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ORIGINAL PAPER

Structure as (primary) generator of architectural design: a study of a master dissertation studio

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Abstract
The design studio plays a central role in educating architecture students to develop design skills and be creative when dealing with the complexity of ill-defined design problems. One way for students to cope with these problems, and find a way into the design process, is to reduce the complexity by framing the problem. This can, for example, be established by focussing on the design component of structure as a broad field, ranging from engineering theory over structural materials, products and systems to construction details. It allows to create a variety of structural frames to step into the design process, and generate architectural design proposals. This design generation, starting from the student's structural knowledge, that leads to creative design, is the subject of this paper. For this research, 36 master dissertation projects were analysed, developed under the supervision of the author. In these projects architecture students created a personal link between the realm of structure and their architectural design to generate architecture through structural framing. This resulted in a final design project and a dissertation with reflections on the developed structure-based design generators. This paper shortly introduces the applied studio approach to help students implement their structural knowledge for design generation. Furthermore, it presents 14 identified types of structure-based design generators, to illustrate their potential in architectural design and to provide a frame of reference for students to develop creative design skills.

Keywords Structure · Architecture design · Design generation · Architecture education · Design strategy

Introduction

The design studio plays a central role in educating architecture students to develop design skills and be creative [1–3] when dealing with the complexity of ill-defined design problems [4], also referred to as wicked problems [5]. Developing creative ideas at the start of the design process [6–8], and implementing divergent thinking [9] are hereby recognized as valuable approaches to develop creative design outcomes.

One way for students to deal with the wicked problem of design and find a way into the design process is to reduce the design complexity by framing [10] the problem through a focus on some of its multi-dimensional components [11]. One of these components is the structure of the architectural form that needs to withstand the various loads inherent to the design project.

This component is essential in architectural design, and the relationship between structure and architectural form has often been investigated: several types of this relationship are mapped by Angus Macdonald [12], while Bjørn Sandaker et al. [13] describe the structure's spatial and mechanical functions in architecture. Additionally, many creative design projects can be found in which structure was an important part of the architectural concept and design development. Here creativity is often attributed to the design collaboration of architects and structural engineers [14–17]. Also emerging possibilities in fabrication and construction emphasize the crucial role of this structure component in architectural design [18, 19].

However, for the architecture student in the design studio, the first steps into a design project and the generation of design ideas, are mostly the product of his/her individual cognitive processes and thus not due to creative design collaborations with engineers. And consequently, in order to develop creative design outcomes adapted design strategies are required.

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When framing the design problem through the component of structure, the available knowledge field in which the architecture student can find creative ideas is larger than the strict interpretation of the (materialised) structure needed to support the final architectural form, as described above. The student's cognitive framework reaches from engineering theory over structural materials, products and systems, to construction details. It allows for a variety of structural frames to step into an architectural design and generate various design proposals. This design generation, starting from the student's structural knowledge, that leads to creative design, is the subject of this paper.

After three years of leading a master dissertation studio on architectural design, called "Studio Structure", at the faculty of Architecture, KU Leuven (campus Ghent), the author discovered repeating patterns in the structure-based design generation of the students' projects. This paper introduces the concept of design generator, and the applied studio approach that helped students implement divergent thinking and develop creative ideas when applying their structural knowledge for design generation. It further presents the identified design generators, developed from a broad, structure-inspired field, to illustrate their potential in architectural design and to provide a frame of reference for students to develop creative design skills.

Design generator

Jane Dark developed a model to describe a design process based on a cyclic sequence of *primary generator, conjecture* and *analysis* [20]. According to Dark the complexity of a design problem is reduced by the designer to a cognitive manageable size by focussing on certain aspects the designer finds essential. This is the primary generator, similar to the *organizing principle* of P.G. Rowe [21] and the *frame* of Donald Schön [10]. Based on this reduction a design proposal is developed (i.e. the conjecture) and then analysed. This analysis allows the designer to have a better understanding of the design problem at hand, and to develop a more adapted conjecture, and possibly adjust or change the primary generator for further refinement.

The primary generator is a way into the design (at the start of the process) and linked by Brian Lawson [11] to the *design concept, parti* or *central idea* that mainly shapes the design outcome. Lawson also connects the primary generator of a design project to the *guiding principles* of the designer. These guiding principles, go beyond a single project and express the personal beliefs, values and attitudes a designer develops over the years about the way design in his/her field should be practised.

In this paper, a design generator is understood as a cognitive construct developed by the designer to provide a way into a design problem and help forward the design project significantly. It consists of a cognitive framework (i.e. the primary generator) to reduce the complexity of the design problem, and contains the ability to generate design proposals (i.e. the conjectures). In design, multiple generators can be at play and the implementation of a certain generator is not necessarily visible in the design outcome as its importance can fade during the further course of the design process.

Structure

Structure as a concept in architectural design is often reduced to the set of construction elements (e.g. beams, columns and slabs) of a building that is responsible for transferring the most important loads to its supports [12, 13, 22]. However, in architecture more meaning is attributed to structure than just this physical system of structural elements in a building [23]. For example, according to Eduard Sekler a distinction can be made between structure and construction. Sekler considers structure an abstract concept that follows established principles destined to cope with the forces in a building, while construction is to him the actual materialisation of this structure in a building [24]. This abstract, cognitive construct of structure can also be found in the concept of *Kunstform* of Karl Bötticher, which is considered the ornamentation that clads the essential construction (i.e. *Kernform*) of a building, and is capable of expressing the structural forces and rules hidden behind the visual surface [25]. This expression, importantly, requires a cognitive framework of an observer to interpret the structural story.

A similar role of the cognitive abilities of the interpreter of the architectural building and its structural story can be found in the corporeal metaphor of a building transferring forces to the ground, and our own body under gravitational loads [26].

It is this broader understanding of structure in architecture, that is applied in this paper, as in the studio learning environment: structure is understood as a cognitive framework, a lens through which architectural form is interpreted (cf. Kunstform). This framework is developed through a personal understanding of experiences and precedents that find their meaning in the realm of structural engineering theory with its established principles and rules.

Consequently, structure as a (personal) framework that helps the observer to make sense of architectural design, stands next to other sensemaking frameworks of architecture like function, light, thermal comfort, organization, texture and culture. It is within this broad and abstract understanding of structure that design generators are mapped in this paper, to open up a potential for creative design.

Studio structure

The Faculty of Architecture, where the design studio is offered, has a history in education based on the Ecole des Beaux Arts tradition [27], and values students to develop creative and personal designs. The investigated design studio (30 ECTS credits) is the master dissertation course for architecture students. It ends their five-year programme (300 ECTS credits) in which half of the courses focus on design in studio learning environments, and the other half are theory courses in Building Technology and Architecture History & Theory, mainly taught in classrooms. The courses on structure theory focus on developing an understanding of first principles and structural behaviour, and less on teaching how to dimension and calculate structures.

In this "Studio Structure" students are required to develop a design strategy that generates creative ideas through divergent thinking, and apply this strategy when designing their architecture project. (This project acts as a test case for the design strategy under development, and symbolizes a set of similar projects in which the strategy is applicable). Students are asked to find a personal link between the broad realm of structure, as described above, and their architecture project in a search to generate architecture through structural framing. In their project they are free to choose the programme and context to allow for additional personal themes in their dissertation project, which helps their engagement in the studio.

Students have specifically chosen this studio next to others, because of their interest in structures. In their application letter for the studio, students indicate various fascinations for structures: the aesthetics of structure and construction (e.g. Japanese wooden joinery), the relation between the structure and the experience of architectural space, the reality of constructing a building according to regulations, and the integration of structure in a design project. Some students also express their longing to improve their understanding of structural behaviour, and their ability to design structures. The studio aims to have students develop personal design generators based on their personal interests in structures, which in turn can evolve into personal guiding principles.

To help students improve their skills in structural (divergent) thinking for architecture design generation, they are introduced to a conceptual structural design thinking through the abstract language developed by the author [28]: by using symbols the structural function of an element is expressed (cf. Fig. 2), and as such a structural conceptual design can be presented as a system of abstract elements without having to decide materialisation or structural typology. This approach allows for a wide search for conceptual design alternatives, and simple form alterations within one structural conceptual design, while maintaining a large design solution space (since no structural type or material is chosen). (In order not to influence the student's creation of personal design generators, no other hints for generators are provided).

In the studio, tutoring is weekly provided, first in groups of students and then evolving to a more personal approach, while peer learning is encouraged throughout the course. Since developing a design generator is a wicked problem in itself, students are encouraged to follow the design cycle of Dark. They investigate their (ill-defined) link between structure and architectural design, by choosing a personal frame (i.e. primary generator) for the creation of a design generator and then applying this generator in their design project (i.e. conjecture) to analyse the quality of the design generator and also to evaluate the chosen frame for adjustment. Different cycles are followed before a satisfying design generator is found. This design-led research results in (1) a reflection paper in which the theoretical investigations and the developed design generator(s) are addressed, and (2) a design project to demonstrate the applicability of the developed design generator(s).

Research method

In this research, design generators are mapped by analysing 36 design projects created in three consecutive years of this master dissertation studio. All dissertations were supervised by the author of which 19 together with a colleague. Data of the students' design processes were retrieved through the weekly observations during the one semester in which students presented their ongoing work, through informal interviews with the students, reviews, their reflection papers, and final design documents and presentations. In order not to influence the students' development of design generators and allow for the widest variety, no examples of the previous year(s) were presented to a new cohort of students.

For each project, the author identified in detail all project-specific design generators related to the structural field. In the next step, these project-specific generators were analysed for common characteristics to identify types of design generators by focussing on the origin and development of the generators, and their ability to develop design proposals or conjectures. This analysis process started with the batch of 7 projects of the first year, then the next 10, to end with the final 19 projects of the third year. (As a control, the co-supervisor of this last batch identified independently of the author, similar project-specific design generators). For each batch, the present types of design generators were identified before the next batch was analysed. This allowed the author to control (1) if the already identified types would reoccur and have meaning in the new batch, and (2) if new types would still be discovered to check the completeness of the design generator set. For the last batch, which contains more than 50% of all analysed projects, it showed that only

Table 1 Analysis of design projects per batch: number of design projects per batch; applied design generators per batch; newly discovered design generators per batch; other applied design generators per batch; the total of discovered design generators per batch and previous batch(es)

Batch	Design Projects	Applied Generators	Newly Discovered Generators	Other Applied Generators	Total of Discovered Generators
1	7	9	9	0	9
2	10	11	4	7	13
3	19	13	1	12	14

one more type of design generators was discovered and that thus the already discovered thirteen generators effectively covered most of the field (Table 1).

The design generators of studio structure

In the design studio, 14 different design generators were identified, linked to the broad field of structure (Table 2). Each generator was developed within a cognitive framework, through a cyclic process as described above.

For most of these generators, the applied framework belonged to the field of structural engineering: concepts, principles and logics of structural behaviour and design were applied to adapt and refine the generator. Students operated in this framework by mainly applying structure calculations software, rules of thumb and first principles.

However, some students developed their generators within a cognitive framework belonging to the field of aesthetics, in which for example the personal appreciation of structural form stands central (i.e. away from the cognitive framework of engineering sciences). This led to a division into two main groups of the identified design generators: *structural engineering* and *aesthetics*.

For both groups, the final outcome of a generator development, allowed to produce a wide range of qualitative design proposals or conjectures, mostly based on a developed generic catalogue of design possibilities, or by applying explicit and/or implicit design rules or principles.

Another interesting observation is that some students developed their generator through the use of an existing building or type of building. In these cases, this building importantly determined the properties of the generator (e.g. a catalogue of structural interventions in a 19th-century warehouse).

This building dependent development further divides the first group (structural engineering) into three subgroups: generators developed with an existing building (*building dependent*), without using a building (*building independent*) and developed with or without using an existing building (*mixed*).

In the second group (aesthetics) only one type of design generators was identified, developed with and without an existing building determining the final outcome.

To indicate the importance of each design generator, the number of projects in which the generator was applied is indicated in brackets after its title. (Remark: one project can have multiple design generators).

Structural engineering; building dependent

These design generators are developed by using an existing building or a type of building that importantly influences the generator's characteristics.

Remediate intervention (9 projects)

After analysing structurally and architecturally an existing building or type of building for refurbishment, various spatial interventions are imagined by the student based on qualitative spatial needs (e.g. daylight transmission, floor height, free plan) or other types of architectural investigations (e.g. stripping a church building to its stylistic characteristics). These interventions affect the structure of the building and require structural remediations to maintain its stability. The relationship between intervention and remediation is explored by applying a set of specific

Table 2 Overview of the 14 different identified structure-based design generators

Framework of development	Context of development	Structure-based design generators				
Structural Engineering	**Building dependent**	Remediate Intervention	Context-Specific Addition	Structure Mimicry		
	Building independent	Structural Material	Adaptable (Con) Structures	Structural Joint	Structural Typology	Structural Product
	Mixed	Principle Repetition	Grid	Structural Module	Abstract Prototyping	Structure Reuse
Aesthetics	**Mixed**	Structure Experience				

interventions and developing different possible structural remediations for them (Fig. 1). These remediations can be developed through structure calculation software, or by applying rules of thumb and simple first principles of structural design. This process generally leads to an informed catalogue of possible types of interventions as inspiration for their own project, or can result in certain design rules or strategies ranging from intuitively understood to specifically defined.

Context-specific addition (8 projects)

This generator is used to explore possible additions to an existing building by thoroughly analysing the building's structure and selecting (by the student) one or more important structural characteristics for refurbishment. This structural mapping can include soil characteristics, structural order, structure typologies, stress patterns, (non-)supporting walls, foundations, structural history,… By making a personal choice of a few

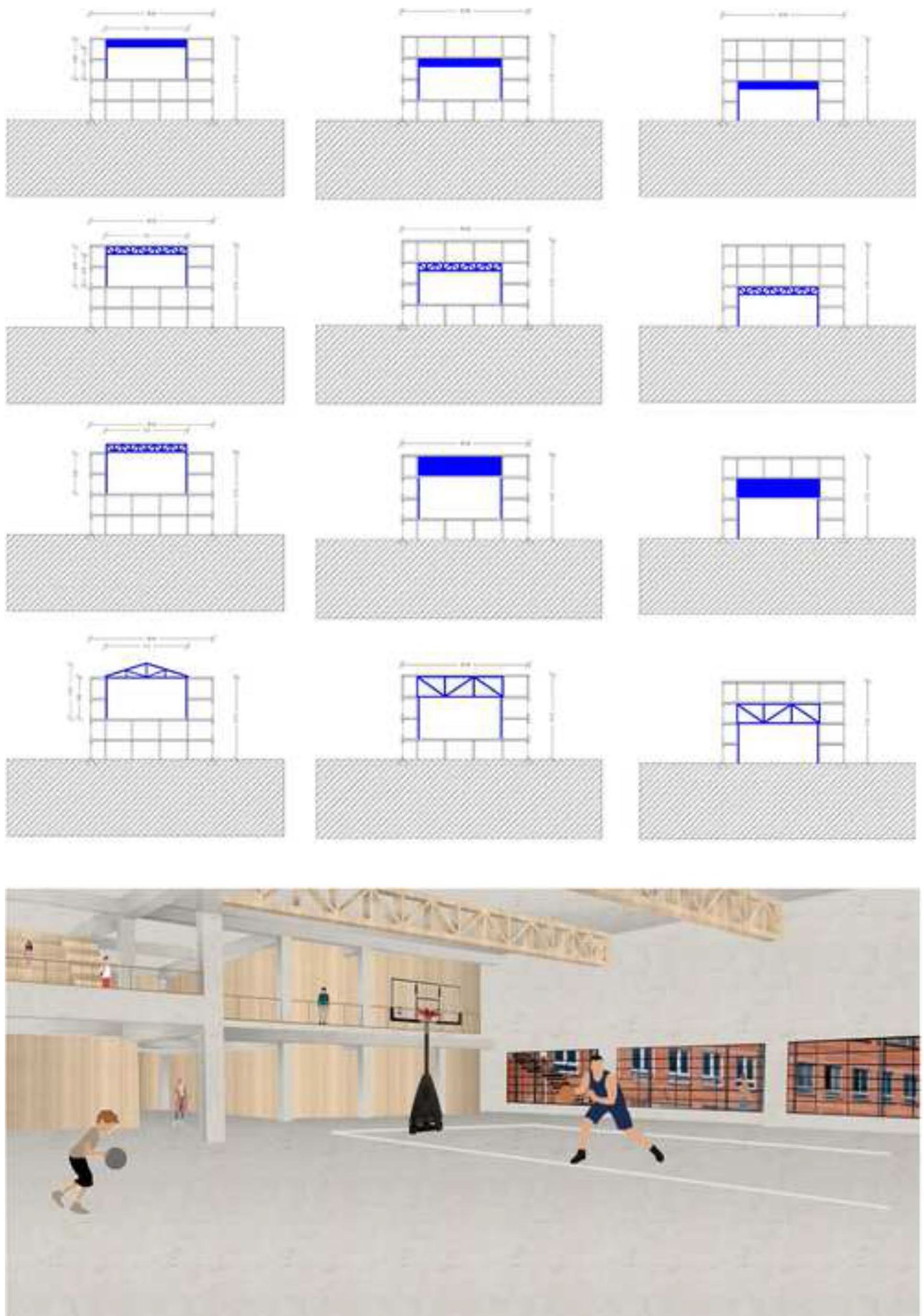

Fig. 1 Example *Remediate Intervention*. (Above) Starting from an existing building with a typical skeleton structure, the student investigates different spatial interventions with their possible structural remediations. (Below) This design catalogue is then used to develop the final design outcome. (Courtesy of Cato Van den brande)

structural characteristics to focus on for the refurbishment design, the design solution space is narrowed down but also made more manageable and is thoroughly explored: examples include focussing on existing supporting walls for positioning a building addition (Fig. 2), using the present foundation setup to add, delete and shift loads, and exploring possible stripping of a building to various structural core systems. This exploration leads to similar outcomes as under *Remediate Intervention,* of design catalogue, rules and strategies.

Structure Mimicry (5 projects)

The development of this generator starts similarly to the *Context-Specific Addition* generator, by analysing the structure of an existing building, but differently it involves creating a structural prototype of (part of) this building. This prototype describes a structure as a system of elements with their structural functions and connections, that allows transferring loads to the supports. This prototype is without materialised form or scale and helps to create and explore various materialisations of a new building design based on a mimicry of this existing abstracted structure.

Structural engineering; building independent

These design generators are created without using an existing building or type of building.

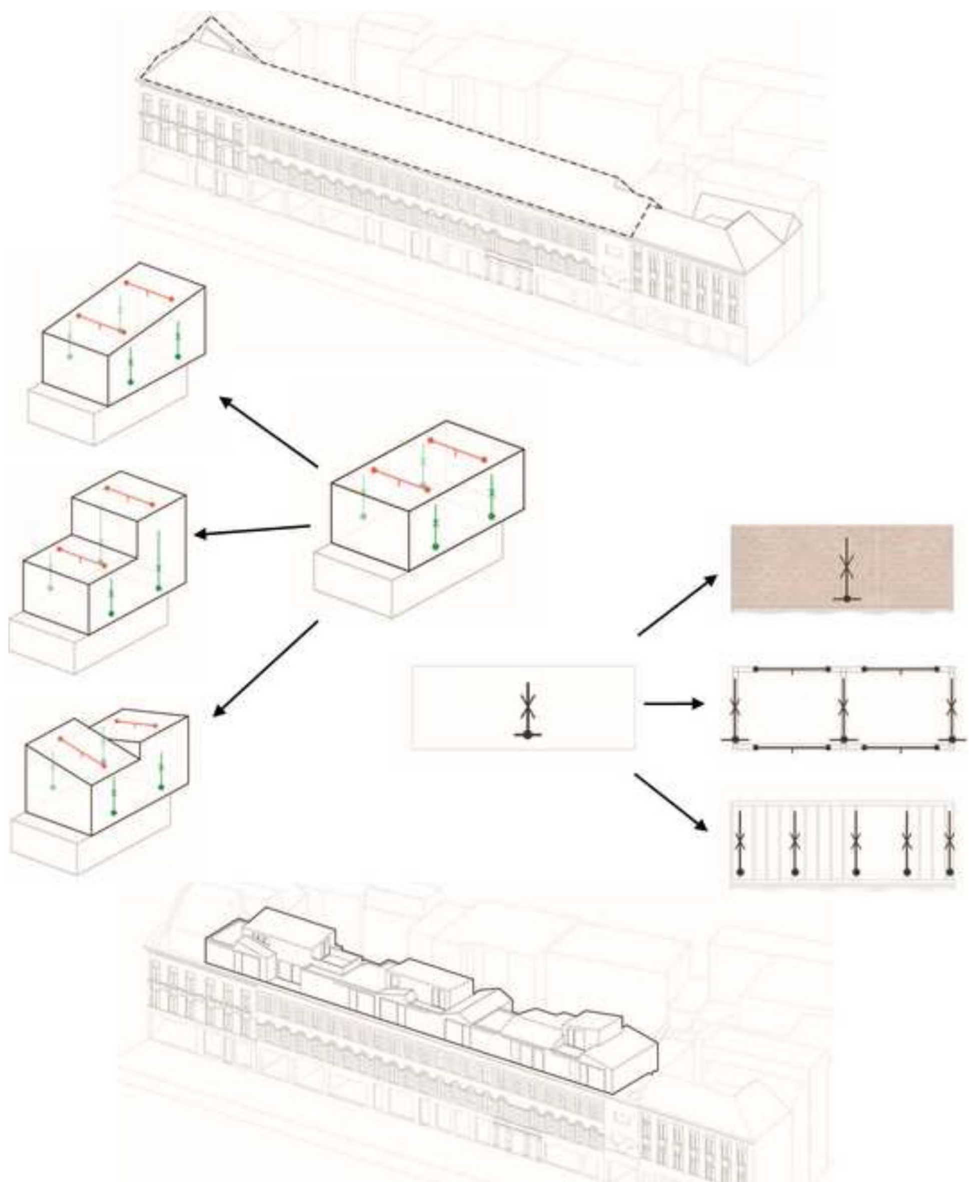

Fig. 2 Example *Context-Specific Addition* & *Abstract Prototyping*. (Above) By analysing the foundations, walls and rooftops of an existing building, the potential for additional loading is explored. (Middle) Various spatial forms of abstract structural prototypes are created, based on the loadbearing surplus of the existing building. (Below) Final design. (Courtesy of Jonas Degroote)

Structural Material (1 project)

By exploring the possibilities in form through determining the structural properties of a material (e.g. rammed earth, Fig. 3), design rules are developed for architectural form design. This exploration ranges from structural details and construction elements to the general form.

Structural Product (3 projects)

This generator is similar to the previous one, except that the starting point is a structural product (e.g. Cross Laminated Timber) instead of material: the student explores the different possibilities in structural form with this product to inspire the architectural design process. Besides the

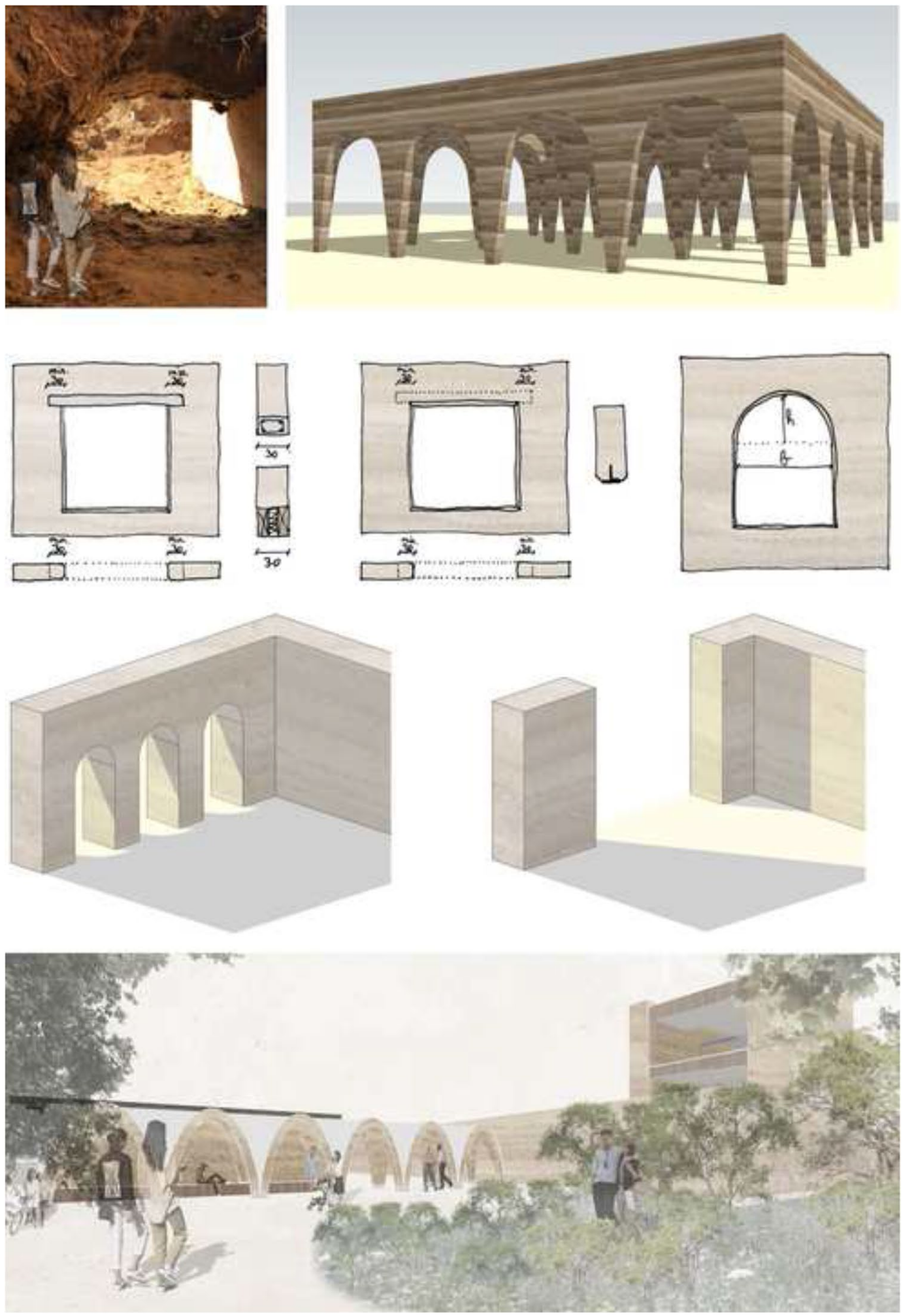

Fig. 3 Example *Structural Material*. (Above) Inspired by the qualities of rammed earth, the student explores its structural form potential through physical and digital models. (Middle) Explorations in window openings. (Below) The developed understanding of form possibilities leads to the final design outcome. (Courtesy of Olivier Meuris)

structural properties of the product, the structural possibilities in connecting the product determine importantly the possibilities in structural form, and thus architectural form. In this exploration, the student often applies rules of thumb, first principles and structural typologies (e.g. folded structures with Cross Laminated Timber).

Structural Joint (3 projects)

By investigating the constructive conditions (e.g. adding sequence of joining elements) and the force transfers in a structural joint (e.g. in Japanese wood joinery), the constructive and structural possibilities of the joint are mapped to explore possible structural and constructive forms (e.g. skeleton or portal frames) (Fig. 4). Often in this exploration, existing joints or connections (e.g. wooden puzzles) are modified and further developed to fulfil specific design needs (e.g. connecting with different angles or detailing of building envelopes). This exploration is then used as inspiration for architectural design by creating a catalogue of possibilities or by identifying specific design rules to create (skeleton) forms.

Structural Typology (7 projects)

A specific structural typology (e.g. shell or greenhouse structure) is chosen for (an important part of) the architectural design form. This typology is structurally analysed by the student to be able to refine and adjust elements, materials, dimensions and details of this typology (Fig. 5). Through this understanding, architectural form is created following these structural design rules. (This type of generator includes kinetic structures as a typology: here the possibilities of structural form transformations are an important part of the student's investigation and exploration in adaptive architectural design).

Adaptable (Con)Structures (7 projects)

This design generator does not necessarily find its core existence in only structural considerations but can be closely connected to certain desired qualities in the construction of a design. Such design is generated by focusing on the ability to easily adapt its materialisation (e.g. to change the qualities of the architectural skin). This desire for adaptability leads to an exploration of the interconnectivity of different construction elements and the

Fig. 4 Example *Structural Joint*. (Above) The student's fascination for wooden connection puzzles leads to physical and digital explorations and developments of the joint. (Middle) Exploring the structural and constructive possibilities through trial and error. (Below) Construction rules and structural principles determine the final design outcome. (Courtesy of Sies Vandevelde)

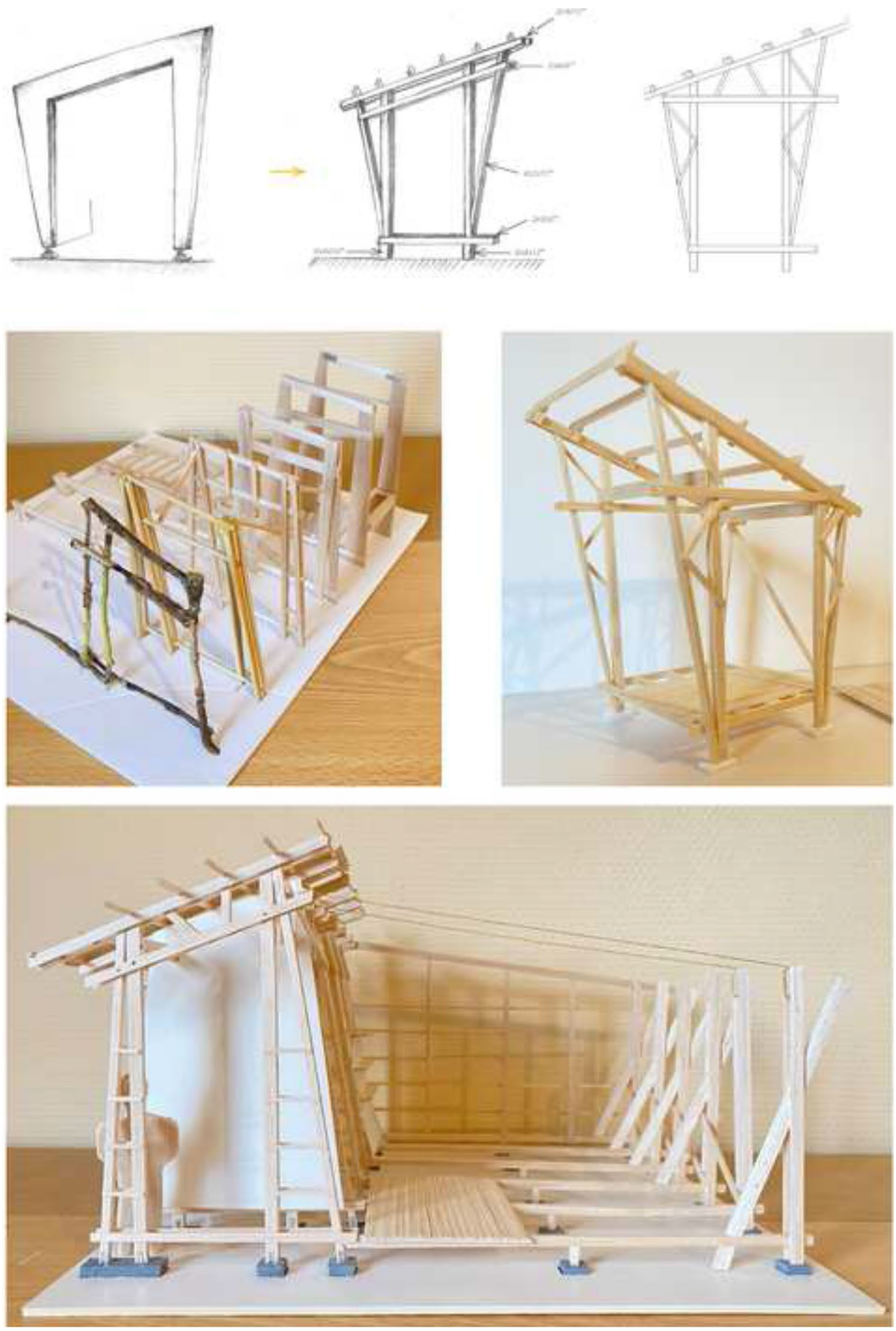

Fig. 5 Example *Structural Typology*. (Above and middle) The student's interest in local Philippine houses leads to structural and constructive explorations of wooden portal frames. (Below) The model of the final design outcome. (Courtesy of Stephanie Alatraca)

development of the elements themselves for interchangeability (Fig. 6). These investigations in turn provide an understanding of possibilities and limitations in architectural form (e.g. modular architecture). Based on this understanding, the architectural project is created.

Structural engineering; mixed (building dependent and independent)

These design generators can be developed by using an existing building, but this is not necessary. However, when

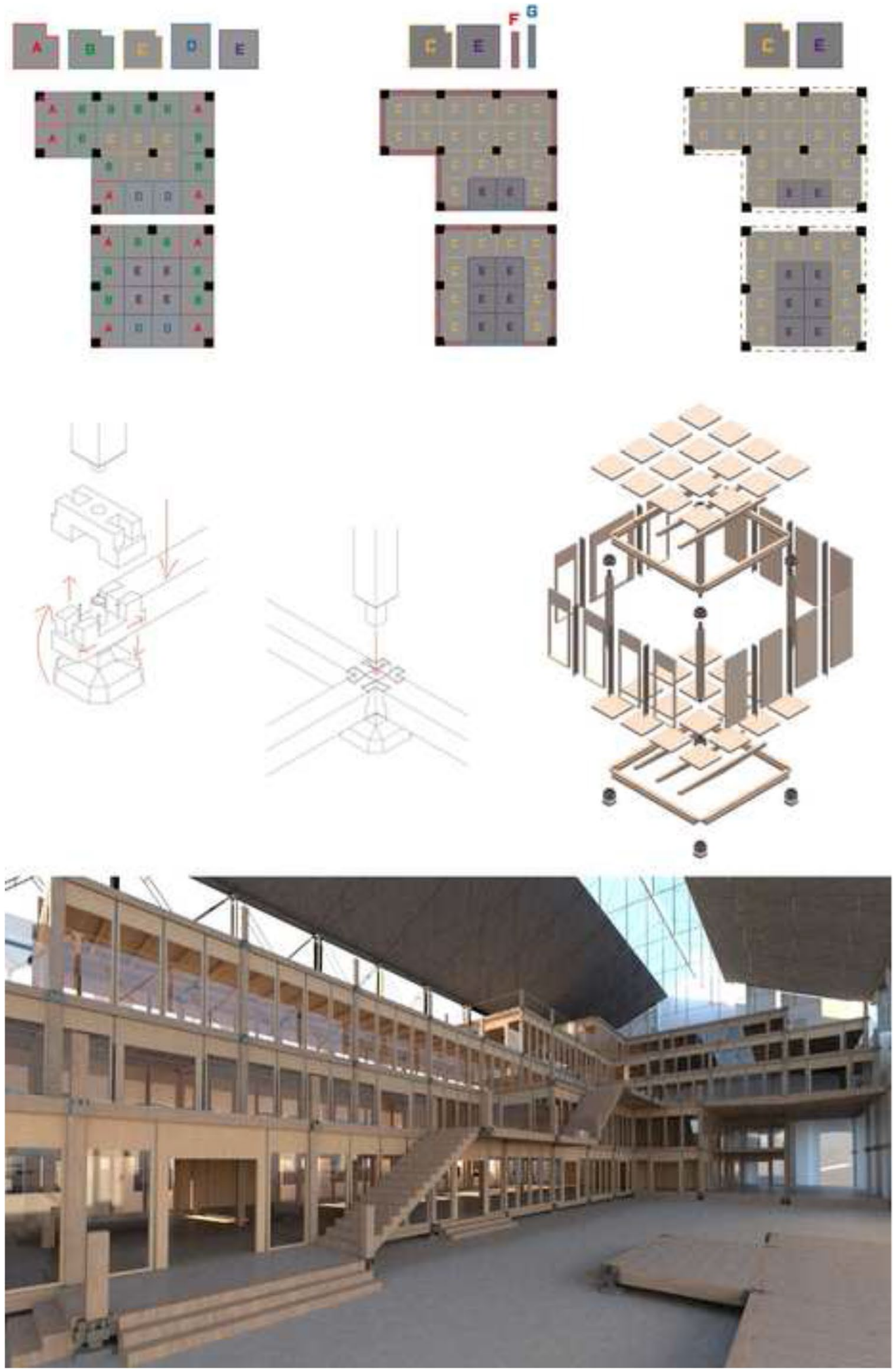

Fig. 6 Example *Adaptable (Con)Structures, Structural Module & Structure Reuse*. (Above) The student explores different sets of floor panels for the uniformization of interchangeable elements. (Middle) The connections and dimensions of elements are refined for modular reusability and adaptability. (Below) The developed modular system is the building block of the final design outcome. (Courtesy of Michael Holemans)

they are developed with an existing building, it will importantly influence the characteristics of the generator.

Principle Repetition (3 projects)

This generator consists of a structural prototype (cf. *Structure Mimicry*) with specific internal structural principles (e.g. tensegrity principles), and is used in materialising architectural form through repetitiously applying this prototype and its principles. The prototype is as such a building block of design and free of scale and materialised form. A reciprocal structural system or a portal frame are examples of such prototypes, but they can also be created by the designer with unique features (Fig. 7). The

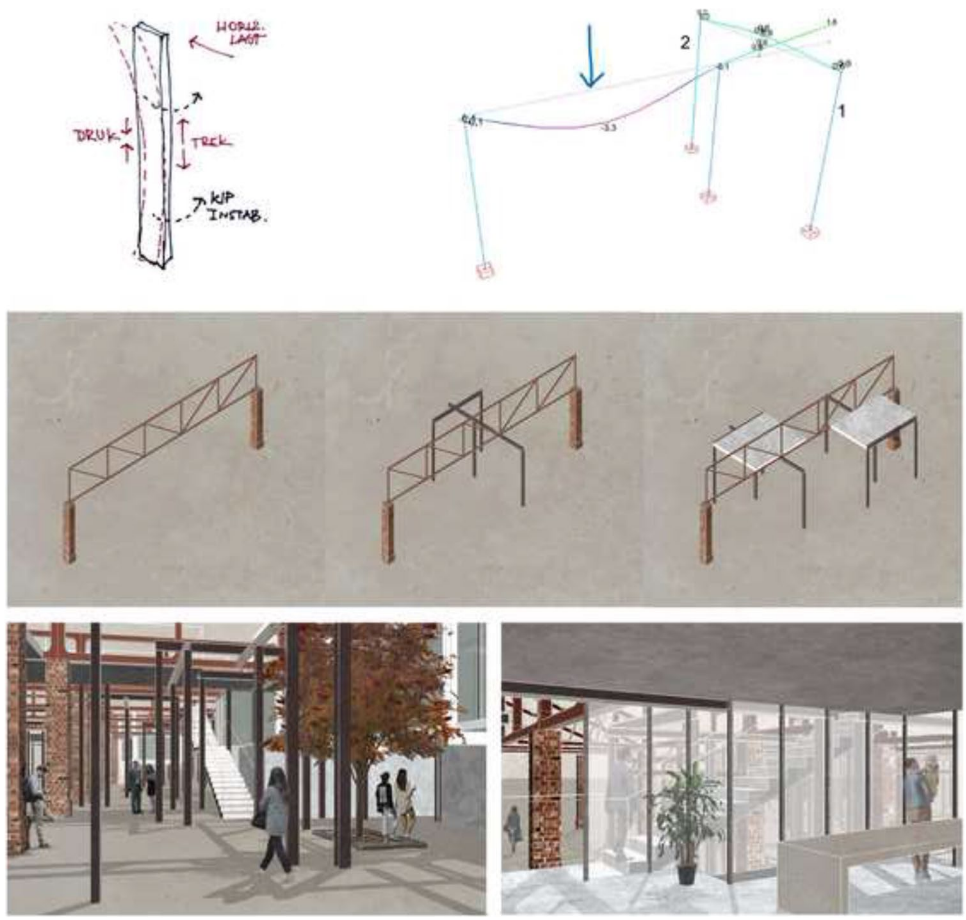

Fig. 7 Example *Principle Repetition*. (Above) In a case study, the student discovers slender columns put under tension to avoid torsional buckling under horizontal load. This leads to the development of a structural prototype for vertical and horizontal support. (Middle) This prototype is then repeatedly applied and materialised in a design project as a building block of design. (Below) Final design outcome. (Courtesy of Tomàs Lepoutre)

generation of the prototype can be based on an analysis of an existing building structure or independent from a building.

Grid (2 projects)

An exploration of the design solution space occurs through the application of a structural and functional grid, and their displacements and transformations. Here the structural grid is used to snap the structural elements on (e.g. columns and beams), and the functional grid to snap spatial separators on (e.g. walls). By (randomly or controlled) changing both grids, the design process is guided towards unexpectedly new creations of spatial qualities. Two or three-dimensional displacements put the structural and functional grid in spatial conversation while transformations can change orthogonal grids into a more chaotic or organic constellation with an important impact on architectural space creation. These changes can be induced through software (e.g. generative algorithms) or directly by the designer for systematic or random exploration. (The structural (or functional) grid can be determined by an existing building grid in a refurbishment project and thus importantly influence this generator).

Structural Module (9 projects)

In this design process, the architectural form consists of a configuration of similar structural (and materialised) modules. This structural and constructive module is developed to achieve certain self-chosen requirements of for example stability, adaptability, (easy) constructability, material efficiency, joint uniformity, grid planning and reuse. During generator development, the design quality of the module is tested in one or multiple case-specific scenarios for adjustments (Fig. 6). Such scenarios can include a specific existing building that importantly determines the development of the module design outcome (e.g. the applied module dimensions).

Abstract Prototyping (2 projects)

Abstract structural thinking is used to develop a structural prototype capable of transferring the imposed loads to its supports (cf. [28]). Such an abstract structural prototype represents a wide range of architectural design solutions. Exploration of the design solution space occurs through developing various structural prototypes that fit load and support conditions within the desired volume setup. This generator allows to easily develop a wide range of structurally sound (abstract) designs that will be materialised only later on in the process when more architectural design criteria are taken into account (Fig. 2). This generator can be importantly influenced by an existing building if it determines the conditions (e.g. possible supports) of the prototype creation.

Structure Reuse (8 projects)

The ability to reuse structures in other constellations for different architecture projects, is a generator for these design processes. It requires the construction process to be reversible and the structural elements reusable (Fig. 6). This generator importantly determines the characteristics of the structural elements and their interconnection and as such the design outcome. These structural possibilities are explored, refined and/or adjusted, and form the building blocks of the architectural design. When connections need to be made with existing structures, it will influence this generator significantly.

Aesthetics; mixed (building dependent and independent)

Different from the above group of design generators developed within the framework of structural engineering, these generators are primarily developed within the framework of aesthetics. Even though only one type of generators is identified so far in this group with only limited project cases, it is believed that more generators are possible.

Structure Experience (5 projects)

The elements of a building identified as structural, can instigate specific experiences with the observer of that building. In these projects, the design is directed towards certain (intended) structure-induced experiences. This generator is developed by analysing such experiences in various existing or self-developed project cases by evaluating the observer experience of the designer self (Fig. 8) or by surveying the experiences of other (external) observers. The developed understanding of the relationship between a structure and its observer experience guides the designer in the creation of architectural form.

Discussion

Findings

By mapping the presented design generators, a frame of reference with examples in the broad field of structure is made available for architecture students to apply in their design project, and even to develop an understanding of how to create novel ones. Furthermore, together with the design studio setup, insight is given into the design strategy of framing as

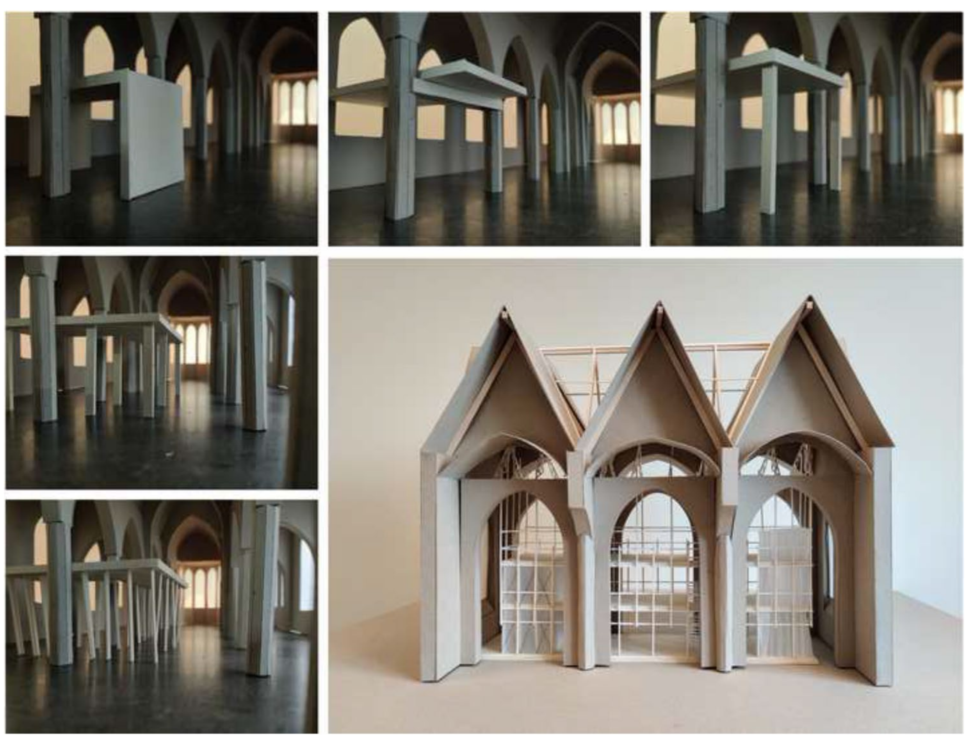

Fig. 8 Example *Structure Experience*. (Above and left) The student's longing to express lightness in an existing church leads to an investigation in the observer experiences of different structural interventions through model making. (Below right) The model of the final design outcome. (Courtesy of Fien Dequeker)

a way into the complexity of design problems. This understanding in developing effective framing of design problems is recognized as an important design skill [29, 30].

This set of design generators also allows evaluating the architecture curriculum in its ability to teach students to develop such design generators: the type of structural and technological knowledge that needs to be learned, but also design skills (e.g. framing and divergent thinking) and abilities in aesthetic articulation.

(In addition, the broad variety of different design generators that link structural understanding with architectural designing, adds potential to the concept of 'structural integrated design processes' with new types of integration).

However, this study is limited as it only investigates 36 projects of specific Belgian students with a common interest in structures. Also, the analysis of the design processes is based on what the students decided to present during consults and reviews, which does not necessarily reflect these processes accurately. And although a specific research method was followed, another organisation in different groups and subgroups of generators, is possible.

Observations

The creation by the students of their project-specific design generators, was often a difficult process of finding an appropriate link between their interest in the field of structure and the development of their design project: this way into a design project, proved unfamiliar and often required students to reinvent their approach in starting a design process. However, once a link was identified, and students started their first cycles of developing their design generators, the further refinement proceeded more smoothly.

Also, when their design project was related to an existing building (e.g. in refurbishment project) and thus the design solution space already narrowed down, it often helped students find their design generators faster.

Students were stimulated to introduce additional design generators outside of the field of structure, based on their personal interests (e.g. in sustainability or development aid). This proved to motivate them to engage in the design studio.

Additionally, by asking them to focus on developing a frame for a type of design projects, instead of one specific pre-defined project (i.e. with a set context and programme), the studio setup stimulates students in developing their personal guiding principles in designing, that go beyond the singular project.

Remarkable in this study is that starting from 36 students with a common interest in designing with structural input, and a design assignment with total freedom in programme and context, similar design generators are identified in the various developed design projects. Even more, during these three years of studio courses in which each batch of students was not introduced in previous studio projects and their design generators, the same generators reappeared equally spread over projects and years, to a point where only a few new ones were discovered in the last year's group of 19 projects.

Characteristics of design generators

Different takes were investigated on how to organise the available data in types and characteristics of the identified design generators. It was observed that each generator contained three sequential aspects: at the start of the development, there was often a (1) specific *interest of the student* (e.g. rammed earth, Cross Laminated Timber, an existing building or Japanese wood joinery), then there were (2) specific *processes of generator* development (e.g. investigations through physical or digital modelling, form interventions and remediations, and case studies), to end with a (3) *generator of design proposals* (e.g. through a catalogue of possibilities or rules for design creation).

For the first of these three aspects, not enough data was available for investigation, as only on rare occasions students were clear on their personal interest: often students had a messy start in developing a generator.

For the processes of generator development, a distinction was made between structural engineering and aesthetic framework, but further refinement proved hard to establish.

The last aspect, generator of design proposals, could be better characterised by distinguishing between catalogue of possibilities, and implicit and explicit design rules or principles. Certain design generators even allow for further refinement: creation through (form or principle) mimicry, structural principles, form algorithms, aesthetic principles, construction principles. However, a concise and all-covering set could not be established.

Also looking into already established design taxonomies that link structure and architecture, did not lead to satisfying solutions. For example, the types of relationships between structure and architecture of Macdonald (i.e. structure ignored, accepted, symbolised or true structural high-tech) [12] describe the final design outcome which does not necessarily reflect the applied design generators. Also, Olga Popovic Larsen and Andy Tyas developed an interesting taxonomy for architectural design inspiration from structural design [17]. Even though their classification is mainly historically established and focuses on structural and not architectural design, it contains a set of interesting characteristics of design generation that can be applied in this research: applying intuition, inspiration from precedents, understanding structural principles, and learning from physical models. These characteristics mainly make sense within the aspect of generator development, but do not cover all identified once (e.g. in aesthetics), and are mainly not well demarcated (e.g. the difference between understanding principles and applying intuition) to further develop from.

Because no appropriate existing taxonomy was found to compare with the found data, it was chosen to present the set of design generators broadly (i.e. with a maximum of types) to allow for future investigations.

Conclusion

During three consecutive years of the same master dissertation studio under the supervision of the author, 36 design projects were developed in which architecture students created a personal link between the realm of structure and their architectural design, to generate architecture through structural framing. In these projects, students developed design generators to provide a way into an ill-defined design problem and to help forward the design project significantly. Each generator consists of a cognitive framework, within the broad field of structure, to reduce the complexity of the design problem, and contains the ability to generate design proposals.

Based on different data sets from supervising the students' investigations and design developments, together with their final design projects and dissertations with reflections on their design-led research, 14 distinct structure-based design generators were identified (cf. Table 2).

Most of these generators were developed within a cognitive framework belonging to the field of structural engineering, but others were developed within aesthetics. A further distinction between generators can be made if their development was determined, or not, by an existing building (or type of building).

By identifying these structure-based design generators, a frame of reference with examples is developed for architecture students to apply in their design, and to create novel ones as part of learning to design through framing.

Future research involves analysing a new set of design projects from a new year of this master dissertation studio with the author as supervisor. The focus lies in evaluating the completeness and recurring of the identified set of 14 structure-based design generators, together with a special focus on discovering new generators within the field of aesthetics. Also, valuable contributions lie in further research into the observer experiences of their structural reading of architectural forms.

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Declarations

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