

Realistic Structural Stabilization based on Spatial Zoning

Boonstra S, Claessens DPH, Hofmeyer H, De Vries B
Eindhoven University of Technology, The Netherlands

s.boonstra@tue.nl

Abstract. An automated stabilization procedure for structural designs is presented and applied in conjunction with a building spatial zoning algorithm. The stabilization procedure can stabilize kinematic systems in a building's structural design model while taking into account structurally relevant zones within that building's spatial design. A case study shows that the presented stabilization procedure, compared to an existing stabilization technique, can find stiffer and more practical structural designs that are less sensitive to progressive collapse.

1. Introduction

Structural Design (SD) of buildings aims at the design of structural systems that are stiff, strong and stable. The strength of a structure is related to the forces at which structural components will fail. Stiffness is related to the deformations that can occur in the structure, which is important with respect to usability, sense of security, and possible load accumulations. Stability is related to any kinematic system that may develop in the structure when there are no or insufficient structural provisions to prevent such kinematics. Stability and stiffness—which influence each other—are primarily determined by the synthesis of structural components like trusses, beams, or slabs. In this work, only statically under-determinate structures are considered for stability, thus no phenomena like (local) buckling. An automated stabilization procedure is presented which can extend a structural design such that becomes stable and stiff. Moreover, the procedure can find designs that have structural redundancy, i.e. no progressive collapse occurs after one structural component fails. The automated stabilization procedure is applied in conjunction with spatial zoning, which yields a number of geometric layouts of a Building Spatial Design (BSD) that are promising for structural design. For each zoned BSD, a structural design is generated and then stabilized, from these, the most suitable structural design for a BSD can be selected.

This paper is structured as follows. In section 2 the related work and the motivation are presented. Thereafter, in section 3, the methodology behind the new stabilization procedure is explained. Next, section 4 presents a case study, in which the presented method is compared to an existing method. Accordingly, the discussion in section 5 gives critical remarks on the presented work. Finally, the conclusion and outlook are presented in section 6.

2. Related Work and Motivation

The presented work is part of a larger research project that focuses on multi-disciplinary building spatial design optimization. Within that project a toolbox has been developed (Boonstra et al.; 2018), the methods and tools in this work have been developed within its framework.

In this section, first an overview of the related work on automated structural design is given in subsection 2.1. Following that, in subsection 2.2, work on automated structural stabilization is outlined. Thereafter, in subsection 2.3, research on zoning for structural design is treated. Finally, the motivation for the presented work is explained in subsection 2.4.

2.1. Automated Structural Design

The starting point for a building structural design is usually a building spatial design. The BSD determines where the loads (e.g. live and wind loads) are located, and thus where a structure is needed. In an early example to support this process, Rafiq and MacLeod (1988) presented a method to automatically generate a structural design for a BSD. More recently, Geyer (2008) developed a method based on several design rules, that—in combination with each other—can create a large variation of structural designs. By evaluating each variation of structural design, a selection can be made for a high quality/optimal structural design. Steiner et al. (2017), on the other hand, proposed a method that integrates architectural design with structural design. This allows an architect to interactively design the building spatial design as well as the structural design simultaneously. In the toolbox, presented in (Boonstra et al.; 2018), structural designs can also be generated automatically for a BSD by using deterministic design rules that operate on the geometric entities of the BSD. As such, BSDs that are found by an optimization method can be automatically evaluated with relative ease and speed by the optimizer. The automated design methods that are mentioned above, do not explicitly take into account stability. However, stable designs are still achieved by e.g. defining design rules such that a stable structural model is guaranteed, which relies on human experience and programming. If in an unforeseen event an unstable design is generated it should be disregarded or fixed, but chances are it is considered as feasible by the automated structural design method. An automated stabilization procedure could serve to check or fix instabilities, or even become a part of an automated structural design method. Moreover, a stability check may even serve designers in detecting possible oversights in their structural design.

2.2. Automated Stabilization

Automated stabilization of a building structural design was first introduced in (Hofmeyer and Russell; 2009; Smulders and Hofmeyer; 2012). These works assume that an unstable structural design model is provided in the form of a Finite Element Method (FEM) model, stabilization is then carried out as follows. First the Global Stiffness Matrix (GSM) is generated, this system of linear equations relates the displacements of each node (discretized point) in the model to the forces in that model. A Singular Value Decomposition (SVD) is then carried out on the GSM, which is used to find the nodes that have a Degree Of Freedom (DOF)—which can be either a displacement or a rotation—that is not restrained from movement by any structure nor by any boundary condition. Once the nodes with such free DOFs are found, a search for nodes in the proximity of the free-DOF-node is performed. The found nodes serve as an anchor point, to which a stabilizing provision can be attached, e.g. a diagonal truss. More than one anchor point may exist, a selection is then based on suitability based criteria, for example if a prospected anchor point contains no free DOFs itself. This procedure is carried out in an iterative fashion until no more free DOFs are found. The above stabilization procedure has also been implemented in the toolbox of (Boonstra et al.; 2018), which is described in more detail in (Claessens; 2018).

Although stabilization with the described procedure will yield a stable design, one might ask how practical an arrangement of stabilizing provisions is but also how safe it is. Since the procedure stops directly after it stabilizes the model, there will be little to no structural redundancy. In other words, if one of the stabilizing provisions fail, the structural design is unstable again and therefore prone to collapse (Smulders and Hofmeyer; 2012). This issue is also relevant for practical design scenarios, where insufficiently redundant designs can go unnoticed.

2.3. Zoning

In a BSD, the layout that follows from its spaces may not be logical for certain building design disciplines (Hoskins; 1979). More logical layouts may follow from grouping spaces or sub-parts of spaces into zones (Björk; 1992). This is also the case for structural design. Meyer et al. (1993) and Parent et al. (2006) studied how structural engineers apply zoning to BSDs, and concluded that points of interest are the geometric continuities in a BSD and the locations where that continuity ends. Previous work on zoning for structural design by Hofmeyer et al. (2006) was extended in (Claessens; 2018; Hofmeyer et al.; 2019) for the toolbox (Boonstra et al.; 2018) by focusing on the continuities and discontinuities in a BSD. Using this extension, the amount of zoned designs can be limited to only those that have such continuity characteristics, and are thus promising for structural design.

2.4. Motivation

In this section it has been reasoned that automated structural design methods, but also designers, may benefit from an automated stabilization procedure. Such stabilization methods have been developed, but they may yield designs that are safe nor practical with respect to structural redundancy. In addition, zoning has been developed as a method to find structurally relevant zones for structural design. Here a new stabilization procedure is proposed, in which structurally relevant zones are each stabilized individually. As such, structural redundancy is taken into account more appropriately, and in a fashion that is practical from a structural point of view.

3. Methodology

In this section, first some features in the toolbox of (Boonstra et al.; 2018) are explained, where after the new stabilization procedure can be explained. These features are: The tools that can generate a structural model for a BSD in subsection 3.1; Zoning of BSDs in subsection 3.2; And, stabilization in subsection 3.3. Thereafter, in subsection 3.4, sufficient background knowledge has been supplied to introduce the new stabilization method.

3.1. From Building Spatial Design to Structural Model

This subsection gives a brief introduction into the definition of a BSD in the toolbox, a decomposition model of a BSD, and the procedure that generates a structural design model from that decomposition. For more details, the interested reader is referred to (Boonstra et al.; 2018).

Building Spatial Design. In the toolbox a BSD is primarily a collection of cuboid spaces arranged in an orthogonal grid. A space can, as such, be defined by a position vector and a dimension vector, and a BSD as a set of such pairs of vectors. BSDs in the toolbox are limited to this orthogonality so that the research for which it has been developed does not need to be distracted by complex rules, e.g. initialization and modification rules for round spaces. In the left of figure 1, an example of a BSD that can be represented in the toolbox is given.

Conformal Model. In the toolbox, the conformal model is intended to store geometric information and associate this information with the building design. This can significantly simplify queries for geometric characteristics within a BSD, e.g. T-joints, which are relevant connections

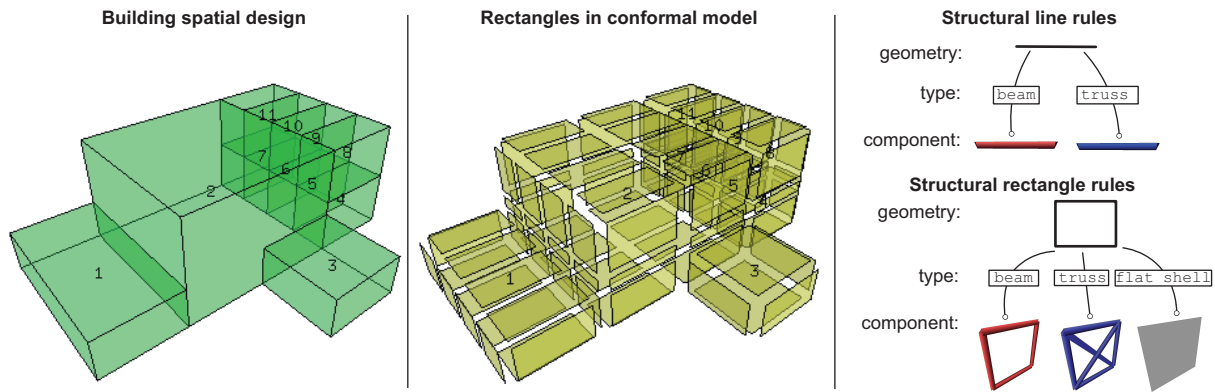


Figure 1: Left, a building spatial design; Middle, the rectangles within a conformal model; Right, examples of rectangle and line rules for structural design, trusses are indicated in blue, beams in red.

in the structural model. A conformal model is generated by considering two decompositions of a BSD. On one hand, a geometric decomposition stores all the unique non-overlapping points, lines, rectangles and cuboids that are present in the BSD's geometry. On the other hand, a building design decomposition is made, in which the points-, edges-, and surfaces of spaces and the spaces themselves are stored. Entities within these two decompositions are associated with one another. For example, a rectangle is realized by four lines and it realizes 1 or 2 cuboids, simultaneously it can be associated with 0, 1, or 2 surfaces. Such associations can be used to query information in the BSD, for example the external boundaries of a BSD are those rectangles that are associated to exactly one surface. Whereas if a rectangle were associated with two surfaces, it describes an internal boundary between spaces. The above queries are illustrated in figure 1 in the middle, which gives a visualization of the rectangles in the conformal model (of the BSD on the left) that are associated to one or two surfaces.

Structural Design Grammar. The associations between the different entities in a conformal model are convenient for a variety of concepts, one of which is the design of a structural model. For example, a rectangle can be used to define what structural component should be placed (e.g. a portal frame of beams or a flat shell). Whereas, the surface(s) that that rectangle is associated with can be used to determine the load, e.g. in case of exactly one surface association (see above) a wind load is applied. Here, a structural design grammar is a set of rules that operate on the rectangles and the lines in the conformal model. Each rectangle or line in the conformal model is supplied with such a rule. Structural components, loads, and boundary conditions are created by these rules depending on: (1) the associations that exist for that rectangle or line; And, (2) possible user specifications. On the right of figure 1 examples are given of possible structural components that can be generated using such rules. By following each rule of the grammar a structural design model is generated in a deterministic way.

3.2. Zoning

Zoning in the toolbox is achieved by using the conformal model. A zone is a collection of cuboids and is itself also defined as a cuboid. The latter is chosen for simplicity and for continuity purposes, which is what structural designs benefit from (see subsection 2.3). A zoned design is then a combination of zones, with the requirement that each cuboid in the conformal model is associated to a zone. Using the conformal model's cuboids to form zones is convenient

because it is merely a combinatory task of connected cuboids that are found using the various associations within the conformal model. Additionally, through the cuboids, zones are associated with a BSD's geometry and building design information. The definition of a structural design grammar for a zoned design is then almost the same as the grammar for unzoned BSDs.

In general, the zoning algorithm searches for all the largest zones which smallest span is less than or equal to a user defined maximum span. Smaller zones are in this way excluded so that the number of found zones is relatively small. This method assumes that a suitable span length is selected for the structural system that will be generated by the design grammar. The next step in the zoning algorithm is the combination of the found zones into zoned designs. In a zoned design, zones are not allowed to overlap. When a combination of zones leaves a number of cuboids in the conformal design unoccupied and none of the remaining zones can be used to occupy them, additional zones are created. These additional zones are created for each unfinished combination by using the unoccupied cuboids. In the toolbox, the initially created zones are deemed most important and are termed primary zones, the additionally created zones are termed additional zones. The zoning algorithm, has been described in more detail in (Claessens; 2018; Hofmeyer et al.; 2019).

3.3. Stabilization of Nodes

Stabilization, similar to what is published in (Smulders and Hofmeyer; 2012), can be achieved as follows. Assuming that a possible unstable structural design model has been generated for a BSD, first a singular value decomposition (SVD) is performed for the global stiffness matrix of that SD model. The free degrees of freedom (DOFs) in the SD model are then identified as described in (Smulders and Hofmeyer; 2012). Nodes with free DOFs are iterated one by one, and for each free DOF it is assessed if a suitable anchor point, i.e. a so-called key point, is present. A key point is suitable if it is rigid in the considered DOF's direction and if it is positioned in the surface of a space (Smulders and Hofmeyer; 2012) or in the surface of a zone (Claessens (2018)). If a suitable key point is found, a stabilizing provision is placed. After a provision is placed, a new SVD is performed after which the nodes with free DOFs are iterated and checked for suitable key points again, this is repeated until no more free DOFs are found.

For key points, a distinction is made in the planes in which they are positioned with respect to the free DOF: in-plane or out-of-plane. If in-plane key points are available an instability can be resolved by either a diagonal truss (figure 2), or when a diagonal would intersect for example a space a portal frame of beam components can be used (figure 2). In-plane stabilization is preferred, because the DOF will then be stabilized in a more direct load path. However, when no in-plane stabilization key points are available for any of the nodes with free DOFs, out-of-plane stabilization will be applied. This type of stabilization (re)places (components with) beam components in between the free-DOF-node and the key points, also see figure 2. More information on the procedure can be found in (Smulders and Hofmeyer; 2012; Claessens; 2018).

3.4. Stabilization of Zones

Stabilizing a structural model with the procedure described in subsection 3.3 yields an SD model that is stable but does not possess structural redundancy. In real world design such redundancy is desired, therefore, it is here proposed to at least stabilize each individual primary zone in a BSD. The procedure is divided into four steps, in which patterns of structural stabilization provisions are applied to the surfaces of the zones, see figure 3. In the patterns of figure 3, each rectangle

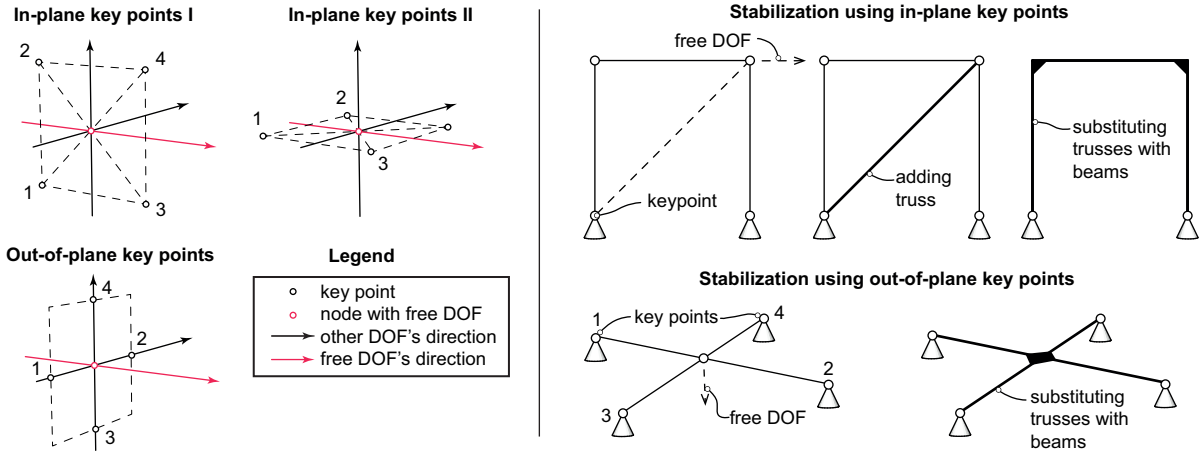


Figure 2: Left, key point positions in the conformal model for both in-plane and out-of-plane stabilization. Right, possible provisions to stabilize using either in-plane or out-of-plane key points

corresponds to a rectangle in a conformal model, all rectangles together are the complete surface of a zone (either horizontal or vertical), and to a coloured rectangle a stabilizing provision will be applied. If a stabilizing provision is applied to a rectangle, then—in the structural design grammar—its rectangle rule is assigned a diagonal truss component. If the rectangle rule has already been assigned a stable component (e.g. a flat shell), that component is maintained. The four steps in which the patterns are applied are presented in the remainder of this subsection, and they are visualized in figure 4.

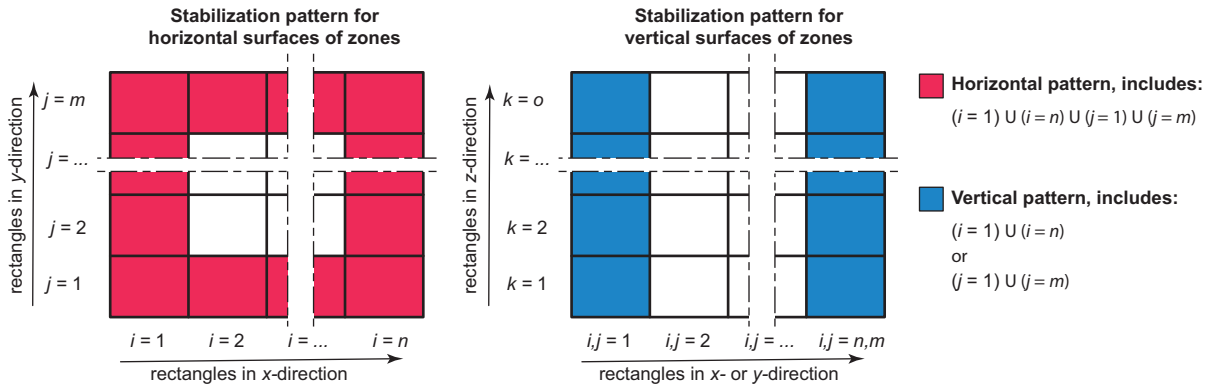


Figure 3: The two patterns of provisions, one for horizontal- and one for vertical zone surfaces.

Step 1. This step is initiated with an SVD, which is used to list the free DOFs for each node. Accordingly, the horizontal surfaces of the primary zones are listed and checked for free DOFs in geometric order (ascending in x , then y and then z -direction), if it contains a node with a free DOF the pattern for horizontal surfaces will be applied. Additionally, if it is the top surface of a primary zone, then the pattern for vertical surfaces will be applied to all vertical surfaces of that zone. Note that an SVD is carried out only once at the beginning of this step, and hereafter each primary zone will be stabilized.

Step 2. The second step is the same as the first, except that it is now performed for the additional zones and the pattern for vertical zone surfaces is not applied. The pattern for vertical zone surfaces is in this step omitted to prevent an excess of provisions in the BSD's façade.

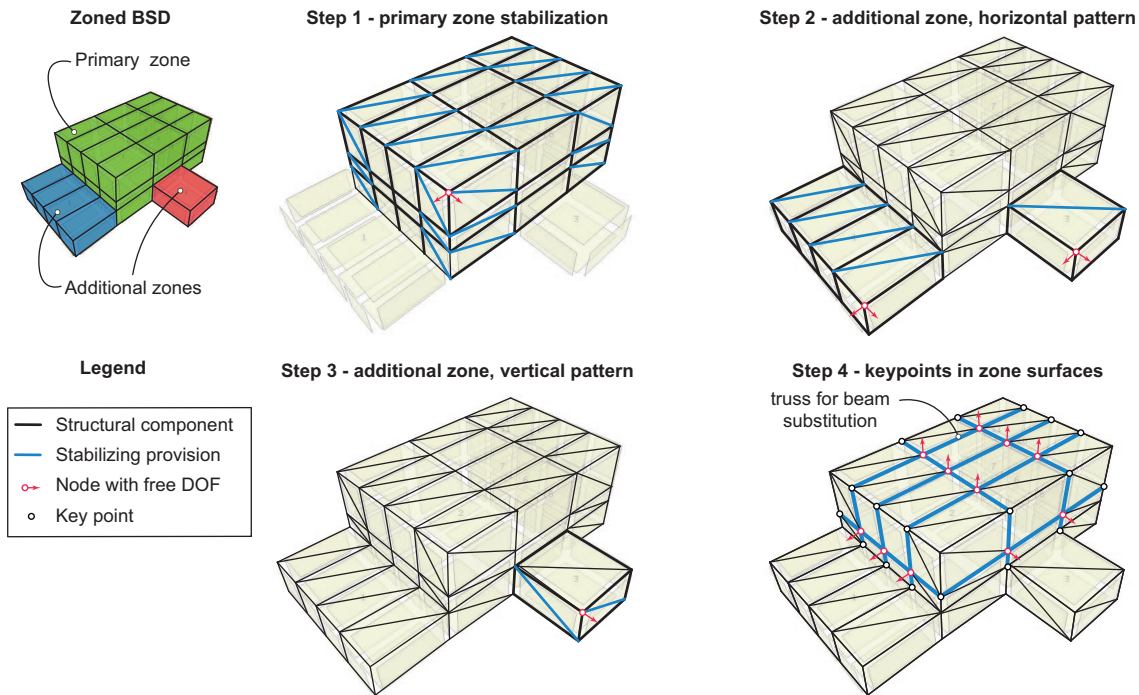


Figure 4: The provisions that may be applied by stabilization through zoning during each step for a given zoned BSD.

Step 3. Similar to the first two steps, first an SVD is used to check for free DOFs. Consequently, all horizontal surfaces of the additional zones are checked in the same geometric order that was used in steps one and two. If a node with a free DOF is contained in the top horizontal surface of an additional zone, the pattern for vertical surfaces is applied to all of that zone’s vertical surfaces. If a pattern is applied, a new SVD is performed before the checks of the horizontal surfaces continues.

Step 4. In the fourth step any remaining nodes with free DOFs will be stabilized by finding key points and adding structural provisions as explained in subsection 3.3. Here, key points should be located on the surface of a zone of the considered zoned BSD. If, after the above, still free-DOF-nodes exist that do not have key points that lie on a zone’s surface, also other key points are allowed.

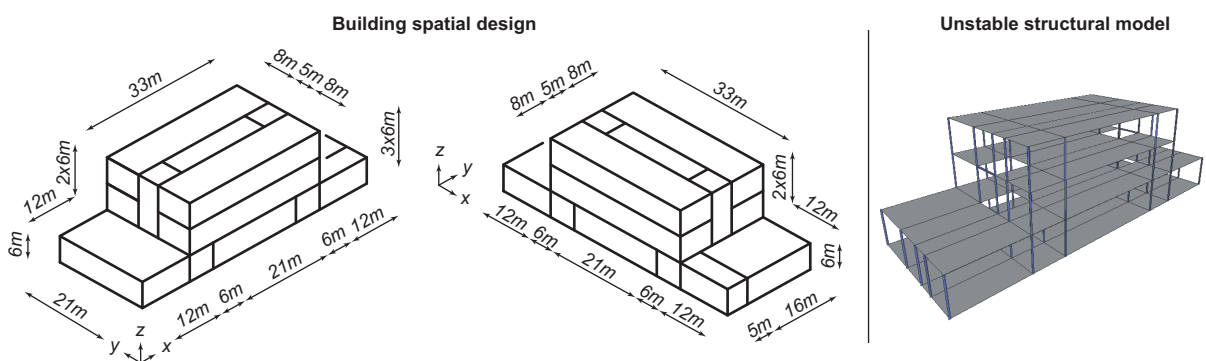


Figure 5: Left, the considered building spatial design model. Right, the structural components that will be generated by the structural design grammar for the BSD on the left.

4. Case Study

In this section, the BSD in figure 5 is subjected to a case study. The two presented methods for stabilization are applied to the BSD, i.e. stabilization of nodes via key points (subsection 3.3) and stabilization based on zones (subsection 3.4). In this section first the settings for the structural design grammar, the zoning procedure, and the stabilization procedure are given in subsection 4.1. Thereafter the results are presented in subsection 4.2.

4.1. Settings

Structural Design Grammar. The structural design grammar assigns flat shell components (elasticity modulus $E = 3 \times 10^4 \text{ N mm}^{-2}$, Poisson ratio $\nu = 0.30$, and thickness $t = 150 \text{ mm}$) to horizontally oriented rectangles that are associated with one or two surfaces of a space. And, the grammar assigns truss components (cross sectional area $A = 5000 \text{ mm}^2$ and elasticity modulus $E = 2.1 \times 10^5 \text{ N mm}^{-2}$) to vertically oriented line segments that are associated to one or more surfaces of spaces. As truss components cannot transfer lateral or bending forces, the structural model is unstable, the resulting structural model is shown in the right of figure 5. Five load cases are defined, one live load case and four wind load cases. The live load acts in $-z$ -direction, is assigned to all flat shell components, and has a magnitude of 5.0 kN m^{-2} . A wind load case is defined in each azimuthal direction ($+x$, $+y$, $-x$, and $-y$), where for each wind load case three types of loads are applied: wind pressure (1.0 kN m^{-2}), wind suction (0.80 kN m^{-2}), and wind shear (0.40 kN m^{-2}). A wind load is applied to rectangles that are associated with exactly one space surface, where the type of wind load depends on the orientation of that rectangle. Because no structure—to which the wind loads can be applied to—exists at vertically oriented rectangles, flat shell components (elasticity modulus $E = 3.00 \times 10^{-2} \text{ N mm}^{-2}$, Poisson ratio $\nu = 0.30$, and thickness $t = 150 \text{ mm}$) are applied in order to transfer these loads to the structure. The low stiffness of these load transferring components ensures that these components do not influence the stiffness of the building structure. As such, the load transferring components function similar to façade systems, which transfer load but do not take part in the building's structural system. Moreover, all flat shell components with a z -coordinate lower or equal to zero ($z \leq 0$) have their movement in x -, y -, and z -direction constrained at their edges. Finally, flat shell components are meshed into 10×10 flat shell elements, beam components (applied by the stabilization procedures) are meshed into 10 beam elements, and truss components are meshed into 1 element.

Zoning Procedure. For zoning, the maximum span in the structure is set to 21 m. Other settings for the zoning procedure have been omitted from this work for brevity. However, in reference to (Claessens; 2018; Hofmeyer et al.; 2019), it is noted that the large solution space of zoned designs (labeled by 'L' in their work) is used for this case study.

Stabilization As mentioned, stabilization will be performed using the two presented methods (subsection 3.3 and 3.4). Here, each method will be applied once to every zoned design that results from the zoning procedure. In order for the method that stabilizes nodes to yield a different solution for each zoned design, here, it is required that each of the used key points lies within the surface of a zone. The latter requirement has in fact proven to lead to better designs in (Claessens; 2018; Hofmeyer et al.; 2019). Both stabilization procedures have the ability to apply truss components (same as in design grammar) and beam components (width $w = 150 \text{ mm}$, height $h = 150 \text{ mm}$, elasticity modulus $E = 3.0 \times 10^4 \text{ N mm}^{-2}$, Poisson ratio $\nu = 0.30$).

4.2. Results

The zoning procedure found 14 zoned designs for the BSD of the case study. Applying both methods once for each zoned design has thus yielded 28 structural models. The performances of each of those designs are compared to each other in the plot in figure 6. Plotted on the horizontal axis is the total sum of volumes of the structural components that were used to stabilize the structural model. On the vertical axis—using a logarithmic scale—is the total sum of strain energy in the structural model, which is a common measure for the stiffness: higher stiffness yields a design with less strain energy. In the plot, performances of structural designs whose nodes were stabilized are indicated with a cross, whereas a circle is used to indicate performances of SDs resulting from stabilization of zones. Moreover, a Pareto front approximation (PFA) is given by drawing a line through the non-dominated points in the plot.

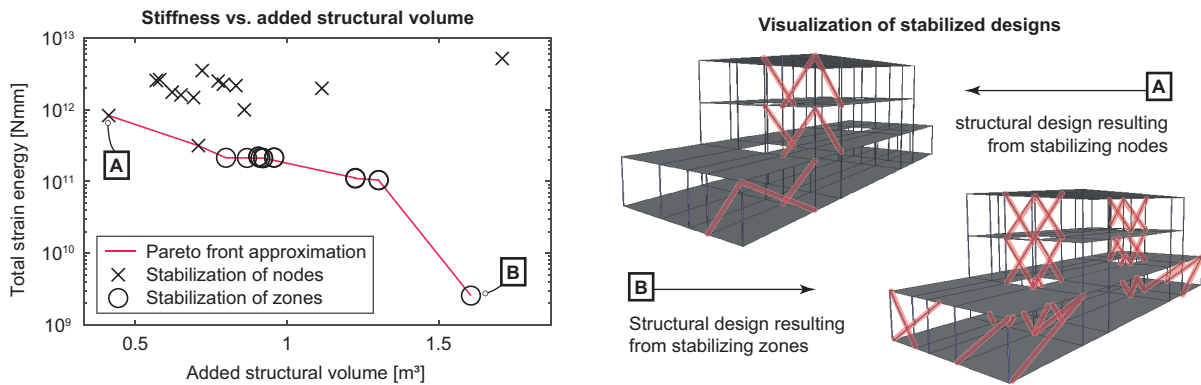


Figure 6: Left, plot with structural design performances that result from the two stabilization methods. Right, from each method one visualization of the found structural designs.

From the plot in figure 6 it can be observed that all structural designs resulting from stabilization based on zoning are on or close to the PFA, whereas the other method mostly yielded dominated solutions. Therefore, any SD resulting from the method that stabilizes zones individually can—for this case study—be regarded optimal in some sense for the contradicting objectives of stiffness and structural volume. Another observation that is made from the plot: stabilization of zones, adds more structural volume to the structural model, i.e. more material is needed. However, considering that a stiff design may allow for components to be dimensioned smaller, this additional volume could be negated. Finally, in the right of figure 6, one of the SDs is depicted for each of the two methods. Comparing these SDs, it is noticed that stabilizing each zone individually indeed requires more components, but it can also be noticed that the method will indeed provide an SD with more structural redundancy and a more organized layout.

5. Discussion

Although results are promising, critical notes can be made. First, the case study is limited, and the presented results may not generalize. Therefore, a more extensive case study should be performed to make the conclusions that were extracted from the results better grounded. Second, a rather simple pattern of stabilizing components has been used for stabilization based on zoning. In practice, more (perhaps better) patterns may be observed, and it would be interesting to also investigate other patterns. Finally, the stated hypothesis that stiff designs allow for components to be dimensioned smaller is not investigated. It would be interesting to also investigate this hypothesis in conjunction with the new zoning method.

6. Conclusion and Outlook

In this paper, a new stabilization method for structural building design is presented. The method uses a zoning procedure to find structurally promising zones within a building design, which are then used to check the structure that is enveloped by these zones for stability. As such, the stabilization procedure can find structurally redundant designs, i.e. designs that are less sensitive to progressive collapse, by placing stabilizing provisions at locations (derived from zones) that are logical from a structural point of view. A case study has shown that the proposed method is promising, as it finds designs that are stiff and structurally redundant. However, critical notes were made in the discussion, which gives an outlook onto an extended case study which includes more design scenarios and additional settings for the proposed zoning procedure.

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