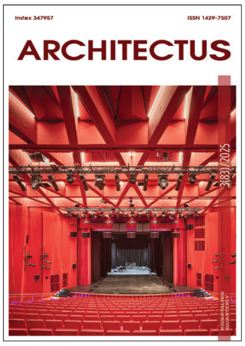

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Inverse modelling as a tool in teaching the conceptual formation of synergistic architectural and structural forms – exploring the reception of the method

Abstract

The article describes the author's experiences in teaching the creation of synergistic architectural and structural forms, meaning those where the architectural form and the structural form are unified. A key factor is the unity in practice achieved through proper collaboration between the architectural and structural professions.

The author, as a civil engineer with experience in teaching structural design at the academic level to architecture students, found that methods based on physical modelling have proven to be very effective, particularly those employing reverse shaping. The article presents a teaching method based on these principles and describes its results. The author also analyses students´ perception of the inverse shaping (form-finding) method, comparing the advantages and disadvantages reported by nearly 90 students.

Currently, the process of educating civil engineers rarely utilizes manual physical modelling methods as a tool for shaping architectural and structural form. For these purpose, computational methods and digital modelling are primarily used. In the author's opinion, these methods are only suitable for the second stage of project verification, after the initial creation of a unique concept. Similar conclusions can be drawn by observing the design workshop and the work of famous designers, who often combine the skills of an engineer and an architect. A properly constructed physical model, developed at the initial stage of design in close cooperation between the architect and the structural engineer, may already contain approximately 70% of solutions consistent with the project's ideology. Therefore, they can serve as a basis for further stages of designing a synergistic architectural and structural form.

Key words: shaping of the structure, structure's architecture, physical modelling, architectural-structural form, flow of forces

Introduction

The development of construction, initiated by the industrial revolution, brought about the end of an era in which the terms "engineer" and "architect" meant the same thing. A new relationship emerged between architects and structural engineers, which led to a separation of competences in common design and construction practice and frequent antagonism between these misunderstood specialists. Responsibility for the design process has shifted from one to two people, and this has given rise to the need for dialogue to achieve a unified view. However, its participants must have common ground – so that the conceptual design stage is not lost (Todisco 2016). This crucial stage is based on a holistic, creative view, qualitative analyses and synergies, rather than the dominance of one party. Exceptions are the few outstanding creators, called structural artists by David P. Billington (1985), among them Rafael Gustavino, Antonio Gaudí, Robert Maillart, Pier Luigi Nervi, Eduardo Torroja, Félix Candela, Eladio Dieste, Nikolaus Otto or Heinz Isler, who combined architectural, engineering and construction skills – and thus created works that have gone down in architectural and construction history.

Interviews with Wacław Zalewski (Zalewski, Allen and Iano 1998), an eminent Polish engineer and professor at the Department of Architecture at MIT, show that he clearly noticed this discrepancy, as well as the fact that the lack of a common ground does not favour the achievement of synergistic, high-quality design effects on the part of both professions, which are equally responsible for creating architectural

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and structural forms. In view of the above, they should work closely together, especially in the first, crucial, conceptual phases of the design process.

The author's many years of experience in developing an awareness of the synergy of architectural and structural forms among students of the Faculty of Architecture at Wrocław University of Science and Technology shows that the best way to achieve this goal is through physical modelling methods, especially since manual skills are declining among young people. This is because these methods engage – already in the initial stages of the conceptual search for form – the natural perceptual abilities, the ability to experience and intuitively predict the behaviour of material form in the field of external forces, the spatial imagination and the creative potential of the designer (Ilkovič, Ilkovičová and Špaček 2014). Gaudí, in his statements, reveals that man can think mainly in two dimensions. Only the sight and touch of a finished object allow him to truly understand space (Hensbergen 2015, 250). The use of sophisticated software at the stage of conceptual form-seeking (Popovic Larsen, Tyas 2003), which supports the calculation of forces and deformations in construction, and various types of form generators, will therefore never replace the independent, physical modelling of matter. As Zalewski said, the *computer method does not, after all, produce the form it investigates*, despite advanced research in this direction (Mueller, Fivet and Ochsendorf 2015; Mueller, Ochsendorf 2011; Gedig 2010). This form has to be materialised in an earlier process, when only qualitative analysis is sufficient When creating a model, the physical designer, like a sculptor, moulds the material in specific spatial configurations; he or she simultaneously controls aesthetics, plasticity, rigidity and functionality. Any software incorporated into the design process at this stage will interfere with the already advanced, often subconscious process going on in his mind.

State of research

The history of the application of methods for the shaping of momentless forms intended for natural materials (stone, clay, ceramics, brick) that do not stretch, according to modern knowledge, is as follows. The first "creator" of this type of form is nature, which eliminates the stretched parts of matter through erosion. The result is then highly durable arched or dome-shaped rock formations, known from mountain or coastal caves, shaped in the earth's field of gravity so that only compression occurs in their cross-sections. It is most likely that man picked up on these forms and tried to imitate them, initially by trial and error and, over time, in a more refined and precise way. The hanging chain method (flat hanging model) was used by Robert Hooke in 1675 and Giovanni Poleni in 1748 to determine momentless profiles of arches and domes. To achieve purely compressible forms, Antoni Gaudí used three-dimensional hanging models (made of strings and sandbags) between 1880 and 1926, notably in the design of the Colònia Güell and intuitively in the Park Güell (the landmark here is the use of inclined columns and curving in line with the pressure line of the retaining wall – the Portico De La Lavandera).

For further work, the Catalan architect used measurements, reversed photographs and probably a mirror reflection. Heinz Isler, on the other hand, worked between 1950 and 1960 on hanging reversed cloth membranes, coated with plaster and then dried or poured with water and frozen, to obtain funicular forms after reversal, used in the design of momentless, extremely slender reinforced concrete shells with large spans.

Contemporary "convenient" experimental physical methods used for the conceptual design of funicular structures are realised by the author with students by constructing anti-funicular rib physical models or anti-funicular shell models. The former are realised from chains of different weights, reflecting proportionally the level of materiality of the structural elements (ballasted, for example, with plasticine at the points of future concentrated forces), then stiffened with hot glue or resin. The latter are formed from a combination of chains and gauze coated with dental plaster.

In the digital world, tools are being developed for the early stages of mesh mould design, such as CADenary, TL Catenary, JTB Catenary, Grasshopper Catenary and Kangaroo or Food4Rhino-Spider, which simulate the behaviour and geometry of hanging models and allow relatively easy parametric exploration of moulds. There are also programs based on the force density method (FDM), among them: Rhino Vault 2, Sofistik, Easy or Tensyl, Formfinder, and the thrust network analysis (TNA) method from the Block Research Group at ETH Zurich, used in Rhino Vault and Compas.

The use of such software and physical modelling has enabled some exceptional contemporary developments. These include the stone-built exceptionally large Global Vipassana pagoda in Mumbai (96 m high and 85 m in diameter dome; inside it accommodates approx. 8,000 people), the steel-tubed, single-skin atrium at the Smithsonian Institution in Washington, D.C., the Great Courtyard at the British Museum in London (Schlaich Bergermann Partner and Foster+Partners) and the impregnated cardboard tubes for the Japanese Expo 2000 pavilion in Hanover (designer: Shigeru Ban).

Basic concepts of inverse modelling method theory

Physical model

The physical model is understood here as a material structural system, made on a reduced scale, reflecting the spatial form and mode of operation (in terms of force transmission) of a real building object on a real scale of 1 : 1. The author's many years of experience in teaching confirm the usefulness of physical modelling in developing structural awareness among students of architecture. The great advantage of this method is that it can be used by almost anyone, even an inexperienced user with only a preliminary knowledge of structural mechanics theory. All that is needed is to follow a few basic principles, and the results quickly illustrate the play of forces at the initial stage of the conceptual search for form. The simplified model, which is easy to make from commonly available materials, allows many ideas to be tested, encouraging experimentation. This allows observation of the behaviour of the assumed form of the object under load, as well as qualitative assessment of the structural system and its rapid verification. Constant physical contact with the model fosters a subconscious process of creating modifications to the model and immediately applying new solutions to it. It also contributes to maintaining the high emotional involvement required to create new solutions. However, the so-called reverse modelling, used by the author in his work with students, plays a special role in physical modelling.

Thrust line theory

Inverse modelling, in the form of planar or spatial models, is known in the literature as the hanging models method (Rippmann 2016), the catenary and the line of thrust (Graefe 2021), inverted tensile models (Tomlow 1989) or anti-funicular structures (Todisco 2016). This method was used, for example, by Gaudí when he designed the church in Colonia Güell, and his model was faithfully attempted to be reproduced in 1989 by a team led by Frei Otto (Tomlow 1989). In contrast, a contemporary method of inverse shell formation was used by Heinz Isler (Campbell et al. 1980; Chilton 2001). Knowledge of the pressure lines is particularly important in materials incapable of carrying tension (stone, brick), limits the occurrence of corrosion of scratch-sensitive materials (reinforced concrete), but also allows the design of material-economical momentless structures. It is worth mentioning that flexural load-bearing elements are less efficient than tensile ones in terms of utilising the strength properties of the load-bearing structure material.

The mechanics of stone and brick arches, which are sensitive to the tension arising during bending, is brilliantly discussed in his work by Santiago Huerta (2005). In it, the author investigates the ultimate load capacity of arch structures using models. This makes it possible to observe the effects of pressure lines approaching the inner or outer edge of the arch, leading to the formation of hinges in the arch. Particularly noteworthy is the earthquake simulation method implemented on a hanging model by tilting the support lines by, for example, an angle of ±15°.

In the methodology of physical, preliminary modelling of structural forms, the full analogy between the drawing line and the pressure line reflecting it is essential. Both lines represent the resultant action of all forces acting on the object under investigation.

Physically, the tension line is a virtual flaccid rope or chain (i.e., funicular line) arising in a structural element from a load applied to it, causing it to stretch (Kuś 2008; Mueller, Ochsendorf 2011; Mueller, Fivet and Ochsendorf 2015). For the forces, this line represents the only possible "transmission channel", beyond which they are unable to physically "pass" between the supports.

Each change in load changes the geometry of the rope, creating the image of a new and unique string line as a new system in static equilibrium. The line of draughts also appears in graphical statics as a string polygon, i.e., a graphical system that balances the concentrated loads acting on the object.

By creating an object of structural material within defined boundaries in space, we reduce the number of possible string lines or pressures that can physically pass through that object. The designer's objective may therefore be to adapt the geometry of the structure so that these lines, arising from all possible loads and their real combinations, run in the vicinity of the core of the cross-section – for the lines that run in the cores of the cross-sections of the structure under study induce in them only tension or only compression. When, on the other hand, the pressure or tension line goes outside the section core, the section is subject to bending. The section fibres closer to the pressure line will be compressed and on the opposite side will be stretched.

Thus, if the designer, for various reasons, cannot maintain the pressure line in the core area or even in the cross-sectional area, he or she has to reckon with an increase in the volume of structural material required to carry the bending in that section where the line will extend beyond the structure (the greater the further the line is from the axis of the cross-section). It is this excessive deformation that will force the designer to use more material in order for the structure to meet performance and safety requirements.

The modelling of this type of semi-funicular solution amounts to creating truss systems inside the available contour. A rod-and-column system is then created, redirecting the naturally formed funicular flows of force into the designer's accessible contour. The geometry of such semi-funicular constructions is based on parabolas, so that the axial forces created in the top and bottom bands of this structure are often of constant value.

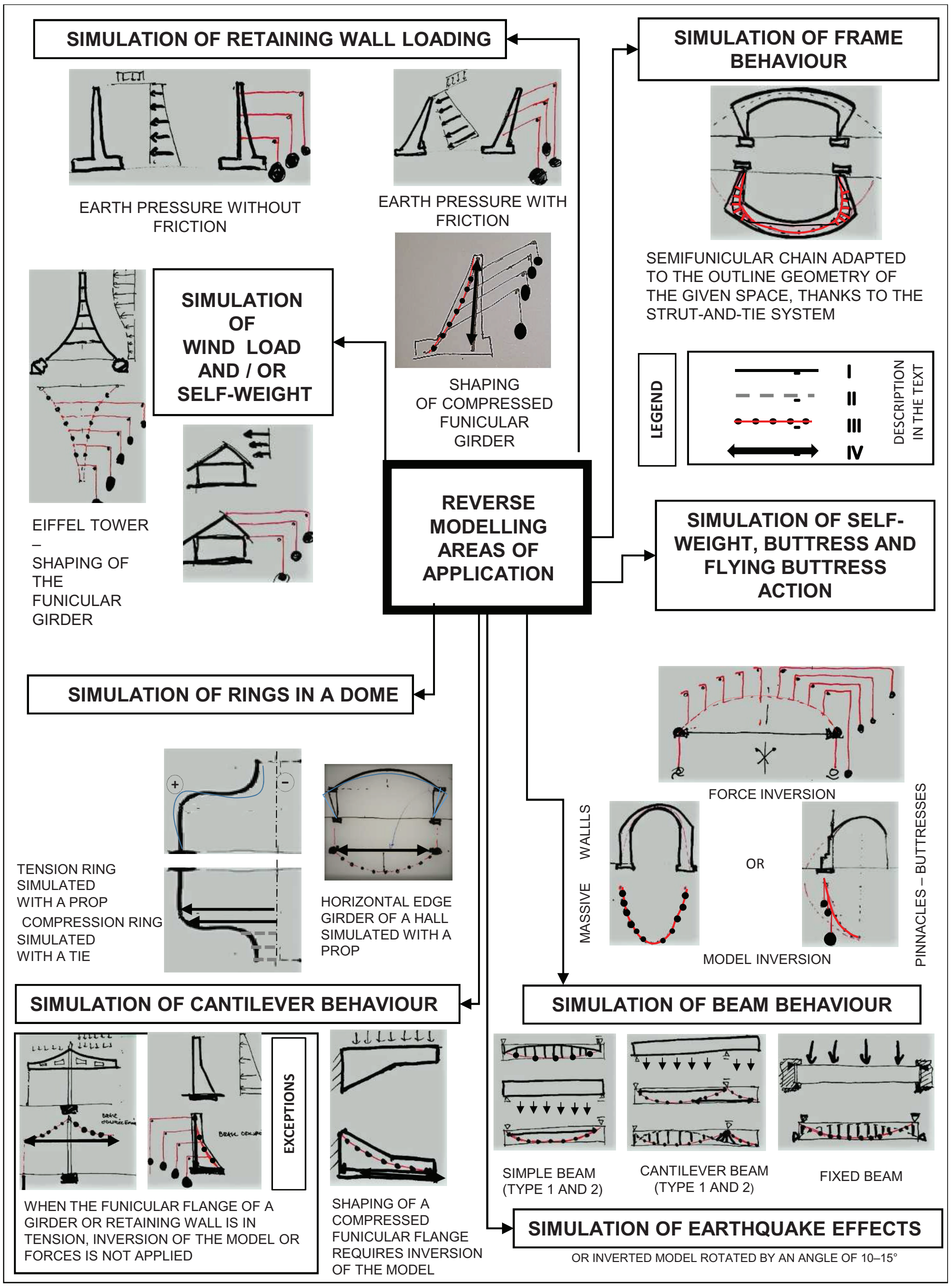
This is because the distance between bands (i.e., the internal force arm) in parabolic systems is proportional to the parabolic bending moment diagram. The constant force in the bands of such a truss theoretically means that there is no need for diagonal trussing and allows the use of a single section along the length of the truss, such as a fixed diameter tube, which affects the architecture of the overall structure.

Inverse modelling method – conclusions and a methodology

From the findings of the theory of lines of pressure and lines of drag demonstrated above, concerning the full analogies occurring between them, it follows, beneficial for the design of structures, that the path of static equilibrium between the forces acting on the designed object in the space between supports can be considered in an inverted state, so as to take advantage of the features of the chain curve giving an image of the line of drag.

By inverting the modelled object or reversing only the direction of the forces, it is therefore possible to simulate the action of dead weight, ground pressure, water and wind pressure on the designed structure (Fig. 1).

Inverse modelling makes it possible to visualise how, under load in the contour accessible to the structure, cooperative compressive force streams and tensile force channels form. Systems built in this way are usually close to optimal, due to the amount of material needed to ensure a favourable flow of forces from the structure to its foundations. It is, of course, possible to create many other geometries of force



I – thin line: flexible connector used to suspend and hang, through deviators, the ballast simulating an external load; thicker line: flexible connector forming and stabilising semi-funicular and/or funicular bands in a bar-tension truss system, visible in the working diagram of the frame and beams
II – flexible connector which, when the model is inverted to its final position, will act as a bar or compression ring
III – flexible connector (chain) loaded with ballast to simulate the self-weight of the arch, which after reversing the direction of the forces or after inverting the model to the target position will be a funicular or semi-funicular compression band
IV – a strut which, when inverted to the target position, will act as a tensile element in the form of a tie or reinforcement in plane systems, or a ring in spatial systems

Fig. 1. Catalogue of selected applications of inverse modelling in structural analysis and design (elaborated by M. Pelczarski)

Il. 1. Katalog wybranych zastosowań modelowania odwrotnego w analizie konstrukcji i w projektowaniu (oprac. M. Pelczarski)

flux systems in the available contour, but these will consume more material as they move away from the optimum systems.

The observation of the play of forces and the shaping of structural forms that are most favourable in terms of force flows can be carried out on 2D planar models or, for more complex structures, on 3D spatial models, as Gaudí has done (Huerta 2006).

With only a qualitative type of model analysis in mind, the cross-section of the object to be analysed is divided into strips, e.g., of equal width, and the ballast weights are selected in proportion to the area of the structure delimited by the strip in question. These fields, cut out of cardboard, are numbered and suspended from a chain where it intersects the centreline of the strip in question. Equal elements, e.g., washers or nuts, come in handy when applying the principle of proportional incremental loading, e.g., reflecting the length of a band of matter or ground pressure with increasing depth.

In general, the inverse shaping method can involve proceeding iteratively in a five-step process:

– Stage I: Initial definition of the designed functional-spatial form in the form of a template model.

– Stage II: Inversion of the assumed model (or direction of forces), followed by shaping of the chain curves (lines of pull) by gravity so that the chain falls within the area of the template, and recording of the achieved result from the dead weight.

– Stage III: Loading with a set of expected alternating loads (as these often significantly alter the geometry of the predetermined drawing line configuration) and then recording the new drawing line layout.

– Stage IV: Comparison of the results of stages II and III, followed by an adjustment of the ballast values at critical points, where the drawing line approaches or goes beyond the edge of the bar-band. This corresponds to a proportional change in the width of the critical section in question or to the application of ballast in the form of, for example, a pinnacle or lantern or other ornamentation that is also architecturally advantageous. The changed section geometry should ensure that the chain curves run as close as possible to the central zone of the section, i.e., in the core of the section.

– Stage V (optional): Working on the inverted model and inputting the digital model, possibly scanning or stiffening the chain model by covering it with, e.g., resin or hot glue and inverting the model to the target position.

Description of own research

Principle of instruction and examples of student work using the inverse modelling method

Selected examples of work (Fig. 2) were carried out by students completing assignments under the guidance of the author as part of the course "Structures in contemporary architecture" during the master's degree programme at the Faculty of Architecture, Wrocław University of Science and Technology in the winter semester 2021. The modelling assignment is usually conducted in several stages. These are as follows: selection of one of approximately 60 topics, research of available information materials on the selected object, construction of a 2D flat model demonstrating the operation of the main structural system, construction of a 3D model in a simplified version (A4 format), introduction by the student of the author's innovation and construction of the target model (A3 format), preparation of a report on the course of the research work, its stages, corrections, history of good and faulty solutions, techniques applied and an inventory of materials used (Fig. 3).

A very important stage undertaken during the course: the analysis of the work of the structure allows students to familiarise themselves with the possible force flow systems in an existing prominent object, and enables them to shape and make their own modifications to it. At this stage Inverse modelling enables students to design structures with a high economy of materials and an architecturally attractive expression of forces, which consists in making the structural system explicit in the architecture of the building. The inability to apply the inverse method explicitly during the analysis or creation of a given object indicates that the structure – or rather its form and geometry – is moving away from funicular systems, which implies the need for semi-funicular and/or funicular truss systems with a larger volume of structural material and a less clear system operation for the observer.

Summary – conclusions and demands

One of the most important factors determining the quality of an architectural work and its sustainable ecological characteristics is the unity between functional-spatial form and the structural form it represents. The two professions, architecture and construction, should work more closely together, especially during the formation phase of a common design concept. Both are equally responsible for creating a synergistic architectural and structural form. This requires, among other things, the strengthening of architectural awareness on the part of the constructors and, conversely, of structural awareness on the part of the architects, and its development should begin at a very early level of academic education. Based on this conviction, the author postulates the need for more extensive training in this area than is currently the case at the faculties of building and architecture. The creation of a new course of study is also worth considering: "design of synergistic architectural-structural forms" and, in the long term, perhaps even a new professional specialisation.

The above statements form the ideological basis of the author's scientific and didactic activities at the Faculty of Architecture of Wrocław University of Science and Technology. They are also the basis for searching for the most appropriate methods of teaching architecture students to understand the work of structural systems and their influence on architectural forms. From the author's 10 years of teaching activity, it is evident that the methods using physical modelling, especially using inverse shaping, produce the best results. They are well adapted to the perceptual and creative abilities of future architects, and are similar in terms of technique to the methods used in basic subjects teaching architectural design skills. The executional simplicity of the models makes students perfectly capable of building them at home, and the general friendly principles of physical modelling allow them to carry out the required range of analyses and experiments and reach valuable conclusions on their own (see Fig. 3).

During the project, the student's relationship with the instructor is more personal and more frequent; the instructor, via a popular instant messenger, can provide precise comments and graphic, audio and video comments at key moments for the student. An important value is the students' inventiveness in solving micro-engineering problems, often used when constructing models on their own under conditions of an always limited budget.

The scope of the term paper closure report on structural modelling requires students to comment on their chosen modelling method. Among the positives, they mention the use of spatial models, which facilitates, among other things, an understanding of how a system works, examining it with the sense of sight and touch. They also considered it valuable to simulate the operation of well-known structures.

They often pointed out that research work during modelling, based on experience, strengthens confidence in one's

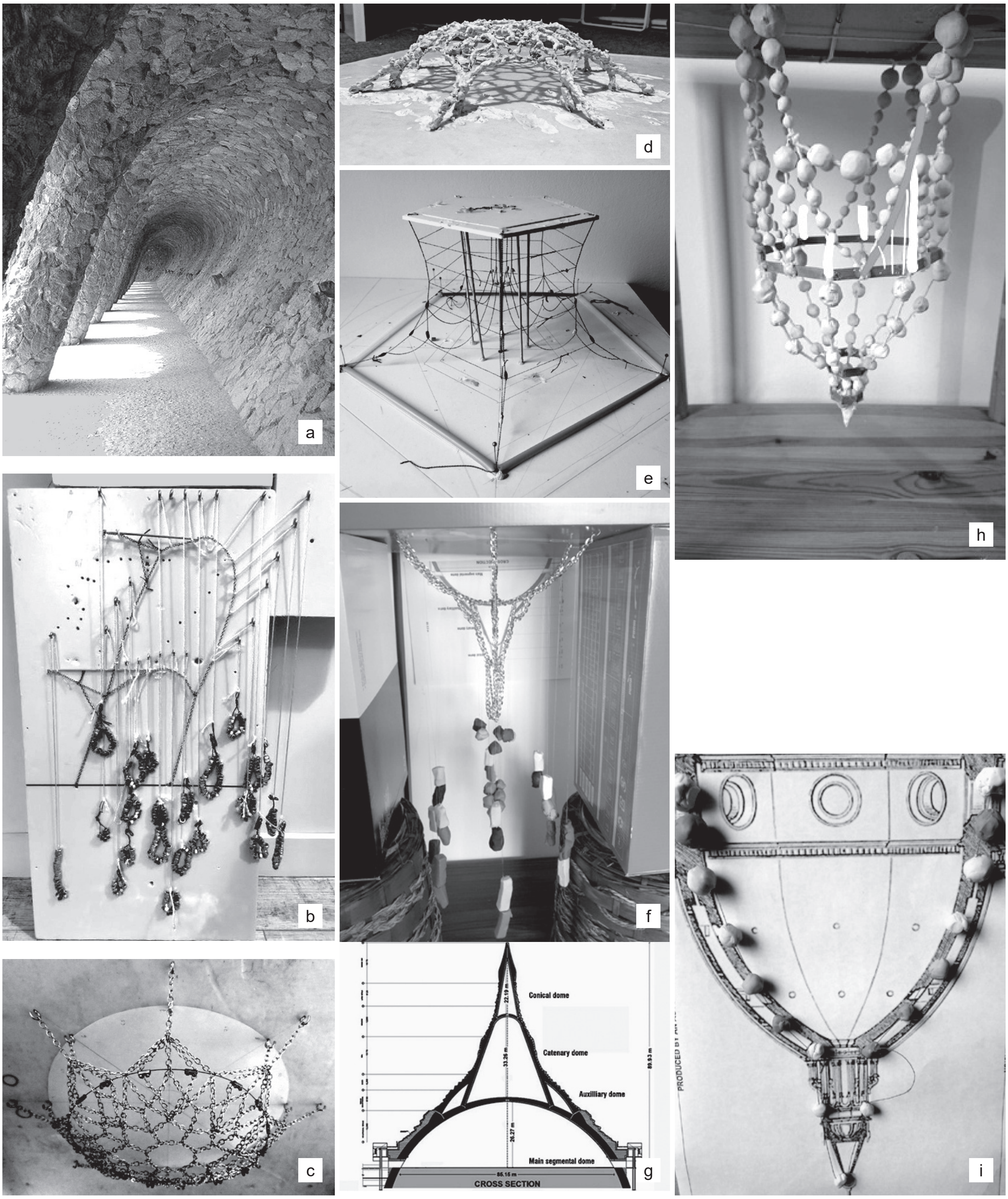


Fig. 2. Inverse modelling – selected examples of student work:
a) inspiration: retaining wall according to the design of A. Gaudí, Park Güell in Barcelona (photo by M. Pelczarski),
b) analysis of the inspired cross-section using inverse modelling (reversing the direction of forces, ballast is in the form of steel nuts which simulating earth pressure with friction, the main line of thrust/tension is created as a loop stretched by inverted forces from soil pressure – terrace cantilevers shaped by struts forming a funicular compression flange (author: A. Łuksik),
c) inverted chain model of Nervi's dome, Palazzetto dello Sport (Little Sports Palace) in Rome,
d) chain model fixed withplaster (author: K. Indyk),
e) author's proposal of a simplified inverse model representing the structural work of the water tower, Fedala Reservoir in Mohammedia, Morocco (author: U. Śliwińska),
f) inverse model of the Global Vipassana Pagoda in Mumbai (2009),
g) sketch of the actual structure, a hall for 8,000 people, monitored by the Auroville Earth Institute studio (author: S. Krawczyk),
h) model inspired by the dome of Santa Maria del Fiore in Florence, Italy (architect: Filippo Brunelleschi),
i) flat cross-section model at the location of the tension ring with an applied strut (authors: E. Naworska, S. Kiciński, W. Włodarczyk)

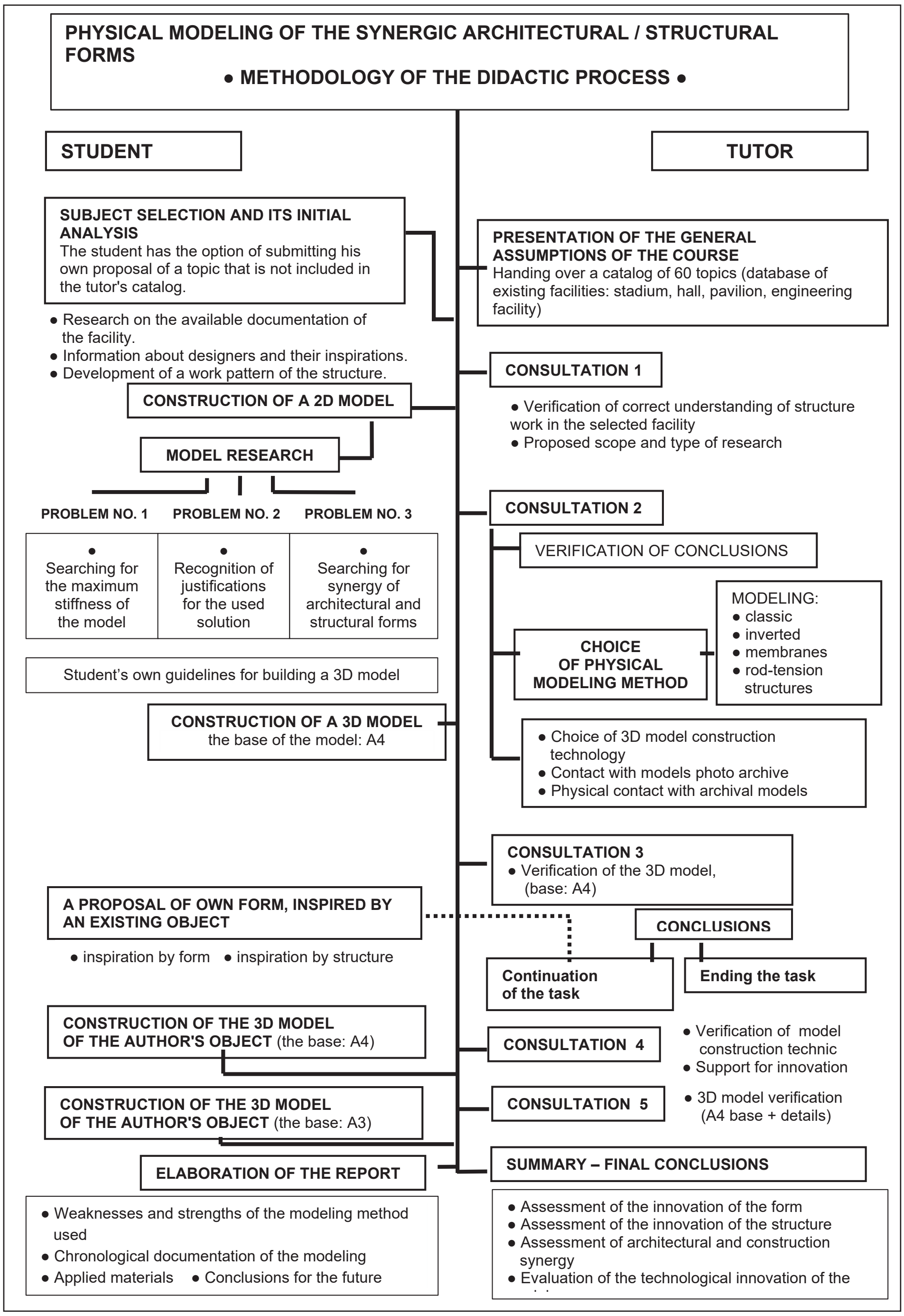


Fig. 3. Physical modelling of synergistic architectural and construction forms – a methodology of the teaching process (elaborated by M. Pelczarski)

Il. 3. Modelowanie fizyczne synergicznych form architektoniczno-konstrukcyjnych – metodyka procesu dydaktycznego (oprac. M. Pelczarski)

Il. 2. Modelowanie odwrotne – wybrane przykłady prac studenckich:
a) inspiracja: ściana oporowa według projektu A. Gaudíego, Park Güell w Barcelonie (fot. M. Pelczarski),
b) analiza inspirowanego przekroju za pomocą modelowania odwrotnego (odwrócenie kierunku działania sił, balasty w postaci nakrętek stalowych symulujących parcie gruntu z tarciem – wsporniki tarasów kształtowane z rozpór tworzących funikularny pas ściskany (autorka: A. Łuksik),
c) odwrócony łańcuchowy model kopuły Nerviego, Palazzetto dello Sport w Rzymie,
d) model łańcuchowy usztywniony gipsem (autorka: K. Indyk),
e) autorska propozycja uproszczonego modelu odwrotnego przedstawiającego pracę konstrukcji wieży ciśnień Fedala Reservoir w Mohammedia, Maroko (autorka: U. Śliwińska),
f) model odwrotny Global Vipassana Pagoda w Bombaju (2009),
g) szkic przekroju hali na 8000 osób monitorowanej przez studio Auroville Earth Institute (autor: S. Krawczyk),
h) model inspirowany kopułą Santa Maria del Fiore we Florencji (architekt: Filippo Brunelleschi),
i) model płaski przekroju z rozporą zastosowaną w miejscu pierścienia rozciąganego (autorzy: E. Naworska, S. Kiciński, W. Włodarczyk)

Table 1. Study of students' reception at the faculty of architecture of reverse modelling methods as a tool for designing optimal architectural construction forms (elaborated by M. Pelczarski)
Tabela 1. Wady i zalety modelowania fizycznego synergicznych form architektoniczno-konstrukcyjnych przy zastosowaniu metody modelowania odwrotnego (oprac. M. Pelczarski)

Disadvantages	Advantages
Labour-intensive	Simple and proven techniques for making physical models
Need for manual precision	Strengthening of intuition
Assistance by another person required	Bolder and independent design
Difficulty in force reversal interpretation	Further development of research tools
High cost of experiments	Independent evaluation of one's own solution
	Better understanding of the workings of the design used
	Ability to introduce modifications to the model
	Simultaneous control over form, function, and structure
	Developing design decision-making skills
	Searching for new modelling techniques
	Adaptation of the method to the students' perceptive abilities
	Encouraging micro-engineering problems solving

own intuition. On the other hand, they mentioned the following as disadvantages: labour-intensive, the need for manual precision, patience, the need for assistance from another person, confusion resulting from the reversal of forces. There were also comments about the beneficial effect of physical contact with a collection of models made in previous years, which allows a quicker understanding of the working principles of physical models through touch and the models' reactions to the applied force. The advantages and disadvantages of the inverse shaping method reported by nearly 90 students and the author are summarised in Table 1 (the advantages outweigh the disadvantages, and the indicated disadvantages are solvable).

The research shows that this method, properly communicated to students and supported by interactive exercises or scripts available on the web, can contribute to a significant increase in their self-reliance and confidence when designing new, as yet unknown optimal forms that can be independently verified by them using the inverse modelling technique. The modelling of new forms based on the physical laws of nature used during inverse modelling should and, as the research shows, can become a cornerstone of the contemporary architect's workshop, making him or her an informed creator of new solutions, well prepared for dialogue with all branches of the design process.

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Streszczenie

Modelowanie odwrotne jako narzędzie w nauczaniu konceptualnego kształtowania synergicznych form architektoniczno-konstrukcyjnych – badanie recepcji metody

W artykule autor przedstawił własne doświadczenia w nauczaniu kształtowania synergicznych form architektoniczno-konstrukcyjnych, czyli takich, w których forma architektoniczna i forma konstrukcyjna stanowią jedność. Szczególną determinantę osiągania w praktyce tej jedności stanowią odpowiednie relacje pomiędzy profesjami architektoniczną i konstrukcyjną.

Autor występuje z pozycji inżyniera budownictwa z wieloletnim stażem w nauczaniu konstrukcji na poziomie akademickim (studentów architektury). Z jego doświadczeń wynika, że efektywne w tej mierze są metody wykorzystujące modelowanie fizyczne, w tym tzw. kształtowanie odwrotne. W artykule zaprezentował sposób prowadzenia zajęć opartych na tych właśnie podstawach i opisał przykłady uzyskanych podczas nich efektów. Autor zbadał też recepcję metody kształtowania odwrotnego wśród studentów Wydziału Architektury Politechniki Wrocławskiej, zestawiając wady i zalety zgłoszone przez blisko 90 osób.

Obecnie proces edukacji inżynierów budownictwa rzadko wykorzystuje manualne metody modelowania fizycznego jako narzędzia kształtowania formy architektoniczno-konstrukcyjnej. W tych celach stosuje się głównie metody obliczeniowe i modelowanie cyfrowe. Zdaniem autora metody te są właściwe dopiero w drugim etapie weryfikacji konstrukcji, po wcześniejszym stworzeniu unikalnego konceptu i zarysu obiektu podczas wstępnego modelowania fizycznego. Do podobnych wniosków można dojść, obserwując warsztat i dorobek słynnych projektantów, łączących często równocześnie kompetencje inżyniera i architekta. Model fizyczny, zbudowany poprawnie już we wstępnej fazie projektowej i przy ścisłej współpracy architekta i konstruktora, może zawierać około 70% trafnych ideowo rozwiązań, a te mogą stanowić podstawę dalszych faz koncepcyjnego doskonalenia synergicznej formy architektoniczno-konstrukcyjnej.

Słowa kluczowe: kształtowanie konstrukcji, architektura konstrukcji, modelowanie fizyczne, forma architektoniczno-konstrukcyjna, przepływy sił