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StructuralComponents – a parametric associative design toolbox for conceptual structural design

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Abstract

Current analysis tools available to the designing structural engineer do not support the early design stage on a conceptual level, since these tools are mainly aimed at precision rather than flexibility, the generation of alternatives and providing oversight over a design concept. The authors propose a parametric associative design toolbox for early stage conceptual structural design; a prototype implementation consisting of several .NET add-ins for GenerativeComponents (Aish [1]). The designer can generate different structural concepts for a high-rise building quickly and easily. The tool improves the interaction between the architect and engineer by increasing the flexibility and speed of the design process. The structural engineer can actively participate and is able to work in parallel with the architect during the early design phases. The concept is based on a modular software architecture and dashboard for visualisation. In such a way that a structural model can be built from abstract objects, called StructuralComponents, which represent pre-programmed blocks of differential equations. The dashboard principle allows the engineer to have all the relevant information visible in a single view. The set-up of the model can be adapted during the design.

The analysis method is a combination of the finite element method and differential equations (Steenbergen [7]). The basis is a finite element model with a limited amount of elements, where the elements represent the various structural elements. This results in a system with a limited amount of elements and a limited amount of degrees of freedom, which benefits the computation time. Different from conventional finite element methods, differential equations are used to determine the total system behaviour instead of interpolating the results using shape functions. This offers exact analytical results, providing quantitative and qualitative results. The tool is developed for tall buildings, but the concept is applicable to other structural systems. Future developments include enhancement of the user interface, 3D analysis, and more types of components.

Keywords: parametric associative design, conceptual structural design, modularity, performance output, dashboard, tall buildings, computational design.

1. Introduction

In the conceptual design stage usually the most important design decisions are made. These decisions are often very influential on key drivers, such as cost, material quantities, energy consumption, etc, imposing constraints on the key problem and thereby shaping later (downstream) decisions during the design process. In the early phases it is important to see the consequences of decisions or to get a feeling for the magnitude of the consequences on the drivers as well as risk. This especially, since in these phases changes are relatively easy made, while limited information is available. This is in contrast to the application of these tools in later design phases, where many approaches for modelling and definition of buildings in the phases close to the construction exist. These variations are fairly small to those made in the early phases of design, and the impact of these decisions on the key drivers is relatively small. Current tools available for the structural engineer are often built for the stages at the end of the design process and are intended for analysis or documentation purposes rather than for structural design.

Figure 1: The gap between structural design methods. Courtesy of prof. Wagemans.

Another problem in the conceptual design phases is the lack of (inter)compatibility between tools for architects and engineers. These tools are often not interchangeable and the conversion of information may take a lot of time, slowing down the entire design process. As a result, it is not possible to work on a design simultaneously. The aims of StructuralComponents are to stimulate collaboration between the architect and engineer from the very beginning of a design process. As such, a toolbox for early stage structural design was developed, which enables the engineer to make a conceptual structural design for a high-rise building quickly and easily. By using real time analysis, the architect and engineer are provided a tool that allows them to work shoulder to shoulder and reduce the time necessary for the design process.

The intended user of this tool is still the structural engineer. The tool is not meant to replace structural engineers or their knowledge, but to complement them in the first steps of engineering by providing proper means to perform this task. The engineer conceives the concept of the structure and its behaviour. The engineer is in control of the structural design process, since he can use this toolbox to generate structural concepts or even adapt the tools to fit a certain purpose. The real time qualitative and quantitative information about the structural behaviour allows the engineer to make proper design decisions.

2. Conceptual outline of the tool

StructuralComponents provides a method to make a structural model that gives estimates of the structural behaviour. It should be easy to adapt the model and compare different alternatives in a few minutes in order to be useful during the early design phases. The tool is based upon two approaches, a modular software architecture and dashboard presentation.

2.1. Modular software architecture

The toolbox can be controlled like structural Lego®: a model can be built from a limited amount of blocks called StructuralComponents, which are pre-programmed blocks of differential equations. By adding, changing and removing components infinitely configurations are possible. The components have the ability to perform real-time structural analysis, when the model is changed, the analysis changes on-the-fly due to the parametric associative nature, allowing the engineer to judge and adapt different concepts in a matter of minutes.

2.2. Dashboard presentation

In order for real time analysis to be useful, the results should be easy and quick to interpret. Therefore, only relevant information (key performance indicators) is presented on a dashboard and visible to the engineer in a single look. These results are given in the form of diagrams and dials that show the structural performance of a structural concept.

Figure 2: The modular approach and dashboard principle

3. Software

The features or StructuralComponents have been developed in C# and .NET. Programming offers a lot of advantages, such as versatility and flexibility and the possibility for the user to adapt or create features. It also generates only the desired output. This prevents any superfluous information that only slows the model down.

The projects created in C# can be loaded into a parametric associative software application. The programming architecture is set-up in a modular and generic way in order to facilitate future developments and integration with other platforms.

The parametric associative nature is an effective and efficient method to generate a lot of alternatives and adapt them in (near) real time. The design logic is captured in logical definitions defined by parameters and linked by associations. Using definitions the models can be small, only containing the necessary information.

4. Structural model of a tall building

The elements represent actual structural components of a high-rise building. As buildings increase in height, lateral forces due to wind and earthquakes become increasingly important in structural design considerations. Most high-rise structures tend to be tall and slender; these structures have relative uniform properties over the height, alternative continuum models can be formed, which can be analyzed by closed form solutions of the characteristic differential equations.

4.1. Components of the toolbox

The components used within StructuralComponents represent idealised structural elements that only contain the most important structural properties with their dominant modes of behaviour. Each element is given specific stiffness parameters, which depend on the structural system and determine the influence of bending, shear, axial compression or tension, torsion and warping. To incorporate all the modes of behaviour of an element, each node needs seven degrees of freedom: an axial deformation, deflections in two directions, three rotational degrees of freedom and a warping degree of freedom. This gives a 14x14 stiffness matrix for each element.

4.2. Different structural components

Tall building structures can be modelled in two ways within StructuralComponents. The first method divides the structure of a tall building in several super components, like a core, columns and outriggers. The second method divides the structure in sections over the height. On each component the continuum approximate theory has been applied (Smith *et al.* [6]). This theory involves using the stiffness parameters of the individual elements to determine the overall parameters αH and k for the total component, and then applying the differential equations to determine the deflections of the whole structure. Coupled walls, rigid frames, braced frames and tubular structures are well represented by the theory.

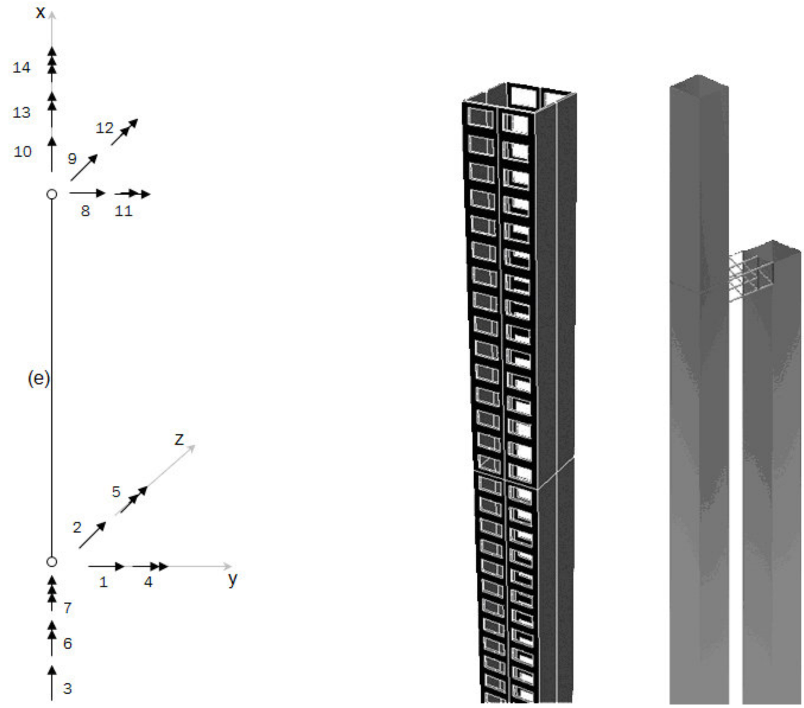

Figure 3: The figure on the left shows the degrees of freedom of an element. The right shows different components.

4.3. Structural behaviour of a component

The axial behaviour under vertical loading (dead load) is described by the following second order differential equation:

$$\frac{d^2u_x(x)}{dx^2} = \frac{q(x)}{EA} \tag{1}$$

where EA is the cross-sectional area of stiffness. To describe the lateral behaviour a fourth order differential equation is needed in both y and z direction:

$$\frac{d^4u_i(x)}{dx^4} - (k\alpha)^2 \frac{d^2u_i(x)}{dx^2} = \frac{1}{EI}\left(\frac{d^2M(x)}{dx^2} - (k\alpha)^2 \frac{k^2-1}{k^2} M(x)\right) \tag{2}$$

where $\alpha^2 = \frac{GA}{EI}$, EI the flexural rigidity, GA the shearing rigidity and M the applied external moment. The relative stiffness parameters k and α determine the distributions of axial forces, shear flow and bending moment to the total external moment. Due to eccentricity of the lateral loading the components are subjected to warping. To describe the warping torsional behaviour of an element another fourth order differential equation is needed:

$$\frac{d^4\theta(x)}{dx^4} - \alpha^2 \frac{d^2\theta(x)}{dx^2} = \frac{m(x)}{EI_\omega} \tag{3}$$

where $\alpha^2 = \frac{GJ}{EI_\omega}$, which is a structural parameter that characterises the behaviour of the component.

4.4. Loading on tall buildings

Wind and earthquake loadings are random in nature and difficult to predict. StructuralComponents calculates static and dynamic loadings based on the size and shape of the building, as well as occupancy and the geographic location of the building. The used method is based on the work of Davenport and is included in the national building code of Canada (Taranath [8]). This method determines the external pressure or suction on the building surfaces and the acceleration at the top.

The loads can also be applied manually. The modular approach allows the user to create multiple load cases for a model; uniform distributed loads, triangular distributed loads and point loads can be applied.

5. Analysis of StructuralComponents

As described in Section 5.1, each element is described by differential equations which include stiffness parameters. The first step in the analysis is to determine the element properties, such as the mechanical properties and any possible restraints. This results in a local stiffness matrix $\mathbf{K^e}$**.** The stiffness matrix describes the homogeneous displacements of the nodes caused by nodal forces. This means that the stiffness matrix can be determined by finding the homogeneous solution of the differential equations that describe the behaviour of the element. The general expression for the homogeneous solution is (Van Dalen [9]):

$$u_{\text{hom}}(x) = \sum_{i=1}^{n} C_i u_i(x) \tag{4}$$

where vectors $\mathbf{u_i}$ are the partial solutions corresponding with the roots of the characteristic equation, and $\mathbf{C_i}$ the corresponding constants. The relation between the degrees of freedom and the analytical expressions for displacements as determined by Equation 1 is given by:

$$u_{\text{hom};node} = Hc \tag{5}$$

Matrix **H** is a square 14x14 matrix which contains the geometrical information of an element. The next relation that is required is the relation between the element forces $\mathbf{f^e}$ and the section forces occurring at the ends of an element, these relations can be written as:

$$f^e = Gc \tag{6}$$

The local system is given by:

$$f^e = K^e u_{\text{hom}} \tag{7}$$

From Equations 6 and 7 follows for $\mathbf{K^e}$**:**

$$K^e = GH^{-1} \tag{8}$$

The proper sign convention needs to be used in these equations to convert from finite element sign convention (Blauwendraad [2], Steenbergen [7]), the sign conventions for differential element equations (Bouma [3]), to the sign convention used by StructuralComponents, which adopts the standard sign convention as used in common geometric modelling software (Pottmann *et al.* [5]).

Next step in the analysis is to assemble the global stiffness matrix from the local stiffness matrixes. The coupling of the elements, which can be either parallel or serial, determines the place of the local stiffness matrixes in the global system. The global boundary conditions are assembled from the local constraints in a global vector.

Also, a global load vector needs to be constructed from local load vectors $\mathbf{f_i^e}$. Therefore, the modelled load needs to be converted to equivalent nodal loads. This is achieved by using the differential equation that describes the behaviour of the element. With this mathematical description the primary force vector is determined. The resulting reaction forces form the node loads. Concentrated loads can only be applied at the nodes and need to be considered in the load vector. The load vector f^e_{tot} is described by:

$$f_{tot}^{\ e} = f - f_{prim}^e \tag{9}$$

Vector **f** contains the node forces, and f^e_{prim} is the primary node force vector. The primary force distribution is the force distribution in the case of fully restrained nodes and consists of two parts. The first part consists of forces that occur when the deformations in the nodes due to the particular solution of the differential equation are prevented. These forces can be determined with the following relation:

$$f_{prim,I}^e = -K^e u_{part} \tag{10}$$

The second part is directly derived from the particular solution.

Once the global system has been assembled it can be solved; the results are displacements in the nodes $\mathbf{u^g}$:

$$f^g = K^g u^g \tag{11}$$

The system can be solved by various solving algorithms (e.g. Gauss-Jordan elimination, LDU decomposition). The global boundary conditions must be processed, each degree of freedom that is restrained will have its corresponding row entries in the global stiffness matrix set to zero, except for the pivot entry which is set to 1.

Having solved the nodal displacements and forces, the distribution for the total structure can be determined using the differential equations. The nodal displacements and forces act as boundary conditions, and the solutions for the displacements and forces are determined. From these solutions the stresses and strains can be determined and checked with the structural requirements.

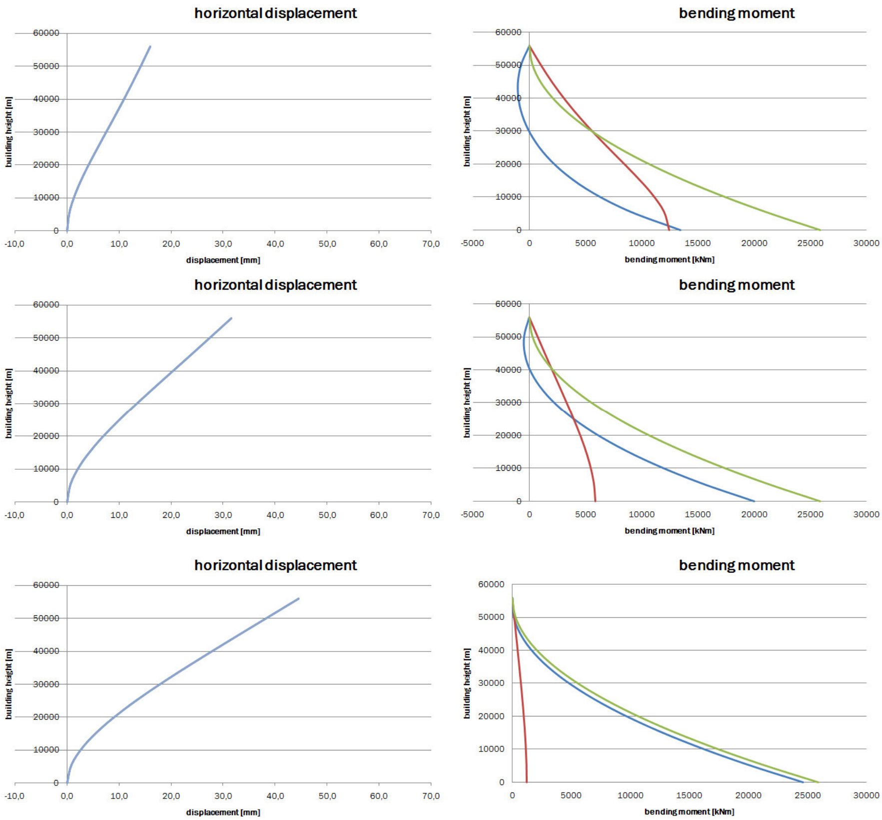

Figure 4: These graphs show the results of the analysis of a perforated core. The graphs on the right show the bending moment in the core (green = applied external moment, blue line = bending in the walls, red line = moment by axial forces). The stiffness of the connecting beams decreases from top to bottom and the results change on the fly.

5.1. Performance output

The dashboard can be customised to obtain the desired output, by using a combination of diagrams and dials that display the various results. In order to compare different concepts or to judge the behaviour of a structure a performance index is necessary.

The available results can also be used to investigate the sensitivity of a structural design to changes in certain parameters and stiffnesses.

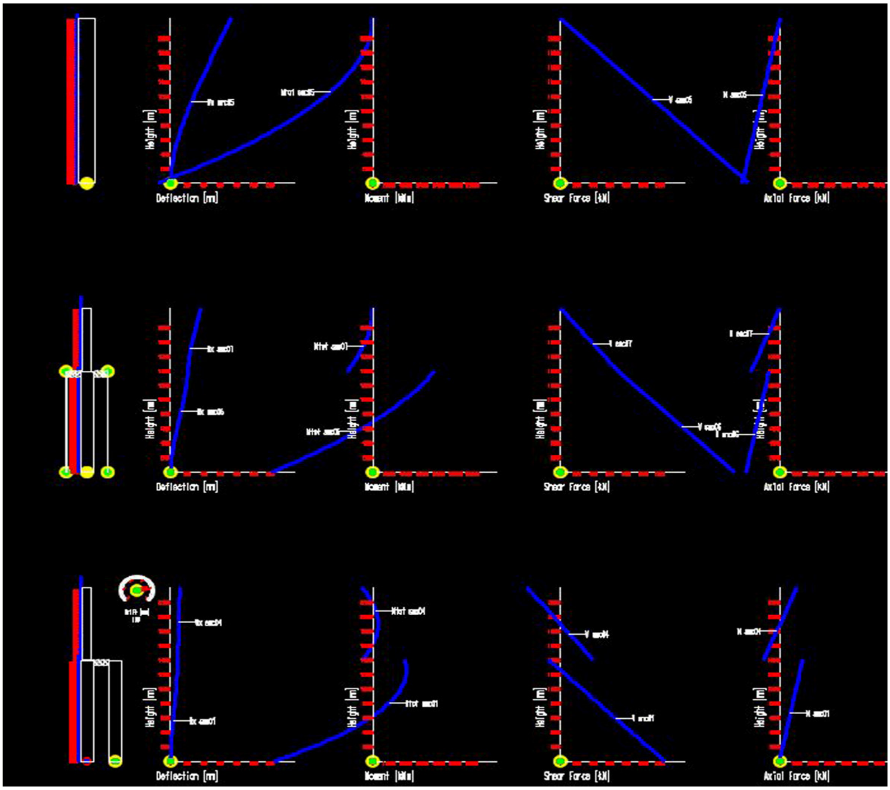

Figure 5: Different concepts of a tall building with analysis output in one dashboard.

5.2. Accuracy of the toolbox

StructuralComponents is based upon the assumption that a component is uniform throughout its height. In other words, the properties of the walls, columns and cores do not change over the height. All structural elements behave linear elastically. To accomplish this, some structural elements, like connecting beams, are distributed over the height of a storey. These simplifications make the tool less accurate than conventional finite element programs, but the tool gives a good qualitative and quantitative understanding of the relative influences of different structural elements.

To validate the results from the toolbox, different models of simple academic cases of high-rise buildings from StructuralComponents are compared with similar models in GSA, Arup's in-house structural software (Oasys [4]). The error in deflections and forces is less than five percent, which is acceptable for conceptual structural design.

6. Discussion

The current status of the toolbox is a prototype which can be used to design and analyse three dimensional high-rise buildings consisting of cores, outriggers and columns in any possible configuration. Although StructuralComponents is already quite versatile using only a very limited number of elements, the aim is to develop the toolbox further and bring it a few levels up in terms of both concept and versatility and flexibility.

The conceptual goal is to develop the structural design tool to a multifunctional performance based design environment. It will not only be focused on high-rise buildings, but on all sorts of structures. It will be able to adapt its dashboard to show the key design drivers for a specific type of structure, whether that is a stadium, a high-rise, an airport roof structure, etc.

The structural design functionality will become a part of the total environment in which other disciplines are also integrated such as (technical) architecture, sustainability, finance, building services etc. This will enable designers to generate a total estimate of a buildings performance on multiple key issues, which can be used to make well informed design choices.

In terms of versatility and flexibility the development will occur in two directions; on one hand the functionality needs to be expanded and become more powerful. This incorporates a higher quality dashboard, more powerful and flexible analysis engines. An important addition is adding flexibility in the work flow of the structural design. In early stages of design the ideal structural design tool should work bidirectional in terms of starting points; one can start with a structure and then compose and design the model until it fits key design criteria. In this case the structure is the starting point of the design. More often, the design starts with certain geometry. This geometry is used to generate a more detailed design, where everything is subject to change. In this case the structural engineer would first define the structural design criteria which are used to generate one or more structural design alternatives. This means that based on shape and location the structural engineer determines requirements such as maximum drift, maximum acceleration, wind load etc. Subsequently, he can determine the desired mechanical properties such as flexural stiffness. Based on such properties the tool can generate multiple structural models which can be evaluated and adapted by the designers to fit the total design. This concept will be expanded to other disciplines as well.

On the other hand the interoperability with other software needs to be enhanced so that various design and/or analysis models can be extracted from the initial model, which can even provide more detailed feedback to the initial design and specify the design in more detail. In this case the model will act more as an integrated information model that collects relevant information from separate detached models used for specific purposes. In this way a more smooth transition into later design phases is realized and no laborious conversions or remodelling are required.

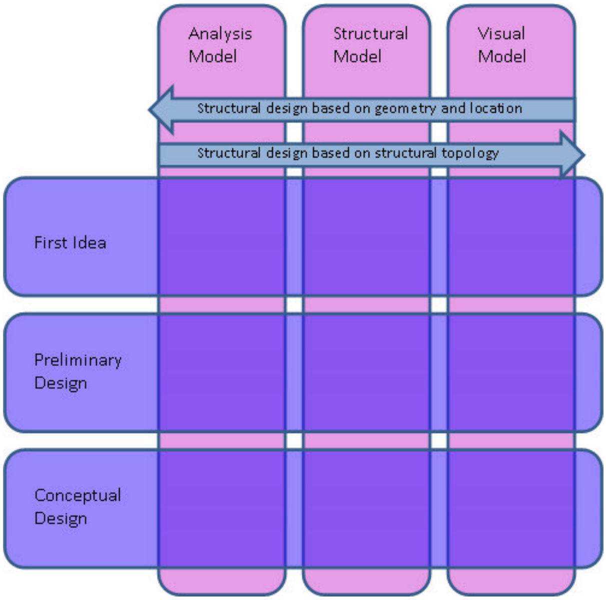

Figure 6: The roadmap for early design phases.

7. Conclusion

The intention of StructuralComponents is to support the early stages of design of tall buildings, to create an environment in which architects and structural engineers can work simultaneously and to provide better and quicker design processes and consequently better building concepts than with conventional approaches. The method is faster and more versatile than rules of thumb or even simple mechanics, while easier to use for conceptual design problems than finite element analysis software. Such a change of the work process is considered an improvement on situations nowadays where architects and structural engineers respond to design changes made by the other party.

StructuralComponents is a parametric structural design tool for high rise structures. It is based on GenerativeComponents (Aish [1]) for which extra features have been developed in a .NET environment.

The chosen approaches for StructuralComponents contribute to the flexible nature of the early design phases. The modular component approach allows composing and changing a structural design quickly and easily, while the dashboard approach contributes to the ease of designing by presenting the key design indicators in a manner that is very understandable.

The analysis method fits into the parametric nature of the used software. It is very fast so that analysis results are processed in near real-time. The nature of this speed lies in the fact that only few elements are used to model a structure. The behaviour of an element itself is accurately described by mechanical differential equations. The element based approach makes the analysis compatible with the modular nature of StructuralComponents.

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