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Sound Conceptual Design for Sustainability in Bridges

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Sound Conceptual Design for Sustainability in bridges

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Abstract

How did the great bridge designers of the past leave behind such wonderful structures in an age before computers and thick standards? This has been the author's question for many years. It was known that the three elements of Roman beauty also applied to bridges. But that alone is not a sufficient explanation. And when the world set sustainability as a new goal, it turned out that it could be successfully explained by introducing the idea of structural sustainability. This paper explains the conceptual design of Japanese bridges in terms of structural elegance and structural sustainability.

Keywords: structural sustainability, conceptual design, structural elegance, bridge

1. Introduction

The last 44 years of the author's career as a bridge designer have seen significant technological developments. And the author has been fortunate enough to witness this process first hand. From calculators to personal computers, from linear to non-linear analysis, from drafters to CAD and BIM, and new structures and materials, the technological developments have been impressive in every way. Figure 1 shows the evolution of the number of pages in Japanese concrete and road bridge standards and the number of pages in calculation documents for conventional three-span box girder bridges. The handwritten calculations, which were about 300 pages in 1980 when the author started working on bridges, are now ten times that number, and most of them are typed by computer. Have we really improved our technical potential as well as the number of these pages?

When the author was young, I used to think a lot while drawing lines on a drafting board, and there was no e-mail or mobile phone. FEM was linear, of course, but it was expensive, so I worked out how to optimise it by simple analysis and formulation. Now, however, we are in an age where we can turn to computers right from the start and use the power of computers in large models in abundance. And we can get to the optimum solution in a short time. Today's engineers should have more time to think along these lines, but in reality this does not seem to be the case. The next job is waiting for them. In other words, design productivity has improved dramatically since the author's time, but I can't help feeling that something important is being lost. I believe it is conceptual design. Conceptual design does not need thick standards or computers. This has been proven historically by great bridge designers. In the extreme, conceptual design is a process where all you need is a piece of paper and a pencil and you can think in your head and come up with the optimum solution. The author belongs to a generation that practised conceptual design by always carrying a 5 mm graph paper and a pencil (Figure 2).

Against this historical background, the new value of sustainability has entered design in the 2000s. This paper reconsiders what is appropriate conceptual design with examples and discusses conceptual design for sustainability.

2. Conceptual design

Figure 3 shows the life cycle of a structure. Conceptual design, which occurs at the beginning of the design process, involves a rough optimisation of the object to meet performance requirements and constraints. Performance requirements include safety, serviceability and durability as specified in the standards. Performance is then given in the design so that these performance requirements are met during the life cycle of the structure. Constraints, on the other hand, differ from project to project and it is necessary to derive a structure that satisfies cost, construction time, bridge alignment, etc. As the performance requirements and constraints differ in their physical quantities, the design becomes a multivariable optimisation problem. And since most of the variables are related to CO_2 emissions, it is necessary to discuss how to optimise them. The Special Activity Group has been organised in 2024 across all *fib* committees. This discussion will continue within this group. The design will now include the new constrains (performance) of CO_2 emission reduction. In other words, we have an increasingly multivariable and complex puzzle to solve.

The clues to solving this puzzle can be considered in two categories. One is structural elegance and the other is structural sustainability. Structural elegance consists of three elements. They are the same as the three elements of architectural beauty identified by the Roman Vitruvius: utilitas (useful), firmitas (sturdy) and venustas (beautiful). Applied to bridges, they are "functionality", "structural efficiency" and "beauty of form" respectively. The author has identified these as the three elements of structural elegance in bridges [1]. The three elements of structural sustainability are the same as the three aspects of sustainability, social, economic and environmental aspects. Each element attributed to the structure is then specifically defined as structural sustainability.

The three elements in these two categories are considered in a three by three matrix (Figure 4). There are nine possible combinations of each element and four main keywords that can be considered to reduce CO_2 emissions. The first is 'lightweight structure'. If this can be achieved through structural ingenuity without increasing the strength of the materials, a significant reduction in CO_2 emissions can be achieved. Of course, this also reduces costs. The second is 'accelerated construction'. Although shortening the construction period generally increases costs, it is known that shortening the construction period can significantly reduce indirect CO_2 emissions when the impact of construction on surrounding social activities is taken into account [2]. The third is 'rational force flow'. A structure designed to minimise the flow of forces from the point of loading to the point of support of the structure is material minimising. This means that CO_2 emissions are also minimised. This principle is particularly important for cable supported structures. The fourth is 'minimum environmental impact' construction. By minimising the environmental impact of construction sites, CO_2 emissions are minimised and biodiversity is protected.

In the following chapters, the 3x3 matrix of structural elegance and structural sustainability will be used to explain how the four keywords for reducing CO_2 emissions contribute to conceptual design, using actual examples from Japan.

3. Structural elegance

It is difficult to translate structural elegance into Japanese. If I had to guess, I would say 'iki and miyabi'. In English it would be 'chic and graceful'. The best example of 'iki and miyabi' in Japanese architecture is shrine and temple architecture. The warping of the eaves and the depth of the eaves, originally imported from China and refined to the highest degree, are the result of the Japanese aesthetic sense, the former by reducing the warping and the latter by deepening the eaves to suit the rainy climate. The connections between the columns and the beams are of nail-less construction, with the beams penetrating the columns, a so-called seismic isolation structure that allows seismic forces to escape to a moderate degree. In addition, the clay walls have the function and strength to retain an appropriate level of moisture and are an excellent material that can be kneaded and reused. Although made of wood, it has a 1,000-year lifespan and is truly a masterpiece of functionality, structural efficiency and beauty of form.

3.1 Functionality

The most important function of a bridge, such as a road bridge, is to allow vehicles to pass. Another important element of functionality is how well it blends into the surrounding terrain and environment. Another aspect that attracts attention is how well the environment is maintained during construction, which can also be considered as a function. It is natural for a thing with a superior function to take on a beautiful form. It is important to be able to explain the need for functionality, while at the same time being able to imagine a structure that is in harmony with its surroundings. The pursuit of functionality requires a very high level of skill.

The Seiun Bridge [3], shown in Figure 5, had difficult constraints. The bridge is located in a national park and as no piers could be placed in the river, even during construction, it was necessary to build a 90m single span bridge. Both abutment locations were also difficult to secure construction yards due to the steep mountains. In such terrain, an arch bridge is generally adopted. However, an arch bridge was excluded due to their high environmental impact, as they significantly alter the terrain during excavation of the arch abutments. A special erection method using a suspension structure was then adopted (Figure 6). The anchoring forces of the suspension structure are released on completion and transferred as prestressing forces to the girders to construct the simple girder (Figure 7). All components of the girders were also prefabricated in the factory as precast and transported to the site. Of course, during construction, analyses were carried out using the large deformation theory, although the structure was concrete. These solutions under severe constraints are considered to be an important functionality and are positioned in ② of the matrix. And the key word is 'minimum environmental impact'.

3.2 Structural efficiency

Structural efficiency is the most obvious element and can be summarised as structural rationality and simple force flow. Structural efficiency is important to ensure that the flow of forces is clear and that forces are transmitted through the shortest possible distance, so that no additional bending moments or shear forces are generated. And bridge engineers can read this philosophy through the structure without explanation when they look at it. Structural efficiency is something that cannot be faked against professionals.

Figure 8 shows a good example of structural efficiency, the Katsushika Harp Bridge. The road spans the canal in an S-shape, which limits the location of the bridge piers. Cable-stayed bridges were then chosen to reduce the weight of the superstructure. The problem is the location of the main towers and the arrangement of the stay cables. Therefore, the main tower is located at the inflection point of the S-shape, which makes the stay cables point-symmetric and eliminates the out-of-plane horizontal component of the stay cable forces. This allowed the main tower to be a single column rather than a frame structure. It is a small but very elegant solution. In addition, due to the limitations of the pier positions, the main towers are arranged at different heights, resulting in a three-span structure. It is positioned in ⑥ of the matrix and the keyword is 'rational force flow'.

3.3 Beauty of form

Structural Elegance cannot be described by this beauty of form alone. The essence lies in the functionality and structural efficiency mentioned above. Therefore, it is considered to be only a subsidiary role. And it is fundamental that the beauty of form can be explained structurally. Beauty of form is a matter of personal preference and subjectivity. And unlike functionality and structural efficiency, which are commonly understood by bridge engineers in different countries, beauty of form is influenced by the specific culture of each climate and ethnic group. Beauty of form can only be developed through exposure to many examples. But it requires a structural background.

The Furukawa Viaduct [4], shown in Figure 9, is a 3 km long motorway built in an urban area. It was built using the precast segmental method, but because of the urban area around it, it was prefabricated and transported at a precast plant 100 km away. Trailers on Japanese roads are normally restricted to a maximum weight of 30 tonnes. Therefore, if a beam with a span of 35 m and a width of 17 m is precast in its entire cross section, the segment width will be 1.9 m. The total number of segments would then be 1,900. In order to reduce the number of segments and thus the transport, a special shape called the U-shaped core segment was conceived (Figure 10). This gave a segment width of 2.6 m and reduced the number of segments to 1300. The decks were cast-in-place, using precast panels instead of formwork. The deck is then constructed in five days. This is the same speed as forming a U-shaped core segment into a girder. Erection costs were also reduced because the weight of the segments suspended from the erection beams was reduced by 60%.

The social impact of the viaduct construction in the city has been minimised and the view from under the bridge is reminiscent of the eaves of Japanese temples and shrines. It can be positioned at ⑦ of the matrix, where beauty of form and social aspect merge. The key word in the conceptual design is 'accelerated construction' through 'lightweight structure'.

4. Structural sustainability

The concept of sustainability has been introduced from the *fib* Model Code 2010 and placed at the centre of the Model Code 2020 [5]. The author felt that when talking about sound conceptual design, it is sometimes not possible to explain it well using only structural elegance. How were the great bridge designers of the past able to build such holistic structures in an era before computers and thick standards? The answer to this question has been a longstanding theme for the author. The three elements of Roman beauty would, of course, have been recognised by them. But that was not enough. It turned out to be well explained by adding the concept of sustainability, which takes into account the economic aspirations, environmental considerations and social impact caused by the structure. This is structural sustainability [1]. The two categories of elegance and sustainability are structure-driven. From now on, bridge designers are needed who can project these into the conceptual design.

4.1 Economic aspect

As infrastructure, bridges are naturally expected to be economically viable. And the quest for economic efficiency is largely driven by the structure. This is all the more true when the constraints are severe. Minimising life-cycle costs, not just initial costs, is now the order of the day. Guidelines against chloride attack were established in Japan in 1984. Since then, measures have been taken to increase concrete cover in areas where chloride attack is a concern. Durability considerations are never about minimising initial costs, but an optimum solution over the life cycle. In Japan, reinforced concrete slabs on motorways built more than 60 years ago have deteriorated by deicing salt and are being replaced with new slabs at great cost. Material minimisation in the 1960s was not an optimal solution. Two examples of the pursuit of initial cost minimisation are presented below.

The first is the Katsurajima Viaduct [6] (Figure 11). This bridge was constructed using the incremental launching method. At the time of the contract, the bridge was a full-section double-cell concrete box girder, which meant that the weight of the main girder was high and the cost of erection during launching was also high. It was therefore necessary to reduce the weight of the main girder for launching. The solution was to change the main girder to a corrugated steel web and to construct the overhanging slab after launching, thereby reducing the weight of the main girder during launching by half (Fig. 12). In addition, the external cables used during construction were re-installed and re-used for the completed girder. These measures resulted in significant cost savings. This, together with rational erection, is positioned at ③ in the matrix. The key word in the conceptual design is 'lightweight structure'.

The second is the Kakehashi Ichigou Bridge [7], an arch bridge with a span of 155 m (Figure 13). In a design-build competition, it was superior to the steel arch bridge proposal in terms of cost. The main difficulty with this bridge is that the road alignment is curved and deviates from the axis of the arch (Figures 14, 15). The client's masterplan proposal included a higher amount of concrete for the arches and abutments to widen the arches to match the road alignment. However, by reducing the four piers on the arches to two, the amount of concrete was reduced without widening the arches. The amount of concrete was reduced by 20% in the superstructure and 30% in the substructure. This bridge is located at ⑨ in the matrix and the key concept of the design is 'lightweight structure'.

The two examples described above represent the realisation of structural sustainability through lightweight structure. However, material considerations and thoughtful detailing are important to ensure durability for life cycle optimisation.

4.2 Social aspect

Bridge construction and maintenance have a significant impact on social activities in the vicinity of the site. This includes noise and vibration caused by construction activities, as well as traffic congestion and detours due to construction restrictions. In particular, traffic congestion and detours indirectly result in additional CO_2 emissions. And it has been reported that these CO_2 emissions are highly dependent on the construction period and in some cases far exceed the direct CO_2 emissions from construction [2]. This section begins with a project of minimising the impact on social activities around a construction site by shortening the construction period.

The Takubogawa Bridge [8], shown in Figure 16, is surrounded by a primary school and a kindergarten. The construction of the piers and foundations had already been completed in a separate project, but the weight of the concrete box girder bridge at the time of the contract award required new reinforcement due to new seismic standards. The operator, the Highway Company, wanted a lighter superstructure and a shorter construction period to minimise the impact on the surrounding area. Naturally, this was to be achieved with a concrete structure. The solution proposed was the butterfly web [9]. The butterfly web can reduce the weight of the main girder by 15%. This weight reduction reduces the number of main girder segments from eight to five per cantilevering. It also eliminates the need for additional reinforcement of the substructure. The reduction in construction time and the avoidance of reinforcement work due to the weight reduction could minimise the impact on surrounding social activities. Positioned in ① of the matrix, the key word in the conceptual design is 'accelerated construction' through 'lightweight structure'.

Not all social aspects can be measured in terms of CO_2 emissions. Another example is the Yamakiri Ichigou Viaduct [10] (Figure 17). The bridge was surrounded by a village on one side and a citrus grove on the other. The basic design at the time of the contract was for construction on falsework. However, the piling for the falsework was carried out using the down the hole hammer method, which had a significant risk of spreading dust into the surrounding area. The 45m span was too short for the cast-in-place cantilevering method. In the end, a precast segment cantilevering was chosen, with the earthworks section behind the abutment as the fabrication yard (Figure 18). To reduce weight during erection, the overhanging slabs were constructed after the girders had been erected. Dust risks were avoided and the impact on social activities in the neighbourhood was minimised by having the fabrication yard on site. This case can be placed at ④ in the matrix. And the key concept of the conceptual design is 'accelerated construction'.

4.3 Environmental aspect

The biggest environmental challenge is the reduction of CO_2 emissions towards carbon neutrality of concrete structures. And from now on, attention must also be paid to the protection of biodiversity in order to minimise the impact of construction on the surrounding environment. Two case studies from different perspectives are presented below.

The first is the Seishun Bridge [11], a pedestrian bridge (Figure 19). This bridge was designed to connect a junior high school with a sports field and was tendered in a design-build competition. The constraints were that it should be a single span of approximately 60 m across a valley, that no anchors should be left in the ground and that the longitudinal gradients should not exceed 5%. And first of all, the stress ribbon bridge disappeared from our proposal. The author had the know-how of the Seiun Bridge mentioned in 3.1. However, the method of erecting members from the bottom up using a suspension structure was unstable until the load was finally applied. For this bridge, a new construction method was considered in which the members were erected from top to bottom, and a new type of structure, the double suspension structure, was adopted (Figure 20). All loads during erection were carried by the upper primary cables and lifted upwards by the lower secondary cables to achieve the required girder alignment (Figure 21). The anchor forces are then released and transferred to the girders as prestressing forces, as in the Seiun Bridge, to make it a simple girder. After construction, the author knew that there was a wheelchair-bound student at the junior high school and that the completion of this bridge would make it easier for him to get to the playground. This bridge is very dear to the author's heart. Positioned at ⑤ in the matrix, the key words are 'rational force flow' and 'minimum environmental impact'.

The second is the Mukogawa Bridge [12], the ultimate lightweight bridge (Figure 22). The client's basic design was a conventional concrete box girder. The constraints were that the 80m high piers in the river had to be circular with a diameter limit of 5m. A shorter construction period was also required. A structural problem in the basic design was that the piers were unbalanced due to seismic forces being concentrated on the lower piers. To solve this problem, it was necessary to reduce the weight of the girders to eliminate the unbalance of the piers. The piers were half precast using 50Mpa concrete (Figure 23). This method allowed the construction speed of the piers to be halved. The main girders were changed by extradosed bridges with butterfly webs. The construction time of the superstructure was reduced by 270 days because the number of segments was halved by using butterfly webs. As a result, the girders and piers were 20% and 50% lighter, and CO_2 emissions were reduced by 13% and 50% respectively. Although the cost was higher than that of a conventional box girder, it can be placed at ⑧ in the matrix in that it shortened the construction period and gave a slender, beautiful form to the surrounding environment. The key word, of course, is 'lightweight'.

5. Conclusions

In the days of Freyssinet, Torroja, Finsterwalder, Maillart and others, there was no concept of sustainability. Nor were there computers or thick standards of detail. So why were they able to leave behind great structures? Because they were able to invest enough energy and time in conceptual design to find the optimum solution that would be sustainable.

The examples of conceptual design described in this paper have been implemented in the past. They mean that there is still a lot we can do to improve structural sustainability. CO_2 emissions of the past structures are not quantified but will be in the future through LCA.(Life Cycle Assessment) Structural elegance is verified as a performance requirement other than beauty of form. Structural sustainability, on the other hand, is often treated as a measure to satisfy constraints rather than performance requirements. There is an urgent need to discuss how to find a multivariable optimisation solution with different physical quantities. Sound conceptual design is an indispensable element for LCA optimisation. Within Commission 1 of *fib*, the Task Group 1.5 on Structural Sustainability is active [13]. A bulletin for sound conceptual design for structural sustainability will be published this year.

How can conceptual design skills be developed? The author's answer is to actually see a great object and listen to the 'language' through the structure that it speaks to you. It is a conversation about why the structure is the way it is, how it was built and why it works. Imagine for yourself, and talk to the designer through the structure, how it can be explained in terms of structural elegance and structural sustainability. That way you can hone your own skills. I think that is the only way.

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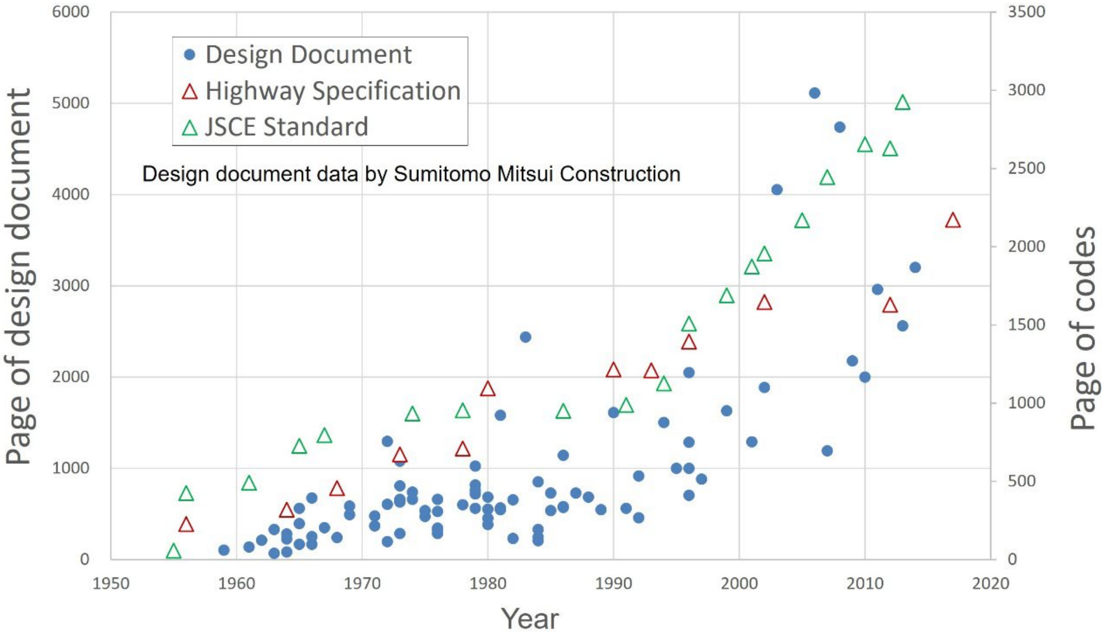


Figure 1 Changes in the number of pages of standards and design documents

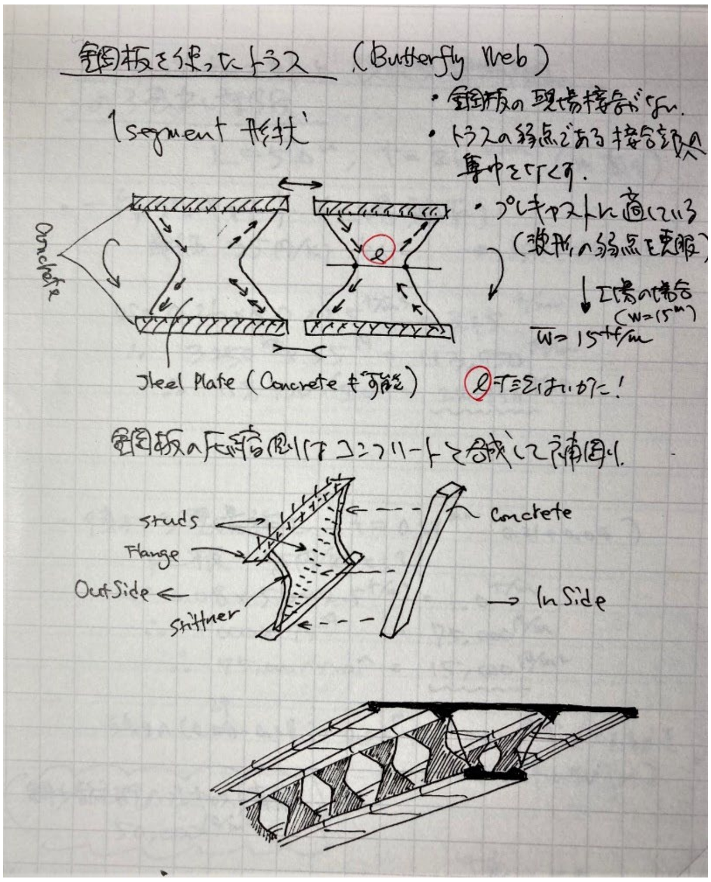


Figure 2 Sketch of butterfly web in conceptual design

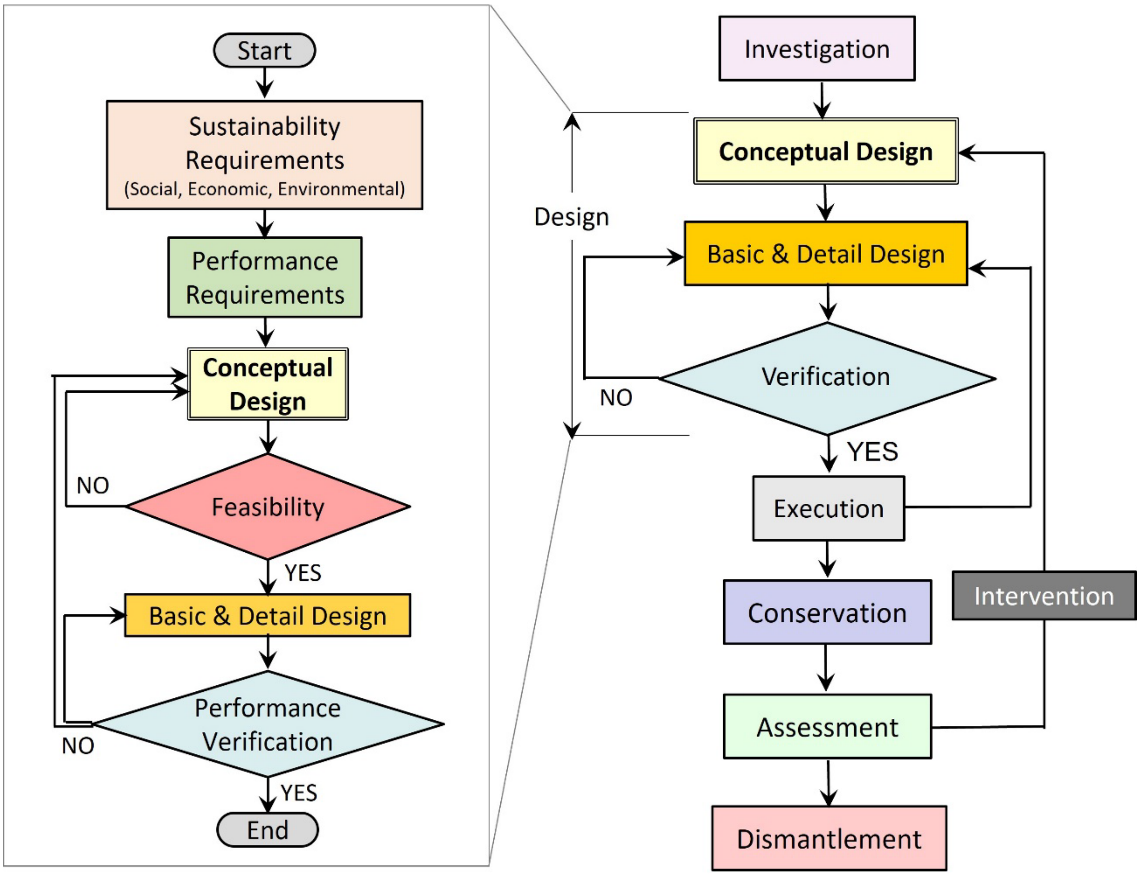
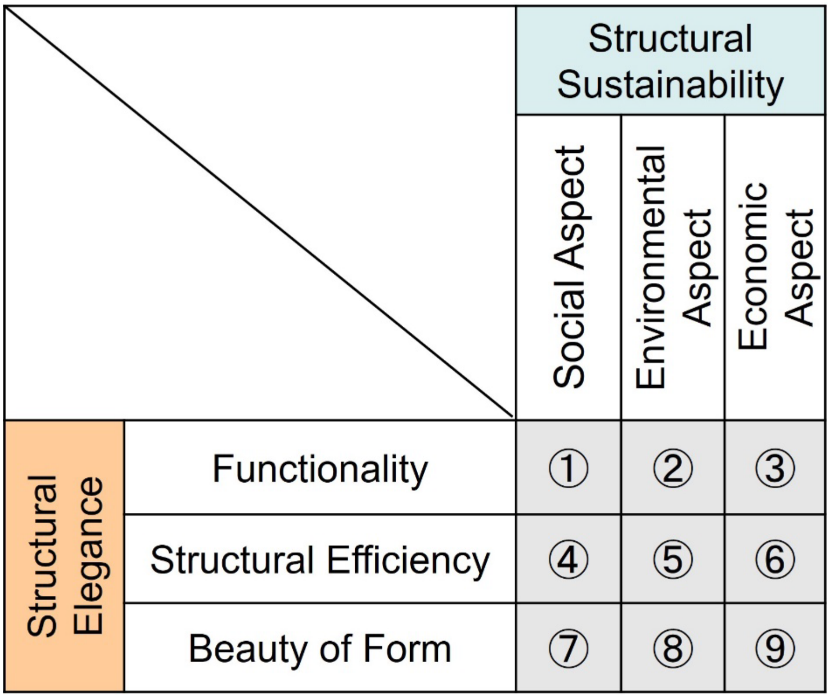


Figure 3 Conceptual design in life cycle flowchart



		Structural Sustainability		
		Social Aspect	Environmental Aspect	Economic Aspect
Structural Elegance	Functionality	①	②	③
	Structural Efficiency	④	⑤	⑥
	Beauty of Form	⑦	⑧	⑨

Figure 4 Matrix of structural elegance and structural sustainability

Figure 5 Seiun Bridge (2004)

Figure 6 Installation of precast member using suspension cables

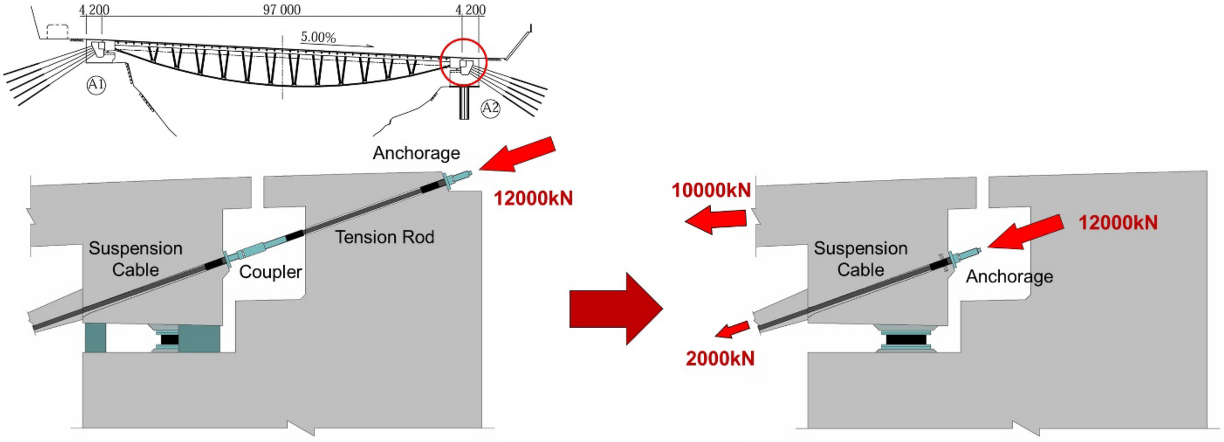


Figure 7 Structural system conversion

Figure 8 Katsushika Harp Bridge with S-shaped planar alignment

Figure 9 Furukawa Viaduct with factory fabricated segments

Figure 10 Erection of U-shaped core segments

Figure 11 Katsurajima Viaduct by incremental launching of core segments

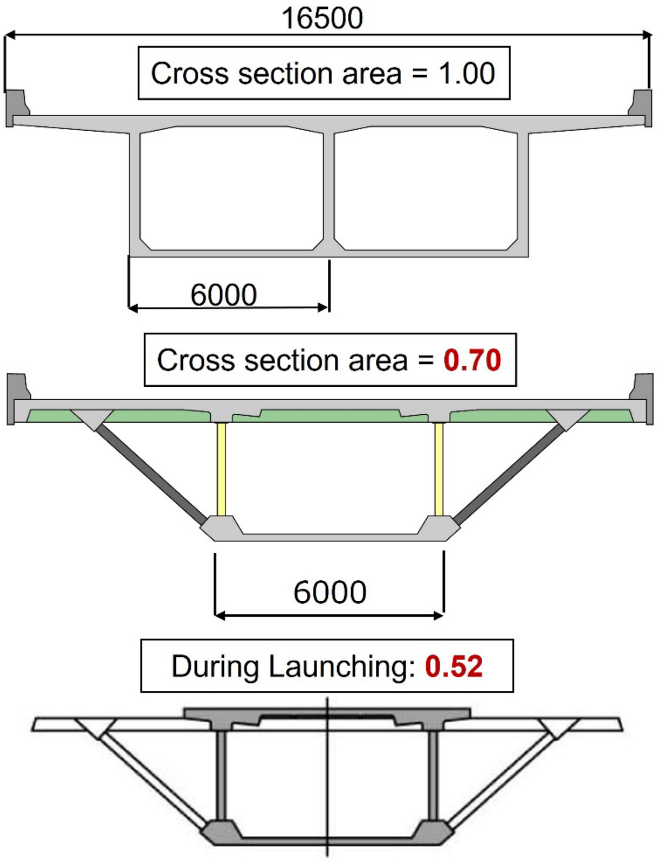


Figure 12 Lightweight structure during incremental launching

Figure 13 Kakehashi Ichigou Bridge with concrete arch

Figure 14 Deviation of arche and curved girder

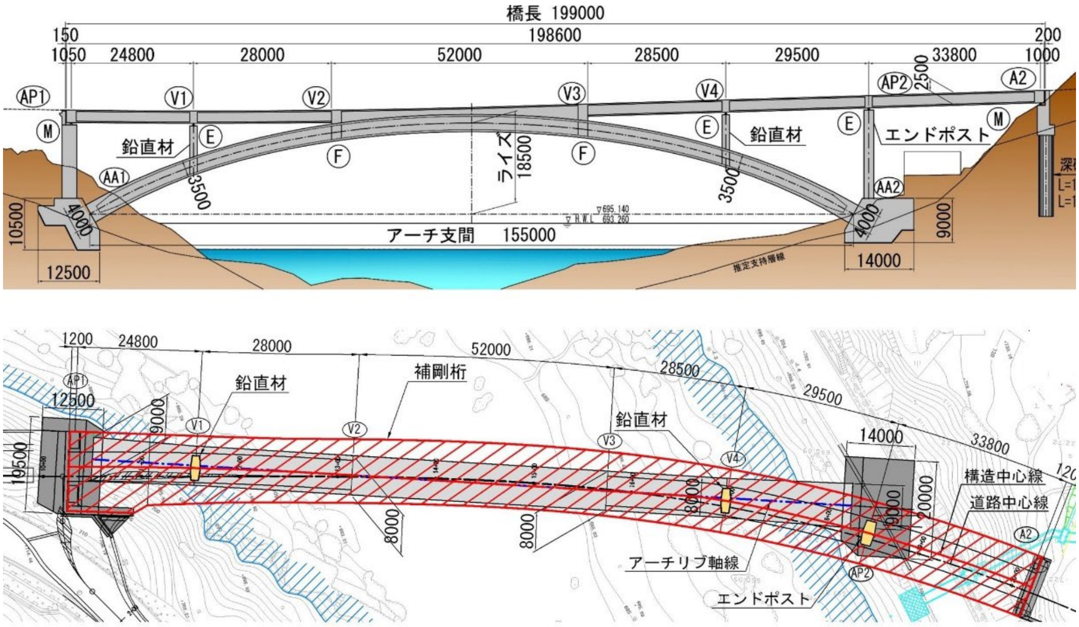


Figure 15 General view of design and build scheme

Figure 16 Takubogawa Bridge with butterfly web

Figure 17 Yamakiri Ichigou Viaduct in a difficult surrounding environment

Figure 18 Precast segment cantilevering with erection girder

Figure 19 Seishun Bridge with double suspension cables

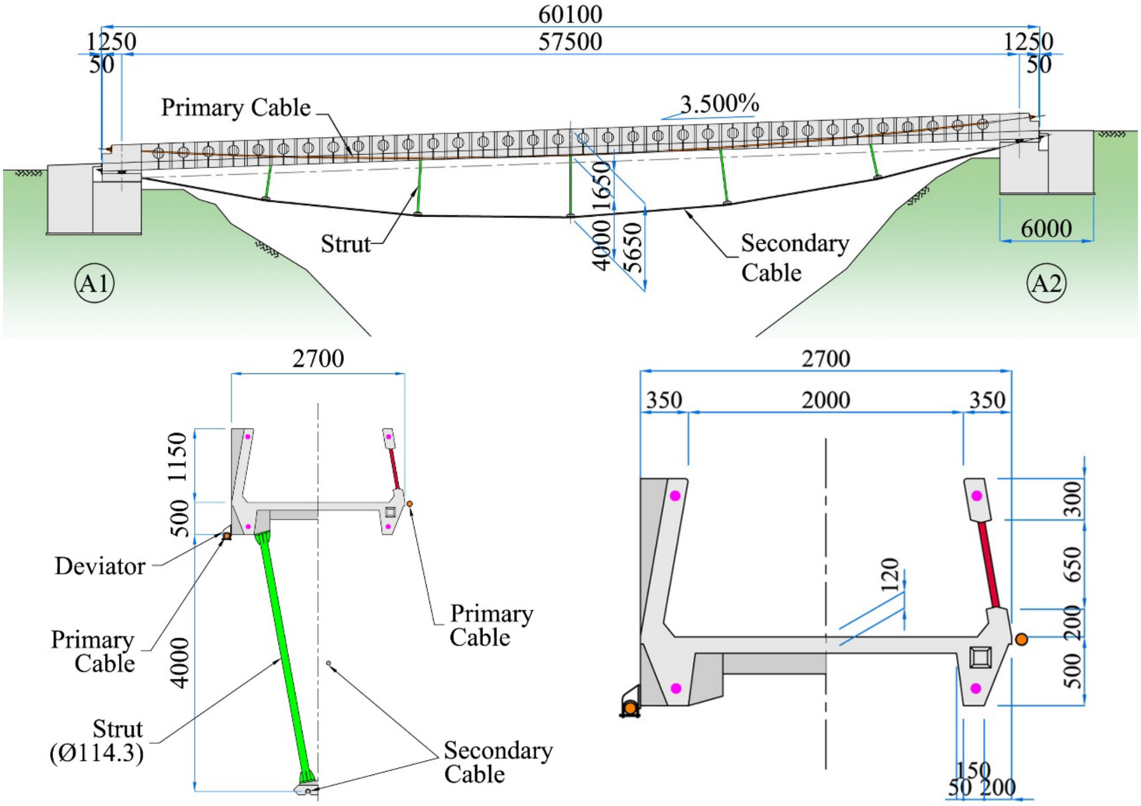


Figure 20 General view of Seishun Bridge

Figure 21 Adjustment of girder alignment using secondary cables

Figure 22 Mukogawa Bridge with lightweight structure

Figure 23 Half precast erection of 80m high pier