PERFORMANCE-CREATIVE CONCEPT FOR INFRASTRUCTURE DESIGN

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***ABSTRACT*:** It is essential in the social management to create and to manage the wealth and the ability of nations. The activity of the human beings could be performed in the suitable artificial environment which consists of various kinds of infrastructure. The artificial environment should protect the society from natural and artificial hazards. Obviously, infrastructures not only produce wealth of the society but also are inherently the wealth of the society themselves. The performance-creative concept will become crucial for the infrastructure design to produce high quality social wealth and civilization of the future.

This paper will introduce a new design method for concrete infrastructures with performance-creative concept. In order to meet the required design performance, lots of tests in laboratory for new materials will be needed. The performance-creative design concept helps and supports these situations. This is based on the Structural Concrete Concept of 1991 IABSE Colloquium in Stuttgart and unification of reinforced concrete and prestressed concrete design concepts under the overall structural concrete approach. In this context, created performance, for examples, reduction of environmental impact for sustainable development, long term serviceability, ultimate safety, maintainability, clear design philosophy, aesthetics etc. can easily be introduced when high performance structural concretes are utilized in the creative concept.

KEYWORDS: performance-creative design, structural concrete, infrastructure, wealth of nations

1. INTRODUCTION

The aim of social management is to create and to manage the wealth and the ability of nations.

The infrastructures that we build constitute the fundamental artificial environment for human society, and their construction must ensure that various performance attributes are appropriate, including functionality, serviceability, safety, aesthetics, durability, maintainability and economy. Such construction should be dealt with creativity, and we must have a clear recognition that the results will play a definite role in human society in the future. For this reason, there is a great need to create the logical framework of design concepts from the recognition that the design creates the performance of a structure.

In recent years, concrete with a compressive strength of 60 MPa or greater has come to be used. At the same time, the so-called ultra high strength fiber reinforced concrete (UFC) with a compressive strength of 160 MPa or greater has become viable. Accordingly, the varieties of concrete have been classified as follows: Concrete with a compressive strength of less than 60 MPa is classified as ordinary concrete. Concrete with a compressive strength of 60 MPa to less than 160 MPa is considered to be high strength concrete. Concrete with a compressive strength of 160 MPa or greater is referred to as ultra high strength concrete.

Of these three classes of concrete, no design approach has yet been proposed regarding the method of application for high strength concrete.

From this perspective, and with the use of high performance, high strength concrete in mind, this paper will present the approach of the authors to the concept of performance-creative design for construction of infrastructures which become the wealth of nations.

2. BASIS OF SOCIAL MANAGEMENT

Requirements for social management are enormous in the human society. Governmental activity is a comprehensive social management system of nations so far.

It is essential in the social management to create and to manage the wealth and the ability of nations. The activity of the human beings could be performed in the suitable artificial environment which consists of various kinds of infrastructure. The artificial environment should protect the society from natural and artificial hazards. Obviously, infrastructures produce not only wealth of the society but also are inherently the wealth of the society themselves. The performance-creative concept will become crucial for the infrastructure design to produce high quality social wealth and civilization of the future.

The high quality infrastructures can activate human society and the nations can enjoy the civilization by using the infrastructures. Infrastructures are built by investment and they can be the wealth or assets of the society. Adam Smith stated that consumption is the sole end and purpose of all production. However, investment for infrastructures should be added independently to the consumption for the purpose of production in present era although he clearly stated the importance of transportation infrastructures and their maintenance. On the other hand, the situation in which human ability or product is more than demand is thought to be an accomplishment of human efforts and should be applauded. Unfortunately, however, this situation invites economic depression. Then, increased human ability should be utilized to construct newly desired infrastructures for further development of the nations instead of suffering great depression.

The infrastructure should be productive and wealth –creative in nature and not costly for maintenance. In the case of poor cost performance the infrastructure will become bad assets. To construct wealth-creative infrastructures the performance-creative concept is inevitable for the design of high quality artificial environment.

This paper will introduce a new design method for concrete infrastructure with performance-creative design concept. In this context, created performance, for examples, reduction of environmental impact on sustainable development, long term serviceability, ultimate safety, maintainability, clear design philosophy, aesthetics etc. can easily be introduced when high performance structural concretes are utilized in the creative concept.

3. TRENDS IN DESIGN METHODS

Recently, limit state design has come to be adopted in place of the allowable stress design method that has been used for many years. The limit state design method makes it possible to reduce variations in the safety level of various states by incorporating the non-linearity of materials and structures and establishing safety factors for various limit states. To introduce the limit state design method, a calibration method, one involving the establishment of a safety index based on reliability theory, has been adopted in order to prevent structures from being radically different from those built up to now with the allowable stress design method. Currently, designers are in the process of shifting to performance based design, in which the performance requirements of the structure are defined before starting the design. With this method, the designer selects and verifies the performance of the completed structure in order to allow more rational structures to be achieved.

These changes in design method represent a shift from the allowable stress design method, an easy to understand method in which the strength of materials and structures and variations in load were summed up in a single safety factor, to a more advanced design method in which safety factors are finely subdivided into the load side and the resistance side and the designer is expected to have a thorough understanding of their significance. This "more rational design" is made possible by a more accurate determination of the limit states of structures.

With regard to the philosophy of theories in physics, Einstein wrote: "A theory should be as simple as possible, but not simpler." It is important to recognize that it is not enough for the limit state design method to be simple. At the 1999 fib Symposium, J. E. Breen sounded a warning about the approach to codes, saying "Small minds and small rules stifle creativity." Even when codes did not exist, designers were able to build many outstanding and durable structures, such as the Roman aqueducts. These structures were the result of the creativity of those designers, and modern designers must recognize that they will be unable to surpass the designers of old by simply following codes and relying on progress in materials and construction methods. The advancement of design methods is the current trend, but creativity represents the spirit that designers in any era must possess at their core.

The authors would like to propose a shift from a passive design system, one that consists of performance verification, to a performance-creative type design in which designs incorporate the designer's own creative approach. This design concept would be essential when conducting the design of structures with such performances, loads and limit states that cannot be included in codes. Moreover, under these circumstances it would truly be necessary to "create" performance. To put it another way, design would not be possible without creativity.

4. CONCEPT OF PERFORMANCE-CREATIVE DESIGN

Design is the act of subjectively determining the various conditions required for a defined subject and then providing rationality to the structure as an object and giving it form for realization.

Performance-creative design is a method of designing a structure in such a way that its performance is creative. As structures have various types of performance requirements, all types of performance must be developed from a creative perspective. Even if the result of study is exactly the same as that produced with conventional methods, this is all right if the result is judged to be the best possible one. Nevertheless, there is an infinite variety of conditions for the design of individual structures, so in many cases it is expected that new concepts will be produced. As the design and construction of a structure represents the creation of a artificial environment of the future, it is essential to design while envisioning the circumstances after that structure is constructed (for example, the situation in ten years).

What do we mean by the "performance" of structures? This refers to such qualities as durability, minimum environmental impact, sustainability, safety, economy, life cycle cost, lightweight structure and speed of construction. It is also likely that the question of how the structure will be able to survive will also be debated as a performance issue. In other words, performance is defined from many perspectives including material, structural, environmental and economic aspects.

Accordingly, the performance-creative design that we propose can be divided into the following three levels:

(1) Performance-creative level 1: Creation of performance within the scope of codes or only slightly beyond this scope.

(2) Performance-creative level 2: Creation of performance through the use of materials beyond the scope of codes or erection methods designed to reduce environmental burden and so on -- in other words, performance not clearly defined in codes, or the performance at the time of construction and so on.

(3) Performance-creative level 3: Establishment by the designer of limit states for new technologies that go beyond the code, through the application of extremely high-level creative technologies. Performance-creative approaches at this level take into account the life cycle of the structure as well as follow-up and maintenance after construction. The design goes far beyond the scope of existing codes in terms of materials and the anticipated limit states and so on. In such cases, verification through experimentation or the like is needed.

5. HIGH PERFORMANCE STRUCTURAL CONCRETE

Structural concrete was proposed at the International Association for Bridge and Structural Engineering (IABSE) Colloquium in Stuttgart in 1991 by Schlaich and Breen. The definition is as follows [1]:

- To unify reinforced concrete and prestressed concrete design under the overall “Structural concrete” approach
- To redirect the engineer’s focus to overall structural behavior and flow of forces
- To introduce rational, transparent models to improve detailing
- To encourage the unification of codes and standards for non-prestressed and prestressed concrete into single documents with a consistent approach

Structural concrete requires strict quality control and scrupulous construction technologies. The structures built with structural concrete have high durability. Moreover, while new concrete materials with various types of performance have been developed in recent years, there are differences in the design approach as compared to classical reinforced concrete theory and prestressed concrete theory, for example in terms of the manner in which creep is handled, allowable stress of concrete and so on. Designing with a unified approach to reinforced concrete and prestressed concrete within the concept of structural concrete is an extremely important fundamental concept for the performance-creative design method.

One new material that has been used increasingly in recent years is ultra high strength concrete. This material has greatly altered the concept of concrete which heretofore has been cement + sand + gravel. But can this high performance material really be used in design simply by extending the code that has been in place up to now? When a material is employed up to the limit, this means that non-linearity is employed in the design. Even in such cases, however, thorough care must be taken with regard to the reliability and versatility of the data. Moreover, it is not appropriate to treat with only performance-based approach for high strength materials. For example, as high strength materials are more brittle than conventional materials, the extent to which the limit state can be tolerated for structures made of these materials, for which prestressing has been introduced without ordinary reinforcement, is an open question. The emergence of ultra high strength concrete makes the concept of performance-creative design all the more necessary.

In recent years, there has been a great deal of study regarding constitutive modeling of high strength /

high performance concrete [2]. These types of new materials require not cookie-cutter type standards such as the existing codes but codes that establish only the bare minimum, such as the definition of limit states and test methods and so on, with the rest left up to the creativity of the designer.

Fig. 1 shows the P-δ curve for structural concrete. As the figure shows, there are three major events in the life of concrete. The first is the linear behavior up to the point when cracking occurs. The second is the yield point of the reinforcements. The third is up to the compression failure of the concrete.

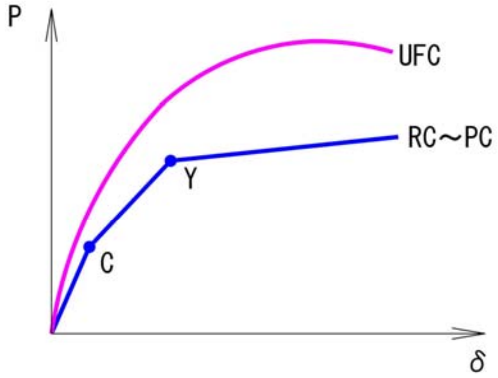

Fig. 1 Ordinary Concrete and UFC

The serviceability limit state is at a point between C and Y. Beyond the point Y, the ultimate state is reached. The final state is the ultimate limit state. Ultra high strength concrete is a new material that is sometimes prestressed with external tendons, but it is not the reinforcements but the steel fibers that resist tension. Accordingly, after cracking occurs, the concrete reaches failure with no clear yield point, and for this reason no unambiguous definition of the various limit states is possible as in the case of conventional concrete. This is the reason that creation of an integrated design system for structural concrete is needed.

In the case of a large structure, the weight of the structure itself has a proportionately large impact on design external forces. Let us consider, in the simplest example, the effect on the economic viability of the members of the strength and specific gravity of the material.

The equation below shows the height h at the center of the span of a simple beam with a rectangular solid section whose width is constant.

$$h = \frac{3}{4}\,\frac{w}{f}\,\ell^{2} \qquad \cdots\cdots\cdots \quad (1)$$

where

w : weight per unit volume
f : edge stress intensity of section
l : span of simple beam

As this equation shows, the greater the strength of the material is and the lower the specific gravity of the material is, the lower the height of the beam will be. There is a direct correlation between the height of the bridge and the material costs and construction costs. Accordingly, if for example the material strength doubles and the specific gravity remains the same, the bridge height will be reduced by one half. If the price of the material is twice as high, the material cost will be the same in both cases. Furthermore, reducing the quantity of the material will also reduce the construction costs. Taking these factors into consideration, the following equation can be used to study cost performance [3].

$$i = \left(\frac{f_N}{f_H}\right)\left(\frac{g_H}{g_N}\right)\left(\frac{(M_H + C_H)}{(M_N + C_N)}\right) \qquad \cdots\cdots \quad (2)$$

where

i : cost performance index
f : compression strength
g : specific gravity
M : price of concrete as material
C : cost of concrete for construction
N : normal concrete as subscript
H : high strength concrete as subscript

In recent years, the strength not only of concrete but of prestressing steel as well has been increased. High performance prestressing steel that is approximately 30% stronger than conventional materials has been introduced. [4] This kind of trend will become more and more prominent in the future. From now on, performance will not be determined by the material as it is at present. Instead, the desirable state for materials and members will be proposed as requirements, and designers will seek materials that satisfy these requirements in order to build structures. Moreover, the boundary between steel and concrete will become even less prominent than it is now, and the concept of "hybrid" structures will become commonplace. It would be difficult to say that high performance materials have achieved their true value at the level at which they are being used simply to make conventional structural members thinner or used in place of steel. They will only show their true worth with creativity that causes a complete shift in existing concepts.

6. CREATIVITY FOR THE CONSTRUCTION PROCESS

Let us examine the approach to design when a bridge is constructed. Even now, when technology is said to have made great strides, erection related accidents still occur during construction. In conventional design, the safety factor was set to a low value because the interval during erection was short. As high performance materials come to be used more and more from now on, however, this approach must be reconsidered. The erection load and so on must be accurately determined and an appropriate degree of safety established. The higher the performance of the materials is, the more sensitive the mechanics will become with respect to non-ideal conditions. Accordingly, although lessons will need to be learned to some degree with regard to this last factor, it will become essential to conduct accurate simulations of the load side and set an appropriate level of robustness and safety factor with respect to boundary conditions (such as whether ends are fixed or held in place with pins) and changes in load conditions (uniform distribution or non-uniformity, etc.). As a result, the approach up to now, of setting a low value for all safety factors during erection, should be changed completely. As shown in Fig. 2, reducing costs to the absolute minimum is a dangerous proposition.

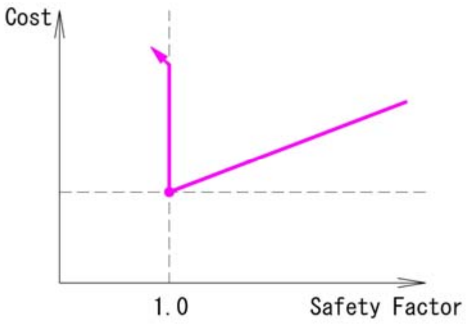

Fig. 2 Safety Factor of Construction VS Cost

7. EXAMPLES OF PERFORMANCE-CREATIVE DESIGN

Fig. 2 Safety Factor of Construction VS Cost

The preceding sections have dealt with the concept of performance-creative design and the need for high performance structural concrete. In this section, actual examples of performance-creative design will be presented.

(1) Ibi and Kiso River Bridge

These bridges have spans of more than 270 m and are constructed over the Ibi River (Fig. 3) [5] and Kiso River estuaries. As the pile length extends to 40 m, there was a need to reduce the superstructure weight. Therefore, an extradosed bridge design was adopted in which steel girders were employed for the 100 m center section of the span, and stay cables were used to suspend the concrete section. 60 MPa concrete was used for the main girders, and the precast segment method with a maximum weight of 400tf was employed. This enabled the construction to be competed in the shortest possible time while remaining unaffected by river conditions. In addition, prefabricated stays utilizing wires were used, and as a result of conducting fatigue design, serviceable stress was set to 0.6 fpu. Due to the lightweight design, shortened construction period, fatigue design for the stays and so on, the resulting bridges are an example of the creation of performance that is outside the scope of the code.

Fig. 3 Ibi River Bridge

(2) Corrugated steel web bridge

It was the research of Shimada into the "ripple web" that represented the first use of corrugated steel in a main girder web [6]. Subsequently, the corrugated web bridge was developed in France as a hybrid bridge. (Fig. 4) However, the former design was developed in order to omit stiffeners, while the latter was developed to prevent the prestressing force from being transferred to the steel plates in order to reduce the weight of the main girders. Corrugated steel had been used for various applications up to that point, and although the progress of development was different in these cases, the idea of using corrugated steel in bridge webs greatly expanded the possibilities of bridges. In this sense, this is a classic example of performance-creative design.

Fig. 4 Dole Bridge

(3) Katsurajima Viaduct [7]

The Katsurajima Viaduct (Fig. 5) was changed from a concrete bridge to a corrugated steel web bridge in order to reduce the reaction force during incremental launching. To reduce the weight even further, only the core section was incrementally launched. The cantilevered deck was constructed afterwards. This reduced the weight by 50% during incremental launching and by 75% at the time of completion as compared to a concrete bridge. The cantilevered deck is supported by struts, and precast panels were used for deck construction to reduce labor requirements. Moreover, as the shear deformation of the corrugated steel panels produced by the reaction force during incremental launching produces great stress in the concrete of the lower deck, precise reaction control technologies were employed to ensure quality during construction. And also, reuse of prestressing cables during launching as completed cables was new application. This solution satisfied both design and construction requirements and is an excellent example of creativity.

Fig. 5 Katsurajima Viaduct

(4) Furukawa Viaduct [8]

The U-shaped segments of the Furukawa Viaduct (Fig. 6) represent a solution to the construction requirements for this project, which involved reducing to the greatest extent possible the number of bridge segments. This was done under the conditions for transportation on public roads in Japan, in which regulations set the maximum weight limit at 30 tons. The unique segments have ribs for deck reinforcement. The U-shaped sections were used to make the bridge girders temporarily independent, with precast panels then being used to construct the deck. During placement of the deck concrete, however, the U-shaped segments that are low in torsional stiffness were subjected to torsional moment. FEM analysis was employed in the design, but in order to verify the design an actual scale single-span model was used to confirm safety. Detailed study and experimentation were conducted to confirm the aspects of the design that had no precedent. This embodies the fundamentals of performance-creative design.

Fig. 6 Furukawa Viaduct

(5) Seiun Bridge [9]

The Seiun Bridge (Fig. 7) has a span of approximately 100 m and extends across a deep valley. As this bridge was constructed inside a national park, it was not possible to put in place bridge piers and supports, even during the construction process. Moreover, there was very little work space for erecting a conventional arch bridge. The solution for these requirements was to conduct the erection using a suspension structure. By conversion from a ground anchored structure to a self-anchored structure after completion, the environmental impact was kept to a minimum. This is yet another example of performance-creative design and was awarded fib outstanding structures in 2006.

Fig. 7 Seiun Bridge

(6) Bridges using ultra high strength fiber reinforced concrete

Ultra high strength fiber reinforced concrete is a new material with a compressive strength of 200 MPa. The tensile strength of this unreinforced concrete is also 8 MPa. The material can be used in truss bridges, arch bridges and girder bridges (Fig. 8), and major use of this new concrete was made in the Haneda Airport runway expansion project. Similar to the case of steel construction, this type of concrete enables the weight of the bridge to be reduced, and its fine material structure provides it with high durability. This new material possesses great potential for performance-creative design.

Fig. 8 Sakata Mirai Bridge [10]

(7) Confederation Bridge

This bridge, which extends for a total length of 13 km, was constructed under unique environmental conditions: namely, the fact that in the wintertime it is subject to drift ice. Together with more than the construction method of single lift erection of girders weighing 7,000 tons, the design conditions in which the bridge piers are subjected to the pressure of the drift ice were unique. Although measures were taken in the shape of the bridge piers to enable the bridge to escape the pressure of the drift ice, measures also had to be taken for the structure to ensure that the collapse of a single span would not lead to progressive collapse of the entire bridge. In addition, careful maintenance was conducted following the completion of construction, and this included ongoing confirmation of the conditions for the design [11]. The result was the achievement of an extremely high level of design, construction and maintenance, and a classic example of performance-creative design.

8. CONCLUDING REMARKS

Performance-creative design is based on the idea of actively incorporating the creativity that is an inherent part of the design. This type of design will become more and more important as a result of the high performance materials that have begun to appear in recent years. Moreover, by incorporating the structural concrete approach, it will become possible to establish an integrated concept. We are now in an era of requiring materials, structures and construction methods that are used to create desired performances through the entire life of structures. The elegance of a structure will totally represents the creation of performance when its structural elegance, functional elegance and high durability come together.

Japan's bullet train system, although suffered some damage in the Great Hanshin-Awaji Earthquake of 1995, it has not had a single accident in the 40-odd years since the system first went into operation. At present, trains traveling at nearly 300 km per hour go back and forth once in every five minutes. The conditions to which bullet train structures have been exposed are extremely harsh, more so than anywhere else in the world. Tremendous effort has been poured into its maintenance that has preserved the safety of this system. And yet its operations have been profitable to a sufficient degree. The same can be said to the Tomei and Meishin Expressway systems. These projects represent the achievement of grand performance-creative design and eventually these infrastructures are the wealth of nations.

The performance-creative design discussed in this paper is now being stipulated by the code writing committee (chaired by the first author) in the Japan Prestressed Concrete Engineering Association

In the social management system, increased human ability which has been accelerated by computer and information technologies should be utilized to construct newly desired infrastructures for further development of nations instead of suffering great depression. The infrastructure should be productive and wealth-creative in nature and obviously not costly for operation and maintenance. To construct wealth-creative infrastructures in high quality artificial environment, the performance-creative design concept is definitely crucial.

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