Operative Diagramatology: Structural Folding for Architectural Design

Conference Paper · September 2013

Pierluigi D'Acunto
Technische Universität München

Operative Diagramatology: Structural Folding for Architectural Design

Toni Kotnik and Pierluigi D'Acunto

1 Introduction The comprehensive digitalisation of contemporary architectural production on the intellectual level as well as on the level of fabrication,has resulted in an increased interest in material properties and behaviour within the discipline of architecture. This momentum for a revitalised involvement in material practice and the prioritising of materialisation in the design process is also expressed in the expended collaborative relationships that have developed in the past decade between architects and structural engineers, a cultural development that *Rivka* and *Robert Oxman* have termed "the new structuralism" (Oxman; Oxman 2010, p. 15). This kind of collaboration is not comparable to the conventional hierarchical and sequential interaction of architect and engineer, but is rather characterized by engineers acting as design partners up-front at the conceptual phase as well as throughout the whole design process. Such close interaction of architectural intention and engineering thinking could be observed in the past at most only in projects by architect-engineers like *Eladio Dieste, Felix Candela* or *Pier Luigi Nervi.*

It is obvious that digital media have played a significant role in supporting and unifying such interdisciplinary interactions as enabling technologies that enhance the potential for communication and collaboration between architects and structural engineers (Kara 2010, p. 49). The dialogue benefits from computers that are more powerful, the availability of sophisticated analytic algorithms, and visualisation techniques that render the analytic data in ways that make it more immediately understandable.

Toni Kotnik, Pierluigi D'Acunto
ETH Zurich, Switzerland

2 Finite Element Analysis

From a structural engineering perspective, especially the availability of readily usable *finite element analysis* (FEA) software programmes and with it the possibility of the visualisation of the interplay of structural forces, is constitutive to "the creative marriage of structural concepts and architectural expression" (Besserud et al. 2013, p. 50) as it is argued for example by companies like *Skidmore, Owings & Merrill* were architects and engineers have been working closely on projects for several decades. Unquestionable, FEA programmes are of great use in the analysis and refinement of well-developed design proposals. Form an architectural perspective however, the usefulness of FEA at the decisive early phase of the design process has to be questioned.

The transformation of a huge amount of numeric data into a coherent visual representation by means of an FEA software makes an understanding of structural interaction and the detection of weak points easier. However, such ability to read the iconography of an FEA and make it operative requires an amount of engineering knowledge that typically exceeds the knowledge of an architect. In a collaborative situation therefore, the architects depend to a large extent on the interpretation of FEA by an engineer and his conclusion about necessary changes to the design or restrictions and directions for the further development.

This kind of design-relevant feedback in general requires what *Le Corbusier* calls a creative constructor: "Engineer, that means analysis and calculation; Constructor, that means synthesis and creative action" (Schwartz; Kotnik 2010, p. 22) and what *Hanif Kara* describes as design engineer, an "emphatic model that requires inhabiting the mind of the architect … while thinking with the knowledge of the engineer" (Kara 2010, p. 47). In general, people with the ability of transdisciplinary transgression are rare, and that is why the use of FEA software in an early design phase often results in a typological fixation of the underlying building structure: a referring back to well-known structural solutions as neutral engineering background to the architectural intention.

Hence, as a method of visualisation of structural forces and their interaction, FEA is not able to enhance the dialogue between architect and engineer at an early stage of the design process. Largely, this shortcoming is related to the fact that FEA is a direct translation of a numerical approach towards structure. An approach that has its origin in the theory of elasticity, a closed analytical model developed primarily in the nineteenth century. Already in the 1950s, *Pier Luigi Nervi* pointed out that such analytic approach is of limited relevance for the design process:

> "The most advanced chapters of theory of structures … can only be used to check the stability of a structure. They can be used only to analyze numerically a structure already designed, not only in its general outline, but in all its dimensional relations. The formative stage of a design, during which its main characteristics are defined and its qualities and faults are determined once and for all (just as the characteristics of an organism are clearly defined in the embryo), cannot make use of structural theory and must resort to intuition and schematic simplifications" (Abram 2010, p. 57).

3 Structural Diagraming

Architects often use a form of cognition, which is described as visual thinking: a form of direct thinking related to the manipulation of graphical information (Lawson; Dorst 2009, p. 104). However, in order to activate this form of thinking with respect to structural design it is not enough to translate numerical data into a coherent image. To reach intuition and schematic simplification a truly visual approach towards structural design is required that can unfold an operative iconography provided by an inherent simple geometric logic. Thus, what is required to enhance collaboration between architect and engineer at an early stage in the design process is a structural diagramatology as an operative medium of dialogue (Krämer 2009, p. 105).

According to *Sybille Krämer*, the operative iconography of a diagram is characterized by a set of properties: planarity, relationality, graphism, syntactics, referentiality, and operationality. Planarity is ability of the eye to register simultaneously spatially distributed information that enables overview and comparison. Relationality is about the relative localisation of information that is the topological connectivity. Graphism is about discrete demarcation; it is about drawing of distinction with the line as archetypical element of definite differentiation. Syntactics is about the readability of demarcation in the sense of a recognisable pattern of relations. Referentiality is the ability of transcription of the graphical into an empirical or theoretical context. Operationality is the ability of activation of the graphical as tool and means of reflection.

With respect to these characteristics, the shortcomings of the FEA can be identified more precisely. The production of a coherent image of the structural condition is based on the simultaneity of material effects, kinematics and equilibrium of the inner force flow, which aggravates the relative localisation of influences. Thus, FEA lacks clear relationality. In addition, the smoothness of the underlying stress field does not enable an easy demarcation of interacting elements of the structural system, at least not without enhanced expertise, which results in a reduced graphism. Both aspects are closely related to a necessary level of expert knowledge for interpretation and as such to the referentiality of the imagery.

It is exactly these deficits of the FEA that an approach based on plasticity theory is trying to overcome, in order to define a structural diagram that can operate at an early design phase.

4 Plasticity Theory

During the twentieth century the theory of plasticity was developed. Contrary to elasticity theory, plasticity theory evaluates the behaviour of a structural system, not with respect to the serviceability based on elastic deformation but rather with respect to its load bearing capacity based on the resistance of the material. This approach enables a decoupling of material effects, kinematics and equilibrium (Marti 2013), and the application of the *First Fundamental Theorem of Limit Analysis* (Lower Bound Theorem) makes it possible to reduce the question of structural design to equilibrium solutions during the conceptual phase of the design process (Muttoni et al. 1996). These equilibrium solutions can generally be based on resultant forces of underlying stress fields, and can be visualized by an inscribed network of compression and tension forces in equilibrium (Fig. 1). With this, the *Lower Bound Theorem of Plasticity Theory* provides a solid theoretical foundation for a simple vector-based method of structural design that has its origin in *Karl Culmann's Die Grafische Statik* from 1866, and is able to illustrate the reciprocal relationship between shape and stress in load-bearing elements (Lachauer et al. 2011).

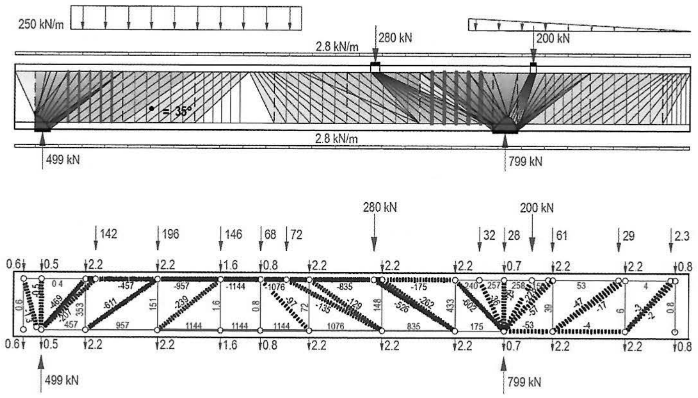


Fig. 1 Stress field in a beam and resulting inner forces (Muttoni et al. 1996, p. 38)

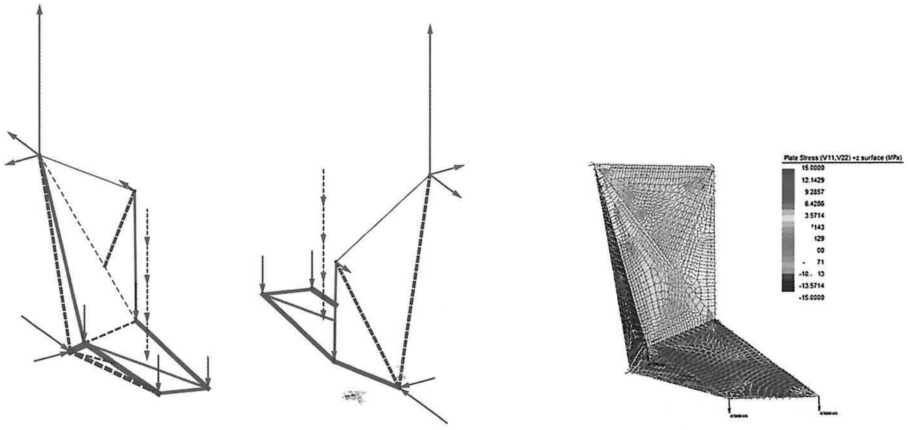


Fig. 2 Inscribed compression-and-tension model and FEA of folded table design

What can be gained from plasticity theory however, is not only a different understanding of structural phenomena with respect to elasticity theory but more importantly a structural diagram as an operative medium for dialogue between architect and engineer at an early design phase. The vector-based graphical approach to structural design is not only a simplified discrete visualisation of essential information captured in an FEA (Fig. 2). In addition, it provides an operative iconography: clearly, it shares with FEA the properties of planarity, syntactics and operationality. Due to the decoupling of material effects, kinematics and equilibrium, and the sole focusing on equilibrium solutions based on the interplay of compression and tension the localisation of influences is substantially improved, resulting in a relationality of the approach. The inscribed compression-and-tension network makes the interacting elements and their relationship easily readable, which improves the graphism of the vector-based design method. Moreover, the reduction to the simple concept of vectorial equilibrium and the transformation of calculation into simple geometric operations reduces the amount of necessary expertise and opens up structural design to empirical and intuitive understanding, thereby allowing for increased referentiality.

5 Folding

The design of an office table out of a folded steel plate has been used as a case study to explore the graphical method of the inscribed compression-and-tension model in three dimensions, as an operative diagram for structural design (Fig. 3). Due to spatial constraints at the office, the design is deprived of the conventional supporting legs that limit the usable surface area. Instead, it cantilevers directly from the wall combining the function of a table with the function of a blackboard.

The interest in folding relies on the fact that by employing such a technique, it is possible to consistently integrate architectural and structural thinking within the design process: "Folding turns a flat surface into a three-dimensional one. It is a powerful technique not only for making form but also for creating structure with geometry" (Iwamoto 2009, p. 61). That is, folding allows one to define a direct relationship between internal force flow, the form of the support structure and the defined architectural space. It is this tripartite relationship that characterizes so-called strong structures: Support structures that do not fulfil their function in the background,unseen, but rather transform the need for load-bearing into architectural space (Schnetzer et al. 2012, p. 194). Due to the geometric logic of the force flow, strong structures are often more expressive and resist the applied external loads through their geometry rather than through the accumulation of materials. The architect-engineer Eladio Dieste used this fact in his design approach: "The resistant virtues of the structures that we make depend on their form. It is through their form that they are stable and not because of an awkward accumulation of materials. There is nothing more noble and elegant from an intellectual point of view than this, resistance through form" (Pedreschi 2000, p. 21).

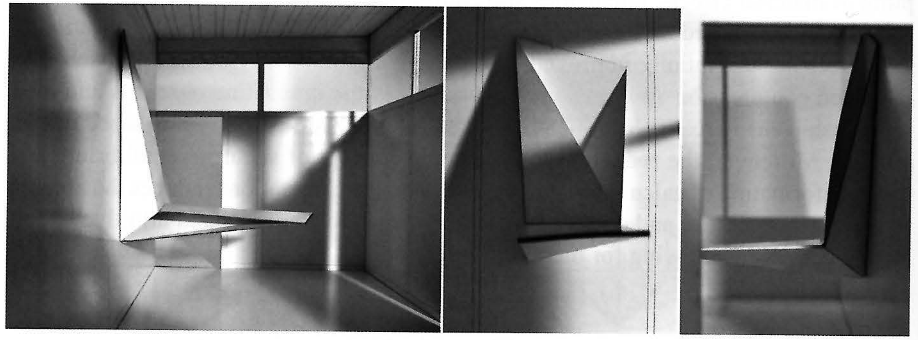
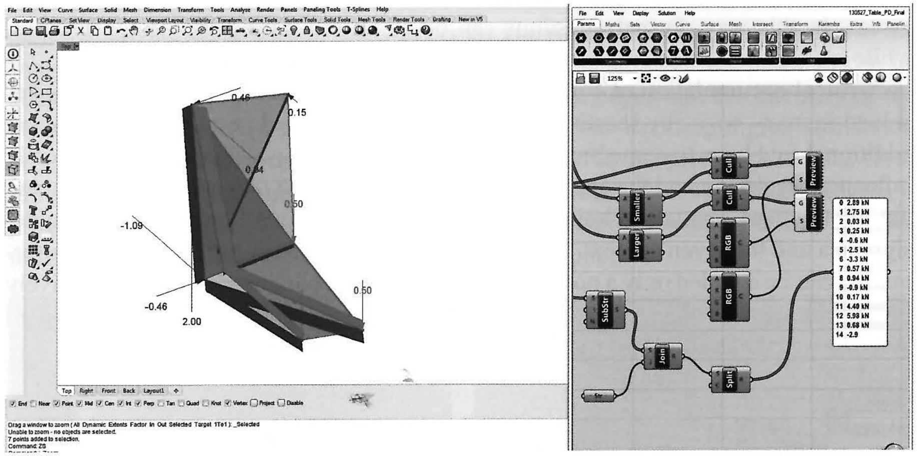


Fig. 3 Views of cardboard model of proposed folded table



```
0 2.89 kN
1 2.75 kN
2 0.03 kN
3 0.25 kN
4 -0.6 kN
5 -2.5 kN
6 -3.3 kN
7 0.57 kN
8 0.94 kN
9 -0.9 kN
10 0.17 kN
11 4.40 kN
12 5.98 kN
13 0.68 kN
14 -2.9
```

```
Drag a window to zoom ( All Dynamic Extents Factor In Out Selected Target 1To1 ): _Selected
Unable to zoom - no objects are selected.
7 points added to selection.
Command: ZS
```

Fig. 4 Parametric digital tool for McNeel's Rhinoceros® for design of folded structures

A static analysis of the distribution of the principal stresses in folded plates shows that the stresses follow a peculiar pattern: There is a local accumulation of high stresses along the edges of the folded structure. This phenomenon can be explained by considering that the stresses in a statically indeterminate system - such as the continuous folded plate - are distributed proportionally to the local stiffness of the structure (Bauchau et al. 2009, pp.144-145). In case of a folded structure the stiffness along the edges is higher than within the plates because of the localized concentration of material along the edges. Thus, the pattern of stress distribution in a folded structure can be well represented by a distribution of an inner force flow along the edges of the folded structure. A distribution pattern that is followed by the inscribed compression-and-tension model of the graphical method of structural design based on plasticity theory. Moreover, using an FEA it can be proven that the intensity of the internal forces along the compression-and-tension model is comparable to the resultant of the stresses along the edges of the folded structure. Hence, for folded structures, the results of the graphical method, based on an inscribed compression-and-tension model, is in quality and relative quantity comparable to the results of a FEA.

In order to enhance the usability of the vector-based graphical approach as an operative medium for structural design at the conceptual phase, a parametric digital tool has been developed (Fig. 4). The tool is free of scale and material-independent and allows the designer to interactively modify the geometry of the folded structure while having a direct feedback on the distribution of the tension and compression internal forces. In this way, formal questions can be addressed during the design process, while making the designer aware of the structural opportunities of folding.

Critical accumulation of forces along an edge of the folded structure can be resolved in many ways, by shorting an edge, by moving an end point or by introducing additional fold lines to name but a few (Fig. 5). All of these possible reactions directly influence the design and the appropriate response results out of a process of balancing out of structural, spatial, technical and material aspects in relation to the specific design idea and the given context. Because of this, the right response to structural information can be decided only a posteriori. That is why the parametric tool is not actively interfering with the design, that is no process of optimisation has been implemented that changes the design with respect to the intensity of the inner force flow.

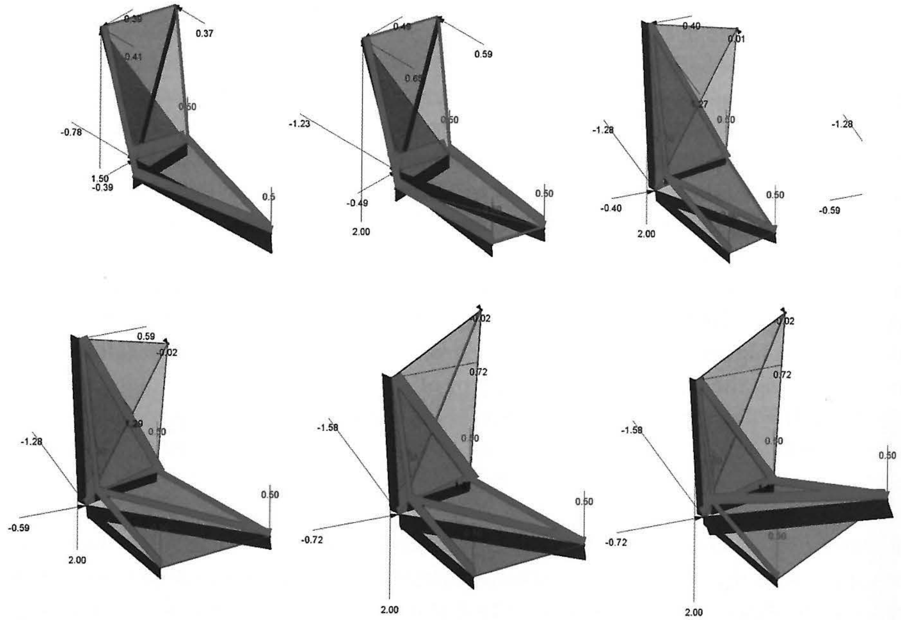


Fig. 5 Variations of design

The parametric tool is also able to provide the designer with intuitive information with respect to the problem of buckling. Based on the topology of the compression-and-tension model, and the kind of inner forces, it is possible to easily locate the edges where buckling is more likely to occur: The risk of buckling corresponds to the free edges under compression. An even better understanding of the problem can be achieved by taking into account the length of the free edges and the intensity of the compressive forces flowing along these edges. A linear buckling digital simulation based on the finite element model has been performed to validate these results. Overall, essential structural information for the conceptual phase of the design process is provided by the tool in an easily readable and intuitively understandable way in order to foster an equal dialogue between architect and engineer.

Fig. 6 Fabrication of final design out of folded steel plates of 3mm thickness

6 Conclusion

The versatility of the geometric operation of folding as an architectural and structural principle enables the design of structures that explore the threshold between the discipline of architecture and engineering (Fig. 6). The close correlation between the inner force flow, defined by the inscribed compression-and-tension model and the fold lines, underlines the operative quality of folding as a structural design method and its inherent diagramatology that allows for dialogue. An inspiring and open dialogue however, requires a common language of inquiry. Because of this, the proposed tool and the implied dialogue between architecture and engineering is not so much based on a numerical understanding of the underlying laws of nature, despite the mathematical precision of the vector-based graphical method, but is much more an iconographic one. The parametric design tool therefore, should not be viewed as an ontological schema that enables scientific working, but more as an epistemological schema, that enables an inquiry into how we learn and know about things (Nelson; Stolterman 2012, p. 78).

The introduction of the iconographic logic into the discourse on design methodology is a critique of our contemporary use of the digital that has been driven for too long by an understanding of computation as an ability to handle an ever-increasing complexity of data and relationships. This has fostered a perspective of the digital in architecture that is comparable to the traditional role of the engineer as consultant. Furthermore, in many of the large architecture offices with their in-house geometry units this is already the case; specialists disjoint from the design process as provider of tools and problem solver. In many cases, this has transformed digital design into a "logico-algebraic text for the emergence of architectural form out of the manipulation of data" (Kotnik 2013, p. 51). However, design is about problems that do not lend themselves to exhaustive analysis (Lawson; Dorst 2009, p. 28). Digital design therefore, should not attempt to replace the designer by automated decision-making process but rather should be used to support the fundamental human ability of design thinking. Digital design is about the granting of an operative medium for a structural diagramatology and that is what the parametric tool for the design of folded structures is trying to offer.

References

Abram, J., 2010. Pier Luigi Nervi: Strength through Form, Form as Structure. In: Pier Luigi Nervi (ed.): *Architecture as Challenge*, pp. 41-57. Milan: Silvana Editoriale.

Bauchau, O.A.; Craig, J.I., 2009: *Structural Analysis.* New York: Springer.

Besserud, K.; Katz, N.; Beghini, A., 2013. Structural Emergence. *AD Architectural Design* 83 (2), pp. 49-55.

Iwamoto, L., 2009. *Digital Fabrications: Architectural and Material Techniques.* New York: Princeton Architectural Press.

Kara, H., 2010. On Design Engineering. *AD Architectural Design* 80 (4), pp. 46-51.

Kotnik, T., 2013: Geometry of the Body. *Proceedings of the Symposium Future Traditions. Porto,* pp. 51-62.

Krämer, S., 2009: Operative Bildlichkeit. Von der 'Grammatologie' zu einer 'Diagrammatologie'? Reflexion über erkennendes 'Sehen'. In: Hessler, M.; Mersch, D. (eds.): *Logik des Bildlichen: Zur Kritik der ikonischen Vernunft.* Bielefeld: transcript.

Lachauer, L.; Jungjohann, H.; Kotnik, T., 2011: Geometry of Structural Form. Taller, Longer, Lighter: *Proceedings of the IABSE-IASS Symposium 2011*. London.

Lawson, B.; Dorst, K., 2009. *Design Expertise.* Oxford: Architectural Press.

Marti, P., 2013. Theory of Structures. Berlin: Ernst & Sohn.

Muttoni, A.; Schwartz, J.; Thürlimann, B., 1996: *Design of Concrete Structures with Stress Fields.* Basel: Birkhäuser.

Nelson, H.G.; Stolterman, E., 2012: *The Design Way. Intentional Change in an Unpredictable World.* Cambridge: MIT Press.

Oxman, R.; Oxman, R., 2010: The New Structuralism: Design, Engineering and Architectural Technologies. *AD Architectural Design* 80 (4), pp. 14-23.

Pedreschi, R., 2000: *The Engineer's Contribution to Contemporary Architecture.* London: Thomas Telford.

Schnetzer, H.; Muttoni, A.; Schwartz, J., Flury, A., 2012: Strong Structures. In: Flury, A. (ed.): *Cooperation. The Engineer and the Architect,* pp. 193-206. Basel: Birkhäuser.

Schwartz, J.; Kotnik, T., 2010: Transparenz, Stringenz, Leichtigkeit: Eleganz im Brückenbau. *werk, bauen + wohnen* 97 (5), pp. 20-25.