phase of the building design. A good plan from the beginning will prevent great cost later in the building design phase (MacLeamy [8]). This concept is illustrated by the MacLeamy curve shown in Figure 1 (The Construction Users Roundtable [4]).

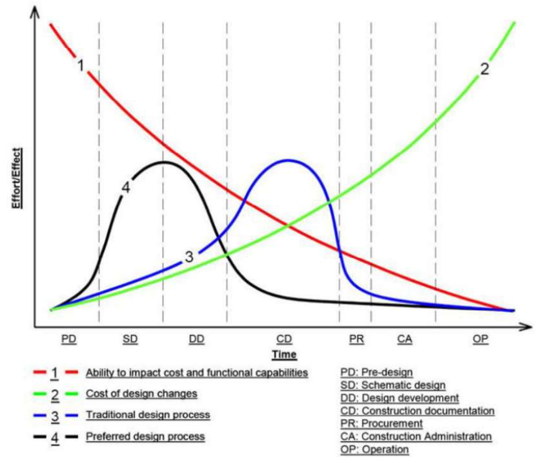

Figure 1: MacLeamy curve (The Construction Users Roundtable [4])

The question arises: How can the building industry shift its effort curve earlier in time? The answer lies within technology. By focusing on developing computational tools that target the early stages of design and improve communication between different parties in the building industry, inefficiency can be greatly reduced. The use of computational tools in the building industry can lead to better control of data and information, better prediction of structural behaviour, among other things (Coenders [2]).

Several computational tools and software to aid the building industry have already been developed. One of the most prominent computational tools used in the building industry is Building Information Modelling (BIM) software. BIM can be defined as a resource where knowledge is shared between different parties involved in a building's life cycle, which enables informed decisions to be made by the constituent parties (Eastman *et al*. [6]).

A number of computational tools for conceptual building design have also been developed. These include graphics statics tools, such as RhinoStatics (Shearer [11]), form-finding tools, design optimisation tools, interactive evolutionary exploration tools, such as IGDT (Intelligent Genetic Design Tool; von Buelow [12]), and parametric and associative design (PAD) tools such as Grasshopper (Davidson [5]).

A previous project related to the development of conceptual design tools for the building industry is Structural Design Tools (Coenders and Wagemans [3]). The goal of this project was to develop a digital toolbox for conceptual structural design, that could be expanded and used to build other software. Structural Design Tools uses a framework called "openStrategy Form Finding" which assumes the design process is varying and flexible and allows the user to choose between a number of different optimisation strategies depending on their design problem (Coenders and Wagemans [3]).

Another previous project is the dissertation project NetworkedDesign (Coenders [2]), which focuses on the creation of a conceptual infrastructure to support computational tools for structural design. The goal of NetworkedDesign is to improve the usability of PAD tools by replacing the current low-code approach with a no-code approach. NetworkedDesign supports a flexible design process: designers may employ multiple different strategies to develop designs, and their design process will vary depending on what type of goals they mean to achieve with their design (Coenders [2]).

The project "StructuralComponents" is a new step towards early-stage tools for the design of buildings. StructuralComponents is an ongoing project that focuses on the development of a conceptual design tool for buildings. Five versions of StructuralComponents have previously been created, beginning in 2008

(Breider [1]). This paper describes "StructuralComponents 6"; a continuation of the StructuralComponents project.

StructuralComponents 6 focuses specifically on the creation of a conceptual design tool for mid-rise concrete buildings laterally supported by shear walls or cores. The goal of the project is to develop a digital tool that allows users to model varying conceptual building designs and provides them with insight on the validity of their designs. In the final tool developed for StructuralComponents 6, the user can create a simple building design composed of floors and shear walls, choosing a rectangular floorplan and whatever number/arrangement of shear walls they would like, and the tool provides structural validation for their building design in terms of the strength, stiffness and stability of the building. The tool is implemented in Grasshopper.

This paper discusses the development of StructuralComponents 6. First, the development of a flexible calculation method to analyse buildings with varying configurations of shear walls and cores will be described. Then, the implementation of the tool in Grasshopper will be described, and a case study used to validate the usage of the tool will be presented. Finally, conclusions and recommendations from the project will be discussed.

2. Structural Principles

2.1. Comparison of floorplans

The first step in developing the tool was to create a flexible calculation method to perform structural analysis for varying configurations of shear walls or cores on a floorplan. StructuralComponents 6 focuses specifically on mid-rise concrete buildings, wherein a mid-rise building is defined as a building of maximum 100 metres in height. It is assumed that in-plane bending of the floors is negligible. To maintain this assumption, it is suggested that the building have a minimum of five floors, although further research is needed to determine the exact minimum height/number of floors required.

In the tool, the composition of the building is restricted to floors and stability elements (shear walls/cores) and only prismatic buildings are considered. Additionally, the following simplifications are made to the structural behaviour of the building:

- Dynamic behaviour is negligible.
- Stability elements behave like flexural beams.
- Connections between the floors and stability elements are hinged.
- Floors are infinitely rigid.

To test the limitations of this approach, three different floorplan configurations were analysed and compared. These different configurations are shown in Figure 2.

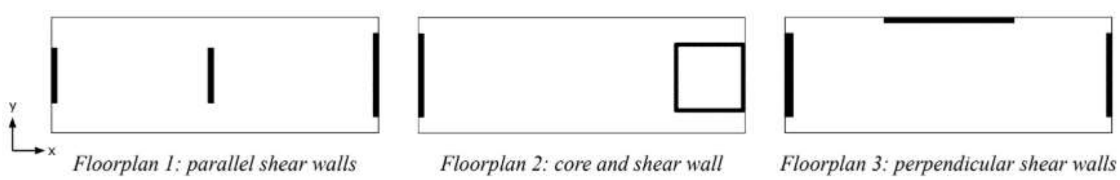

Figure 2: Test floorplan configurations

To compare these floorplan configurations, only wind load was applied to each floorplan and the stability elements were assumed to be rigidly fixed to the foundation and free at the top. For Floorplans 1 and 2, wind was applied in the y-direction only. For Floorplan 3, wind was applied in two separate cases, once in the x-direction and once in the y-direction. In the floorplan configurations, only the core in Floorplan 2 carries torsion; the torsional resistance of the shear walls is negligible.

For each floorplan configuration, a system of equations was determined representing the force and bending moment distribution of the system. Based on this system of equations, the deflection, shear force and bending moment distribution along each shear wall/core was determined, given input wind loads. This process is demonstrated for Floorplan 3 as follows.

The floors connecting the shear walls are infinitely rigid, therefore the floor-shear wall system moves like a unit at every floor level and therefore the deflection and rotation of the unit can be expressed by three general values at the centre of the floor: u_x, u_y and φ. Wind loads p_x and p_y are applied in the x and y-directions, respectively. These values are shown in Figure 3.

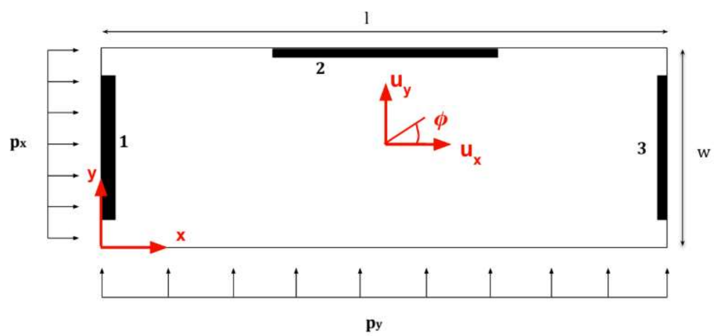

Figure 3: Example floorplan configuration

A general system of equations can be derived as follows:

$$EI_{x1}\frac{d^4u_{x1}}{dz^4} + EI_{x2}\frac{d^4u_{x2}}{dz^4} + EI_{x3}\frac{d^4u_{x3}}{dz^4} = p_x \cdot w \tag{1}$$

$$EI_{y1}\frac{d^4u_{y1}}{dz^4} + EI_{y2}\frac{d^4u_{y2}}{dz^4} + EI_{y3}\frac{d^4u_{y3}}{dz^4} = p_y \cdot l \tag{2}$$

$$\left(a_1 \cdot EI_{y1}\frac{d^4u_{y1}}{dz^4}\right) - \left(b_1 \cdot EI_{x1}\frac{d^4u_{x1}}{dz^4}\right) + \left(a_2 \cdot EI_{y2}\frac{d^4u_{y2}}{dz^4}\right) - \left(b_2 \cdot EI_{x2}\frac{d^4u_{x2}}{dz^4}\right) + \left(a_3 \cdot EI_{y3}\frac{d^4u_{y3}}{dz^4}\right) - \left(b_3 \cdot EI_{x3}\frac{d^4u_{x3}}{dz^4}\right) = p_y \cdot l \cdot \left(x_{centre} - \frac{l}{2}\right) - p_x \cdot w \cdot \left(y_{centre} - \frac{w}{2}\right) \tag{3}$$

where, for a given wall "i":

$$a_i = x_{centre} - x_i$$
$$b_i = y_{centre} - y_i$$

and

$$u_{xi} = u_x - \phi \cdot b_i$$
$$u_{yi} = u_y + \phi \cdot a_i$$

The rotation, bending moment and shear force are derived as follows for a given wall "i" for either the x or y-direction:

$$\varphi_{(x,y)i} = -\frac{du_{(x,y)i}}{dz} \tag{4}$$

$$M_{(x,y)i} = EI_i \cdot \frac{d\varphi_{(x,y)i}}{dz} \tag{5}$$

$$V_{(x,y)i} = \frac{dM_{(x,y)i}}{dz} \tag{6}$$

To validate the accuracy of this calculation method, the calculated deflections, shear forces and bending moments were compared against results from finite element models made using Oasys GSA [10]. The following observations were made from the comparison:

1. Deflections, shear forces and bending moments were well-predicted for all floorplan configurations
2. Predicted deflections, shear forces and bending moments became more accurate as the floor thickness decreased
3. Torsion around the core in Floorplan 2 was very badly predicted
4. Torsion stresses were very small in comparison to bending stresses

Observation 2 can be explained by out-of-plane behaviour in the floors. This out-of-plane behaviour causes an extra normal force to be applied on the stability elements, which affects the bending moment equilibrium of the building and causes the bending moment on the stability elements to increase. As the floors of the finite element models became thinner, out-of-plane floor effects became less significant, which better matched the assumption in the calculation method that out-of-plane floor effects are negligible.

Based on observation 3, it was determined that a rigid-floor calculation method is unsuitable to determine the torsion around a core. However, results of the analysis for Floorplan 2 indicated that the bending stress on the core was fifty-five times as large on the torsional stress around the core, as expressed by observation 4. On this basis, it was determined that torsion can be omitted from the calculation.

It was concluded that this calculation method is generally applicable for prismatic, mid-rise buildings with hinged (pre-cast) floors. The calculation method may however be less accurate for buildings with significant torsional effects. Greater torsional effects tend to occur for buildings that are short and stocky or have highly asymmetrical floorplans.

2.2. Foundation stiffness

In the previous calculation, it was assumed that the cores and shear walls were rigidly fixed to the foundation, but that is not a realistic situation. Since the actual foundation stiffness of a prospective building is not known, a recommended foundation stiffness at the base of the building was calculated using a maximum deflection requirement of height/1000 for each of the stability elements. Thus, the spring stiffness C at the base of each stability was calculated as follows:

$$C = M_{base} \cdot 1000 \tag{7}$$

Rotational spring stiffnesses were calculated for both the x and y-directions, based on the maximum bending moment in these respective directions taken from both load cases. The cumulative deflection on each stability was then calculated as follows:

$$u_{total} = u_0 + \frac{M_{base}}{C} \cdot height \tag{8}$$

which is equivalent to:

$$u_{total} = u_0 + \frac{height}{1000} \tag{9}$$

It should be noted that this calculation is a simplification. The spring stiffness C as calculated in (7) assumes that all shear walls deflect the same amount, which is only the case if there is no lateral rotation in the building. Further research should be carried out to determine a more accurate method to calculate the recommended foundation stiffness at the base of the building.

2.3. Second-order effect

As a last step, vertical load and second-order effect were added to the calculation. To calculate the second-order effect, an overall stiffness of the entire building was estimated as a weighted average of the stiffnesses of the individual stability elements. The calculation of the second-order factor for the entire building for the x-direction is shown below, where C_x represents the total stiffness o the building in the x-direction. $Q_{cr,x}$ refers to the critical downward load calculated for the x-direction. $Q_{cr,fx}$ is the contribution from the foundation stiffness in the x-direction, and $Q_{cr,bx}$ is the contribution from the bending of the building in the x-direction. N_{total} refers to the total vertical load on the stability elements combined. The calculation method is taken from Ham *et. al* [7].

$$Q_{cr,fx} = \frac{2C_x}{height} \tag{10}$$

$$Q_{cr,bx} = \frac{8(EI_{x1} + EI_{x2} + EI_{x3})}{height^2} \tag{11}$$

$$\frac{1}{Q_{cr,x}} = \frac{1}{Q_{cr,fx}} + \frac{1}{Q_{cr,bx}} \tag{12}$$

$$n_x = \frac{Q_{cr,x}}{N_{total}} \tag{13}$$

$$second\ order\ factor\ in\ x = \frac{n_x}{n_x - 1} \tag{14}$$

As a final post-processing calculation, both the deflection and the bending moment in the x and y-directions were multiplied by their respective second order factor for the x or y-direction. At this stage, the calculation of deflection, shear force and bending moment along each wall is complete.

2.4. Automation

The calculation method described in the previous sections can be easily modified for any number and arrangement of shear walls/cores as follows:

$$EI_{x1}\frac{d^4u_{x1}}{dz^4} + \ldots + EI_{xi}\frac{d^4u_{xi}}{dz^4} = F_{x,external} \tag{15}$$

$$EI_{y1}\frac{d^4u_{y1}}{dz^4} + \cdots + EI_{yi}\frac{d^4u_{yi}}{dz^4} = F_{y,external} \tag{16}$$

$$\left(a_1 \cdot EI_{y1}\frac{d^4u_{y1}}{dz^4}\right) - \left(b_1 \cdot EI_{x1}\frac{d^4u_{x1}}{dz^4}\right) + \cdots + \left(a_i \cdot EI_{yi}\frac{d^4u_{yi}}{dz^4}\right) - \left(b_i \cdot EI_{xi}\frac{d^4u_{xi}}{dz^4}\right) = M_{external} \tag{17}$$

The boundary conditions for the initial system of equations can be expressed in terms of the global deflections and rotation u_x, u_y and ϕ as follows:

z = 0: $u_x = 0$ $\quad \frac{du_x}{dz} = 0$

$u_y = 0$ $\quad \frac{du_y}{dz} = 0$

$\phi = 0$ $\quad \frac{d\phi}{dz} = 0$

z = height: $\frac{d^2u_x}{dz^2} = 0$ $\quad \frac{d^3u_x}{dz^3} = 0$

$\frac{d^2u_y}{dz^2} = 0$ $\quad \frac{d^3u_y}{dz^3} = 0$

$\frac{d^2\phi}{dz^2} = 0$ $\quad \frac{d^3\phi}{dz^3} = 0$

The additional deflection and bending moment caused by the rotation of the foundation and the second-order effect can be added as post-processing to this calculation.

In StructuralComponents 6, this calculation process was written into a Python script wherein the number and location of shear walls are variables.

2.5. Structural checks

StructuralComponents 6 must provide the user with structural validation of their building design. The following structural checks were implemented in the tool. These checks are performed for a concrete structure; f_{ck} refers to the characteristic cylinder stress of the concrete. The shear strength check is from Section 6.2.2 of NEN 1992-1-1 (2005) "Members not requiring design shear reinforcement" [9].

1. Stiffness

$$abs(u_{x,y}) \leq \frac{height}{500} \tag{18}$$

2. Strength

a) Compressive strength

$$\frac{N}{A} + abs\left(\frac{M_{x,y}}{W_{x,y}}\right) \leq \frac{f_{ck}}{1.5} \tag{19}$$

b) Shear strength

$$abs(V_{x,y}) \leq \left(v_{min} + 0.15 \cdot \frac{N}{A}\right) \cdot A \tag{20}$$

where:

$$v_{min} = 0.035 \cdot k^{\frac{3}{2}} \sqrt{f_{ck}}$$

$$k = 1 + \sqrt{\frac{200}{d}} \leq 2 \quad \text{with d in mm}$$

3. Stability

$$abs\left(\frac{M_{x,y}}{W_{x,y}}\right) - \frac{N}{A} \leq 0 \tag{21}$$

3. System architecture

3.1. Grasshopper components

StructuralComponents 6 was implemented in Grasshopper in the form of connectable components. Only shear walls were implemented as stability elements. Four components were developed in total:

1. Construct shear wall: Allows the user to define the dimensions and location of a shear wall on the x-y plane
2. Construct floor: Allows the user to define the dimensions and location of the floor on the x-y plane
3. Calculator: Calculates the forces and deflections along each shear wall and performs structural checks
4. Visualiser: Visualises the building, force and deflection distributions and structural checks

Figure 4 shows the construction of a hypothetical conceptual building design with three shear walls.

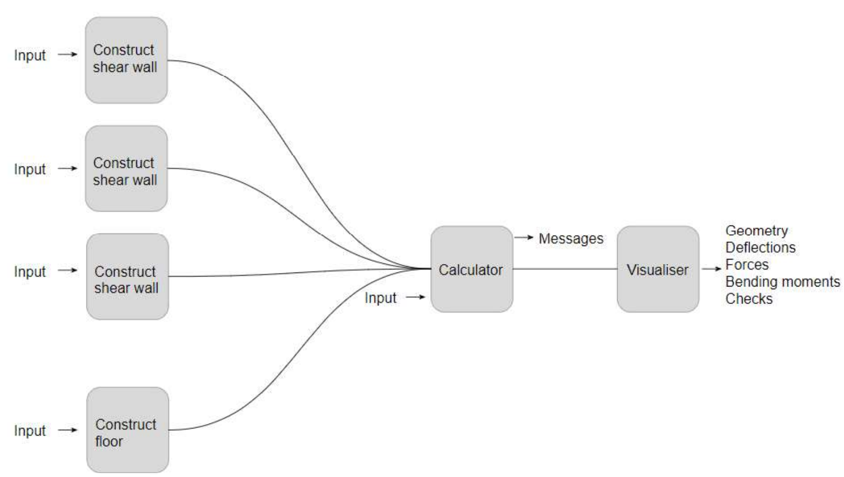

Figure 4: Construction of a floorplan with three shear walls

The user can define their floorplan using the Construct floor and Construct shear wall components. The Construct Floor component is limited in that it can only model rectangular floor shapes, but since the floors are considered to be infinitely rigid, other floor shapes can be approximated as rectangles in the tool without consequence to the structural analysis.

The constructed floor and shear walls are used as input into the Calculator component. Other inputs into the Calculator component are the floor height, number of floors, material properties and applied loads and load factors. Output from the Calculator is used as input into the Visualiser, which visualises the three-dimensional building design in the Rhinoceros 3D viewer connected to Grasshopper and causes individual shear walls to turn red if they fail any of the structural validation checks.

Figures 5 and 6 show the visualisation of a failed compressive strength check, and visualisation of deflection in the y-direction for an example building.

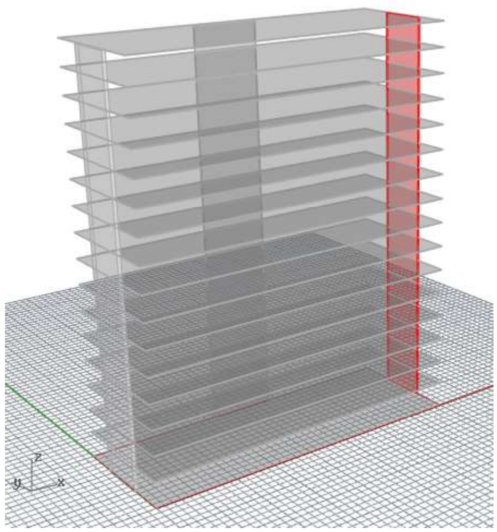

Figure 5: Visualisation of a compressive strength check, floors shown

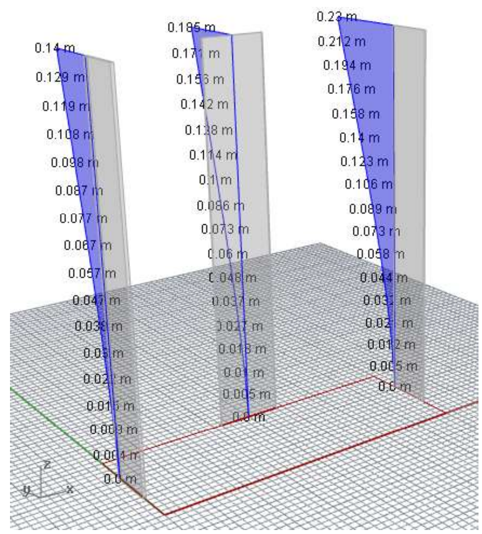

Figure 6: Visualisation of deflection in y-direction, scale factor 50, floors not shown

3.2. Case study

To validate the usage of the tool, a case study was performed using the Electrical Engineering, Mathematics and Computer Science tower ("EWI") at the Delft University of Technology as a model. An image of this building is shown in Figure 7.

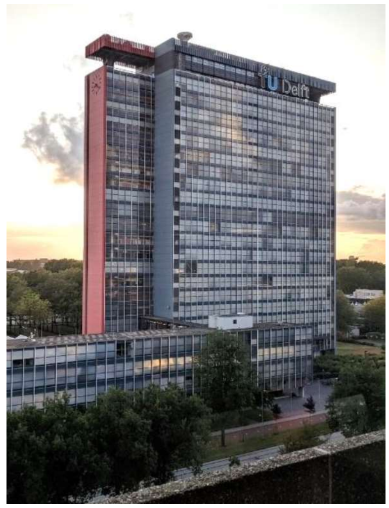

Figure 7: EWI Building, Delft University of Technology

The purpose of the case study was to validate the tool in terms of ease of model construction, speed of analysis and visualisation of results and was not meant to provide an accurate structural analysis of the building structure, since the structure has been greatly simplified for this case study.

Figure 8 shows the floorplan used in the case study, showing only the floor and the lateral stability members. The dotted line represents the actual shape of the floor, which was approximated to a rectangle.

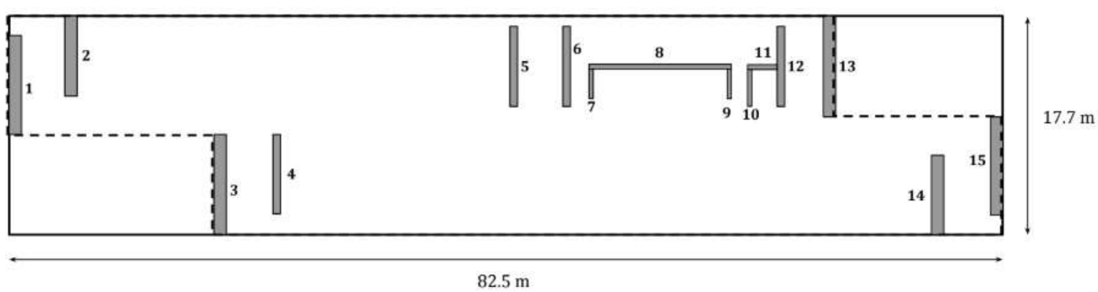

Figure 8: Floorplan used for case study

Each individual shear wall listed in Figure 8 was modelled with a separate “Create shear wall” component. Since only shear walls can currently be modelled in StructuralComponents 6, the C-shaped elements comprising walls 7 to 12 were split up into six individual shear walls. It should be noted that this creates a slight inaccuracy in the analysis because the moment of inertia of separate shear walls is different than the moment of inertia of an entire C-shape.

Table 1 shows the input properties used for the analysis.

Table 1: Properties used in case study

Property	**Value**
Wind in x (kPa)	1.6
Wind in y (kPa)	1.6
Live load (kPa)	2.5
f_{ck} (kPa)	30000
Young's modulus (GPa)	33
Material density (kN/m^3)	24.5
Floor height (m)	3.75
Number of floors	24

Dead load in the analysis comprised of the self-weight of the building.

Four analyses were run in the case study:

1. Wind load in the x-direction, SLS
2. Wind load in the x-direction, ULS
3. Wind load in the y-direction, SLS
4. Wind load in the y-direction, ULS

Deflections were checked for the SLS cases, and strength and stability were checked for the ULS cases.

Results from the analyses indicated that deflection, strength and stability checks all failed for the building. The maximum deflection found in the analysis 0.382 metres on Wall 1, which exceeds the maximum allowable deflection of 0.18 metres by more than a factor of 2. Some possible explanations for these results could be that the structural system of the building was greatly simplified for the case study, and also that the predicted foundation stiffness of the building was much weaker than the actual foundation stiffness. A further explanation could be that modern building codes are stricter than they were in the past.

In terms of the usage of StructuralComponents 6, it was concluded that it can be successfully applied to a building with many shear walls. However, some improvements could still be made to the tool, such as providing more stability elements than just shear walls and allowing the user to model a floor that is not rectangular.

4. Conclusions

In the project, a calculation method was successfully developed that can be used to calculate the deflections, shear forces and bending moments along various configurations of shear walls and cores on a floorplan. The calculation method is generally applicable for prismatic, mid-rise concrete buildings with pre-cast floors, but is limited in its ability to analyse buildings with significant torsional effects. Possibilities for future development of the calculation method are to investigate the effects of torsion and out-of-plane floor effects on the building behaviour, and to develop a more accurate method for determining the design foundation stiffness of the building. Further, an investigation could be taken into the addition of expansion joints in the floors, since expansion joints are common in concrete buildings.

Secondly, the calculation method was incorporated into a tool in Grasshopper wherein a user can create a conceptual building design composed of shear walls and floors and validate the structural adequacy of their design. Through a case study using the EWI building of the Delft University of Technology, it was determined that the tool can be successfully applied to a building with a complex arrangement of shear walls. Further improvements to the tool could include the addition of more stability elements, such as cores or U-shapes, and allowing the user of the tool to create non-rectangular floors.

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