A FEW THOUGHTS ON HOW WE DEFINE STRUCTURAL FORMS

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The first thing that an engineer should do in his structural design is somehow to define the form of his structure in its surroundings. The structural form that is thus defined should be as satisfactory as possible in terms of function, safety and esthetics, as Vitruvius demanded more than two thousand years ago. These requirements produced many classic forms for structures, and even today we often use such forms in design of our structures. However, thanks to the development in structural engineering and computer technology, we also have other means of defining the forms of our structures today. In the present paper a few examples of computer-aided designs are first presented to show how the structural forms are defined by use of computers. Some examples of "Structural Morphogenesis" on the basis of optimization technology are also exemplified in comparison with the results of ordinary design methods. Different design themes can also be very important motifs in defining our structural forms. This issue is discussed in the sections that follow. Structural themes which were pursued by A. Gaudi and H. Isler to define rational forms are very famous. A few examples of Kenzo Tange's works in which traditional themes played very important roles to define the structural forms of his buildings are explained. The design themes can sometimes be expressed in implicit ways, as in the examples of Fuji Group Pavilion designed by Yutaka Murata, where he presented only the geometrical principles which govern every geometrical detail of the structural form. Social themes can also be motifs of structural forms, which is explained by way of examples of a footbridge of granite stone and a communication tower designed for a "science city" in the year of first understanding of human "genome".

Key Words: *structural forms, computer-aided design, structural morphogenesis, design themes*

1. INTRODUCTION

One of the most important tasks in structural design has been to define such structural forms that are rational, often economical, and esthetically satisfactory for each given design project. In the long history of structural design this requirement has given birth to well known structural forms such as arches, domes, rigid frames, trusses, shells, funicular patterns with their innumerable variations and combinations. In classical designs most of such forms have been defined as parts of basic geometrical shapes like circle, parabola, catenary, cylinder, cone, sphere, EP, HP, etc. for the sake of analysis, communication between engineers and architects, and transmission of design information to fabricators and contractors.

Today we still use this type of definition very often for design of our structures, but with increasing use of computers we have also become able to define the forms of our structures in different ways from those described above, that is, computer-aided definition of structural forms. Another important issue in definition of structural forms is the Theme of design. A series of designs attempted by A. Gaudi and H. Isler, for instance, contain a theme that the structural systems should meet the natures of materials used in masonry and concrete structures.

Another example of theme incorporated in structural forms can be seen in the design of Architect Kenzo Tange who attempted to add something to flavorless architectural design of International Style. In the following a few examples of the recent trends in computer-aided form definitions are introduced, and then some other examples of definition of structural forms will be explained on the basis of the experience of the author.

2. COMPUTER-AIDED DEFINITION OF STRUCTURAL FORMS

(1) Tianjin monument

A few years ago the author was involved in the structural design of 50m high cast steel monument in Tianjin, China, designed by A. Isozaki. In this design most of defining work of the monument was done by operation with computer (Fig.1).

If an arbitrary curve is drawn on a plane including a vertical line, and the plane is rotated around the line, the curve makes an envelope of a spindle shape. The intersection of the spindle and the horizontal plane draws a circle on the horizontal. If a spiral drawn on the horizontal starting from the center of the circle is projected upward on the surface of the envelope, a spatial curve is produced on the surface (a, b, c). If the phase of the spiral is shifted by some degrees on the horizontal, another spatial curve that is congruent with the previous one is obtained (d). Connecting the two spatial curves by a group of horizontal lines, a spatially curved surface may be resulted (e). By mirroring the spatial surface in respect to a vertical plane including the axis, a pair of symmetrical twins are produced (f). Finally the whole shape is cut out at a desired height to obtain the principal form of the monument (g).

The above procedure is quite appropriate to produce the form of a monument, since with this method we can obtain an unexpected, peculiar shape that can be a candidate for a new form for a monument. By changing the fundamental geometry of the envelope and the spiral, innumerable forms of the envelope are produced, until the architect selects one of them.

The above procedure is purely geometrical and it guarantees nothing about structural requirements. So the obtained form is subjected to structural examinations. It is convenient that the data for the geometrical information of the form can directly be inputted into computer for structural study. The distribution of the necessary thickness and the details of intersections are given in this process, but there are some important parts where increase in thickness cannot provide sufficient rigidity and

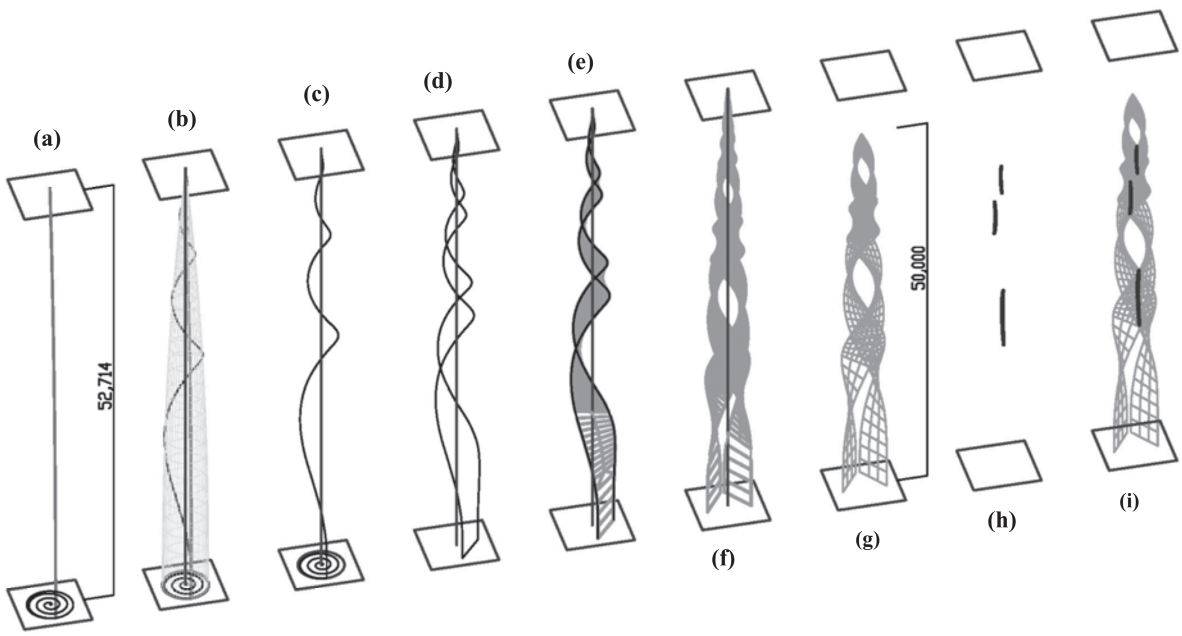


Fig. 1 Definition of form of monument

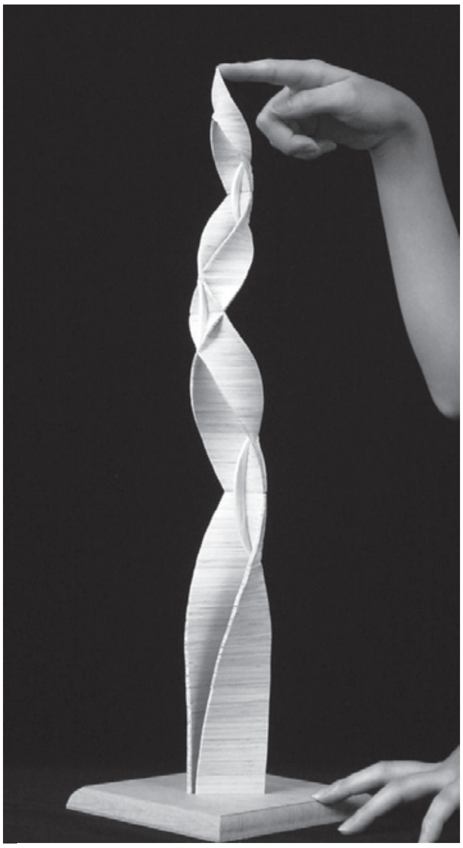


Fig. 2 “Touch & Feel” model

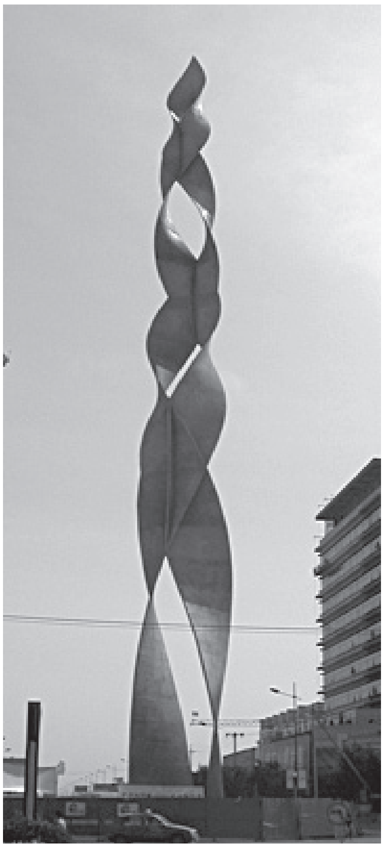


Fig. 3 Completed monument

Fig. 4 Monument, closer view

strength.

So the structural components which are most effective to stiffen such portions of the structure and do not reduce the esthetic value of the monument are sought for. By giving suitable thicknesses to every part of the geometrical “skeleton”, and incorporating necessary stiffeners into the structure, the final form of the monument is determined (h, i).

In the process of structural examination, a study on “touch and feel” model[7] (Fig. 2) is very useful to find out the places and dimensions of the stiffening components. The model is also used to understand the overall behaviors of the monument when it is under construction as well as after completion. Figs. 3 and 4 show the completed monument.

(2)Computer-aided definitions of “optimum” forms

A number of optimization methods can be used to find candidate forms of a structure. In 2005 the Committee on Morphogenesis and Optimization of AIJ (Architectural Institute of Japan) tried an interesting event of “designing” a bridge with four different optimization methods[1]. The bridge was virtually designed to span a valley in Kyushu which was already crossed by a pretty arch bridge (Fig. 5).

The given conditions for the virtual bridge design were as follows:

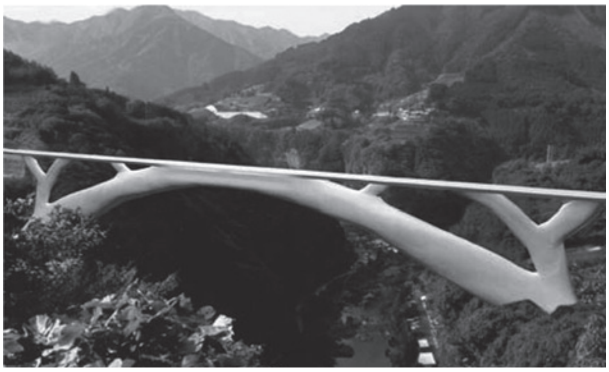
Possible Design domain: Length (Span) =260m, Width=7m, Depth=35m
Material (Steel): Unit weight=78kN/m^3, Young’s Modulus=210Gpa, Poisson’s Ratio=0.3
Live Load: Uniform load of different intensities (3.5 – 100 kN/m^2)

The bridge designs obtained by different methods are shown in Fig.6.

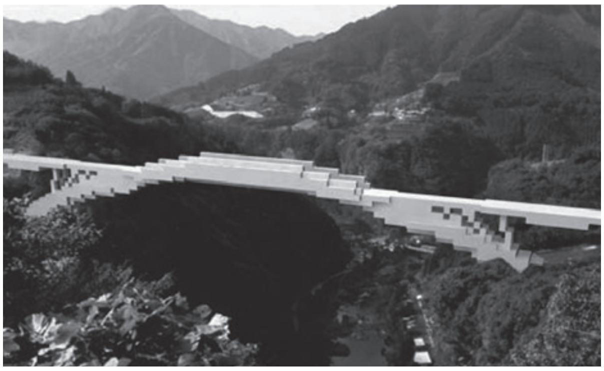
It is interesting to note that different methods define different forms as optimum. Each of the above designs is optimum in a certain sense, and can be regarded as one of the alternative designs which will perhaps be of suggestion in the first stage of a bridge design, although nothing is guaranteed by them in terms of esthetic satisfaction or practicability. Of the above four designs one by Mitsui happens to be closest to the form of the

Fig.5 “Tensho Ohashi”, existing bridge

Ground structure method, Ohsaki, M. [2)]



Extended ESO method, Ohmori.H.[3)]



CA method, Mitsui, K.[4)]

Homogenization method, Fujii, D.[5)]

Fig.6 Virtual design projects for a bridge (CG by Futai,H.)

actual bridge. "Tensho-Ohashi", the actual bridge of arch design which was awarded the JSCE Tanaka Prize in 2000, is no doubt rational and esthetically satisfactory.

3.FAÇADE DESIGNS BY OPTIMIZATION AND BY NORMAL METHODS

In this section two examples of façade design, one done by means of computational optimization and the other by a conventional method, are shown. The first example is a commercial building near Osaka designed by H. Ohmori et al.[1)] (Fig. 7).

Fig. 7 Façade design by XESO method[1)]

Fig. 8 Façade design by normal method (Architects:EASTERN)(Phto: Y. Suzuki)

This five-storied building has two walls, facing the south and west, that are open to the sight, and the designers attempted application of their extended ESO method. The walls act as bearing as well as shear walls. In the process of computation the location and dimension of the openings for entrances are artificially controlled by the designers to meet the functional requirements. Different steps of computation give different possible structural forms of the walls, and the designers are in the position of selecting any one of them that they think most favorite from functional and esthetic viewpoints.

The second example is a three-storied apartment house in Kyoto designed by Eastern Design Office (Fig. 8). In this case the designers did not pursue "optimum" structural design, but they sought for a design that was "practicable" in all aspects, following quite a normal design procedure.

Namely, the architects made their wall design, taking into account all the functional requirements, tastes of the clients, possible structural requirements of the engineers and, of course, comfort of the tenants. Through ordinary communication with the structural engineer who thought much of the architects' idea, they came to the final design (Fig. 8) which was satisfactory in all the architectural and structural aspects, and economical as well.

In the process of design the architects and engineers used computers to the maximum extent in mutual exchange of design data, drawing and computation, but they did not use them for "optimization", since they were confident that by means of "normal" approach they could reach a free form design that they thought sufficiently practical, if not "optimum".

4. DESIGN THEMES IN DEFINITION OF STRUCTURAL FORMS

(1) Structural themes

An example of the most popular themes in structural design may be that materials should be used in compression in masonry and concrete structures. This theme led A.Gaudi and H.Isler to such experimental definitions as inverted hanging arches and suspended mesh shells to obtain optimum forms. Another structural theme may be that longer metal components should be in tension to avoid buckling, which gave a good reason for definition of Pratt type truss girders. The theme of static clarity gave birth to the conceptual forms of Gerber girders and three-hinged arches.

Those examples are so well known that it may not be necessary to illustrate them here.

(2) Traditional themes

Local traditions can sometimes be very important themes in defining structural forms. A few of the most sophisticated examples may be found in the works of Kenzo Tange. Tange had been trying to incorporate the flavor of local tradition into so-called international style in which building forms were similar everywhere in the world and prosaic.

In design of Kagawa Prefectural Office (Fig. 9) which is today evaluated as one of his masterpieces, Tange attempted to define the form of his concrete structure in relation to the structural system of Japanese traditional buildings (Fig. 10). He designed deep balconies around the main body of the office, and made an attempt to express the cantilevering floor joists of the balconies like rafters in traditional temples. This design concept was

Fig. 9 Kagawa Prefectural Office

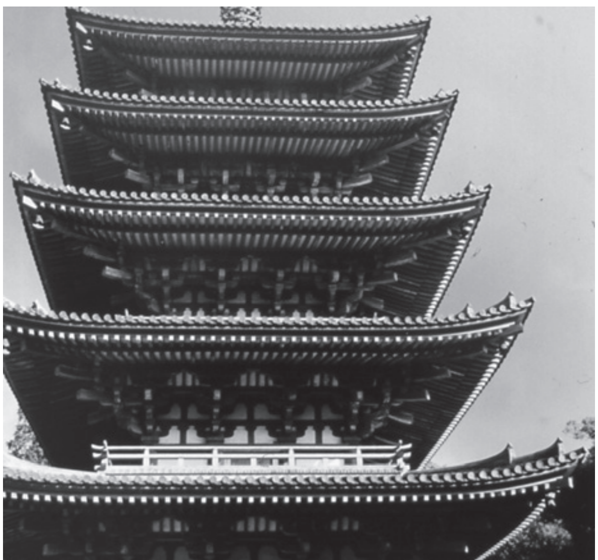


Fig. 10 Pagoda of Daigoji Temple

Fig.11 Gymnasium 1 of Yoyogi Stadiums

Fig.12 Toshodaiji in Nara

comprehensible to everybody, and it was jointly possessed by his structural engineers and builders, which led to a very successful result.

In Yoyogi Stadium (Fig. 11) for the Tokyo Olympics, another example of Tange's masterpiece, one of the most important design themes was expression of the grand roof. Although the structural system of the roof was a hanging one, Tange chose to express it like a solid grand roof rather than a more flexible cable network as seen in the works of other architects like Frei Otto. Expression of grand roofs has been an essential design effort in traditional buildings in Japan (Figs. 12, 13), and the theme presented by Tange was directly accepted by the structural designers and builders with sympathy, again leading to a great success.

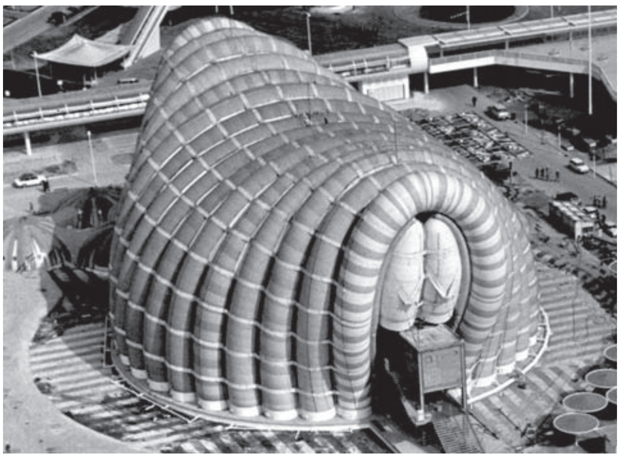
(3) "Let it be" principles

Themes for structural forms need not always be described in an explicit way. It can be presented in an implicit way as well. The late architect Yutaka Murata sometimes took such a design policy. He specified his themes only in the form of geometrical principles, and thought that the structural shapes would be automatically resulted by natural law. Murata called this method "Let it be" principle. In

Fig.13 Daigoji in Kyoto

design of Fuji Group Pavilion for Expo'70 in Osaka[6] (Fig. 14), for instance, he defined the shape of his air-inflated structure as follows.

Draw a circle of 50m in diameter on a plan. The area shall be covered by sixteen air-inflated tubular fabric arches each having a diameter of 4m. The two central arches are semi-circular, standing parallel on the circle in plan. The remaining fourteen arches have the same length as the first two, and they also stand on the circle to form the structure from the center toward the edges of the



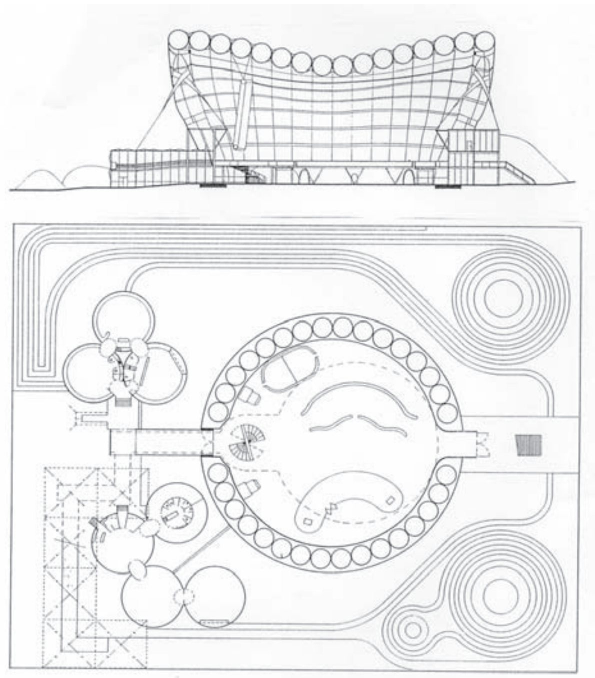


Fig. 14 Fuji Group Pavilion of Expo'70, Aerial view and drawings

building. The springing of every arch should be vertical, and they should keep the continuous contact with the adjacent arches. The above requirements perfectly define the form of the structure. Since the distance between the two legs of an arch becomes shorter when it goes further from the center, the height of the constituent arches having the same length becomes higher toward the ends of the building. The upper parts of the arches are also pushed outside by the foregoing ones, producing a controlled but unprecedented three-dimensional form.

Although the final geometry of the structure was not defined in an explicit way in the design documents (except very rough ones), the above principle is sufficient to define essential nature of the form, and the resulting forms of constituent arches and the whole structure can be obtained by computation.

(4) Social themes

Social themes can often be good motifs for defining structural forms. Social themes are normally rather arbitrary, and do not look to have anything to do with structural forms. However, it is often possible to find something that is particular to the place and time (historical) of the construction of the structure, and suggestive in defining the form of the structure. In the following a couple of such examples are explained.

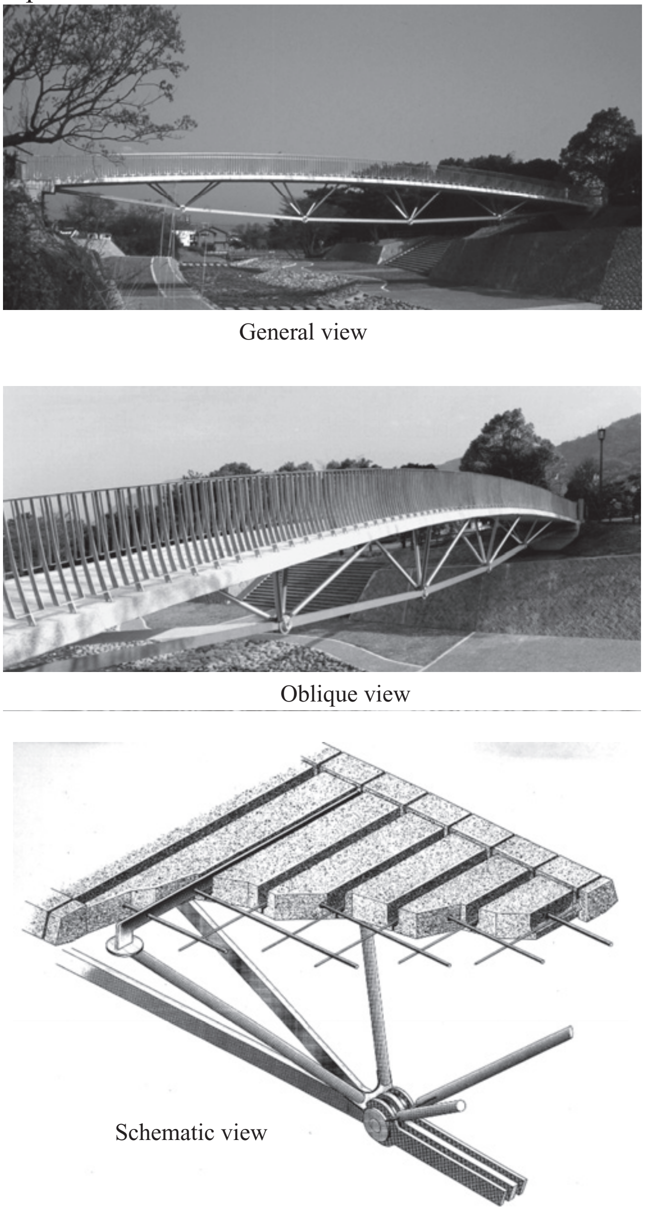
a) “Inachus” bridge

Some ten years ago, the author was involved in design of a footbridge in Beppu. The City of Beppu is located at the north east coast of Kyushu. Beppu is famous for its hot springs and beautiful scenery.

In the west part of the city is located a spacious park named Minami-Tateishi-Koen. As an access to the park from the north, the Mayor of Beppu City wanted to have a pedestrian bridge which crosses a river running along the edge of the park. The span to be bridged was 34 m. Since the construction site of the bridge was a wonderful scenic point, commanding an open view of Beppu Bay to the east and a mountainous scene of Tsurumi Peak to the west, the Mayor asked the author to create a uniquely beautiful bridge there.

In the process of discussions with the Mayor and the staff of the construction division of the city, the author noticed that Beppu has a sister city in China named Yantai which exports granite of excellent quality. He also realized that the city of Beppu has been importing granite from Yantai for pavement of the sidewalk in the streets.

Then it occurred to the author that it might be worth-while to use the granite as a structural material of the bridge which he was to design, in promotion of sisterhood between the two cities.



General view

Oblique view

Schematic view

Fig. 15 “Inachus” Bridge

Laboratory tests on the granite for the pavement proved that the stone was superbly strong and stiff (compressive strength: 130 N/mm^2, Young’s Modulus: 3.0×10^4 N/mm^2) for structural uses. The author decided to use the Yantai granite for the upper chord of his bridge.

The bridge was designed to have a lenticular shape with an arched upper chord and a suspended lower chord, which is sometimes called a “suspen-arch.” The author designed the granite upper chord not only as the principal structural member but also as the deck on which people directly step when they cross the bridge.

It consists of 78 blocks of granite 40cm wide and 25cm deep with a varying length from 2.6m to 3.6m. Through the holes drilled in the center of the depth of the granite blocks, 5 prestressed cables are arranged in the longitudinal direction, parallel to the bridge axis. After the joints between the adjacent granite blocks are secured with filling mortar, the whole upper chord is prestressed to produce a literally "monolithic" structural member.

The lower chord has the longitudinal shape of a funicular polygon which is almost symmetrical with the upper chord. It consists of steel plates arranged into a chain. The upper and lower chords are connected to each other by means of web members consisting of steel tubes arranged to form inverted pyramids.

The web members are constituted in a manner which the author calls an "open-web truss" or "incomplete truss", in which the web of a girder is not closed by a repetition of lattice members as in a normal truss. The author has been using open-web trusses in several designs of his recent works.

In open-web trusses bigger bending moments naturally occur in the upper chords especially under non-uniform load, compared to normal trusses, but in many cases the upper chords have a marginal capacity to accommodate these additional bending moments. Taking into account the savings in lattice members and connecting details and esthetic advantage of a simpler appearance, the author believes that the open-web truss has a good raison d'être in structural design.

The bridge was named "INACHUS" (the name of the God for the river in the Greek myth) through a naming competition among the citizens of Beppu.

b) Genome tower

In 2001 the author was asked to design a 20m high wireless communication tower for the sake of disaster prevention in a city named Harima Scientific Garden City in Hyogo Prefecture. This new city was founded in 1986 with the purpose of establishing an ideal city where people would live in a good harmony with nature and science. The city was then developed by introducing excellent academic research facilities and high-tech industries in it.

One of the most important facilities of the city was "SPring 8", a world-largest accelerator to produce electron beams of huge energy (8GeV). Using the strong beam produced in the facility researchers can investigate the structures of matters including protein to a great precision, of which the city is very proud.

In February of the same year the International Human Genome Sequencing Consortium published the first draft of the Human genome in the international scientific magazine *"Nature"*, which was regarded as the first complete understanding of the human genome.

The author thought that this social theme was very timely and suitable to the city for which he was going to design the tower. He thence decided to materialize in his tower design the molecular model of DNA which was constituted by two sugar phosphate backbones in the shape of helices which were connected with each other by base pairs (Fig. 16). Although a pair of helices alone are not capable of resisting lateral forces, he found that those backbones in a congruent twin helical shape with horizontal struts connecting them would act as

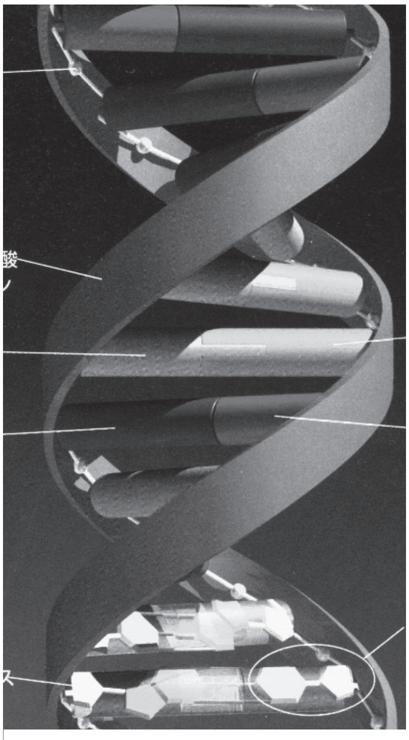


Fig. 16 DNA Model

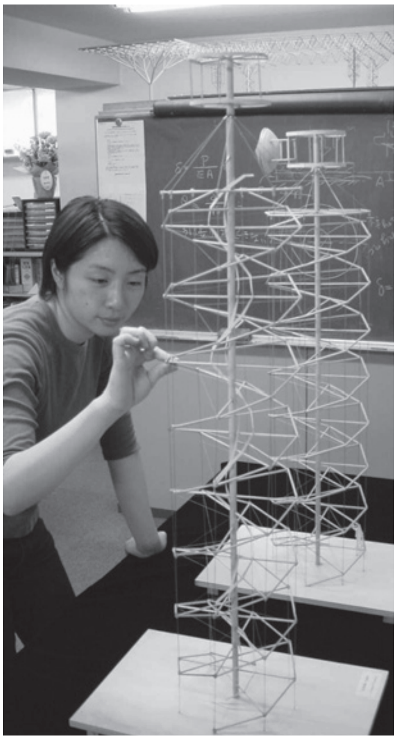


Fig.17 "Touch & feel" structural model[7)]

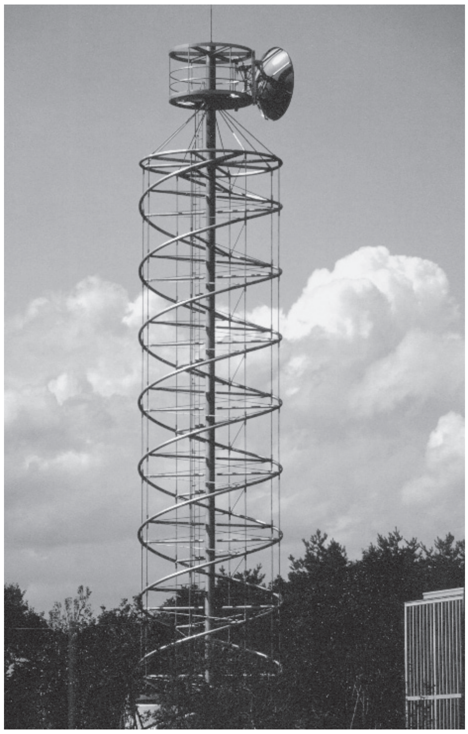


Fig. 18 Built "Genome" tower

effective shear members of the tower against lateral forces, when they were designed with subsidiary thin tension members connected to them. Bending of the tower can be absorbed by prestressed vertical outside cables and the central column as in usual structures.

Then scaled models[7)] were made as the author often does to intuitively check the results of calculation (Fig. 17). They were "touch and feel models" as he had named to see if the human sense of touch coincides with the results obtained by computation. In the present case scaled models of 1/20 were produced[7]. Fig. 18 shows the realized "Genome Tower".

5. CONCLUSIVE REMARKS

In the present paper it has been first shown that computers are conveniently used to define the form of a structure as in the example of Tianjin monument, where the basic rule of producing a geometric form and the parameters involved are the defining factors of the form.

Optimization methods explained in the examples of virtual bridge design are also conveniently applied to obtain design alternatives which have certain kinds of optimum nature in them. In this case the proposed design forms themselves are the interfaces between architects and engineers, since these design alternatives can be the common clues for them to develop their ideas towards the final design.

Sometimes a normal design method gives freer form than a method based on an optimization principle as we have seen in the wall design examples.

When a clear "design theme" is jointly owned by an architect and his engineer, it will be the most reliable interface between them. Themes based on structural principles are examples of such interfaces.

A. Gaudi and H. Isler played the dual roles of architect and engineer in their design activities, but the theme that the structural forms should be suitable for the nature of materials was an essential interface between the two roles.

Traditional themes can also be important interfaces to be jointly owned by architects and engineers as seen in the examples of Kenzo Tange's typical works like Kagawa Prefectural Office and Yoyogi Stadium.

Design themes can be presented in an implicit form as in the case of Fuji Group Pavilion in Expo '70 where Y. Murata described only the basic idea of geometric requirements that completely specified the form of his air-inflated building.

Social themes can also be excellent motifs of structural forms. Two examples, "Inachus" Bridge and "Genome" Tower, have been explained in this connection.

To conclude the present paper it should be noted that no design methods can guarantee the esthetic quality of structures. With or without the aid of computers architects and engineers should always try hard to make the most of their abilities to examine if their structures are really rational and beautiful.

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(Received April 14, 2006)