More recently, around 1930, the application of prestressing in concrete design opened new horizons in the use of concrete. Some considered its value more theoretical than practical. One recalls with a smile the skepticism with which prestressed concrete was viewed at that time by many engineers, especially in this country. In 1949, the first prestressed concrete bridge was built in the United States; it was a girder type bridge in Philadelphia with a span of 160 ft.

## PRESENT STATUS OF CONCRETE BRIDGE CONSTRUCTION

A recent Engineering News-Record survey on all the bridges constructed in 1965 shows that most states use concrete as their prime material for bridge construction. Steel is the prime bridge material in the Midwest, New England and the Middle Atlantic states.

Concrete bridges, both reinforced and prestressed, can be divided into the following main types:

(a) The longitudinal slab bridge, which represents the simplest form of a concrete bridge, can be hollow or solid, and is used for spans from 20 to 40 ft. It can be simply supported or continuous and its economical span does not exceed 35 ft. It can be supported on a separate bent or on a beam integral with and deeper than the slab, or a certain width of the slab can be additionally reinforced to act as a beam.

(b) A second type is the concrete girder bridge. The concrete girder can be cast integrally with the slab as in a T-beam bridge, or separately to form in this case a beam-and-slab type of bridge. The longest bridge in the world, the 24-mile-long bridge that crosses Lake Pontchartrain, uses a precast prestressed concrete girder and slab, 56 ft long, cast monolithically. A new parallel bridge is now in the design stage in order to accommodate the increased rate of traffic.

An interesting example of this type of construction along with a combination of prestressing and the cantilever principle is the Oneida Lake bridge in the State of New York, in which 147-ft-long cantilever girders support the 231-ft T-beams, thus making the span center-to-center of piers a record 320 ft.

(c) A third type of construction is the box-girder bridge. This type of bridge is mostly used in the United States with the standard AASHO-PCI prestressed boxes for spans up to 100 ft. Box girders are widely used in other parts of the world, especially in Europe. A three-span continuous prestressed concrete bridge built recently over the river Seine in Paris, France, consists of four box girders with a cantilever slab on each side of the box; the center span is 180 ft. Another example of the box type of construction is a 1574-ft-long reinforced concrete bridge over Venezuela's Caroni River. It consists of fifty 30-ft-long hollow prefabricated sections joined together and then post-tensioned as a whole along the neutral axis.

(d) The rigid frame bridge with its deck slab cast as a unit with the abutments is a fourth type of concrete bridge. It is usually economical for spans up to 70 ft and, because of its shallow depth at the middle of the span, which can be as little as 1/40 of the span length, it has a great advantage where the vertical clearance is limited.

(e) A fifth type of concrete bridge is the arch, used extensively in Europe and many other parts of the world. In 1964 the world's longest concrete arch was opened to traffic; it is a 1000-ft arch over the Parramata River at Sydney, Australia, and consists of four vouissoir ribs.

(f) An unusual type of concrete bridge is the floating reinforced concrete pontoon bridge. A bridge of this type was constructed across the Hood Canal in the State of Washington and consists of 23 pontoons which form a 6470-ft-long floating structure.

(g) Another unusual type of concrete bridge is represented by the concrete deck and truss of a suspension bridge. A typical bridge of this type was built in Canada; it is the Hudson Hope bridge, which features cellular prestressed box girders hung from suspension cables in the 680-ft main span. This bridge received the top bridge award in the 1965 design competition of the Prestressed Concrete Institute.

## PRESENT STATUS OF CONCRETE BRIDGE DESIGN

At the present time the design of all highway bridges in the United States, with the exception of unusual types of bridges and those with spans longer than 300 or 400 ft, is normally based on the Standard AASHO Specifications for Highway Bridges. The first edition of these specifications was published in 1931. The present ninth edition has been used since 1965. Up to the present time the design of all concrete bridges has been based on the classical working stress method, in which a factor of safety is provided by using stresses below the stress that will cause failure. This factor of safety is the ratio of the load that will cause failure to the working load. But reinforced concrete is not an elastic material; it is subject under normal conditions to fine cracks. The present straight-line stress distribution assumes that both steel and concrete are elastic and their unit stresses are directly proportional to the unit strains.

The publication some time ago by the Bureau of Public Roads of the "Strength and Serviceability Criteria, Reinforced Concrete Bridge Members, Ultimate Design," introduces the ultimate strength design method in the design of concrete bridges. This publication constitutes a step of great importance in the right direction. Many countries have been using the ultimate strength method for the design of their concrete bridges for a number of years. In the United States the ultimate strength method has been used for building designs since 1963 with the publication in the same year of the new ACI Building Code.

A concrete bridge structure, subjected to the dynamic effects of moving loads differs materially from the statically loaded building structure. Fatigue, cracks and deflections are of great importance in a concrete bridge. For these reasons the new criteria of the Bureau of Public Roads are more restrictive than those of the ACI Building Code. In order to control fatigue, they limit the range of the live load tensile stress in the reinforcement and the compressive stress in the concrete. Cracking is also controlled by a maximum permissible crack width according to exposure conditions. Instantaneous, short-time and long-time deflections are also controlled.

The BPR criteria permits the use of high-strength steel with a 60,000-psi minimum yield strength for reinforcement where the strength of the section is controlled by tension and a 75,000-psi minimum yield strength for compression reinforcement in columns and piers. The result will be greater economy and more efficient use of reinforcement.

The AASHO specifications allow a maximum bond stress in the reinforcement of $0.06\,f'_c$ with a maximum of 210 psi for top bars, and $0.10\,f'_c$ with a maximum of 350 psi for all other bars regardless of size. The new BPR criteria are more restrictive because they take into consideration the diameter of the bar. According to AASHO, for a 3000-psi concrete, a No. 11 top bar in tension has an allowable bond stress of 180 psi, while the BPR criteria limits this stress to 132 psi.

## PHILOSOPHY OF A CONCRETE BRIDGE CODE

A specification for the design of reinforced concrete bridges may be in the form of a recommended practice or in the form of a code. A recommended practice serves as a guide for the best design practice, while a code is in the form of a law. The most well known and widely used code in the United States is the ACI "Building Code Requirements for Reinforced Concrete," while the form of a recommended practice is presented in the "Recommendations for an International Code of Practice for Reinforced Concrete" of the Comite Europeen du Beton.

Because the main purpose of a bridge code is the design of a safe bridge, it is natural that it has to be restrictive and conservative. At the same time, a bridge code has to produce an economical design. Economy and safety can be accomplished only when committees in charge of a code include, among their members, representatives of both the engineering research and the engineering practice fields, because the knowledge gained from research has to be supplemented with that gained from experience.

A bridge code should be precise, clear, and free of ambiguous interpretations, and should use a uniform system of notation. It should also be dynamic rather than static in order to incorporate any future revisions in an easy and continuous form.

## AESTHETICS OF CONCRETE BRIDGES

During recent years the aesthetic aspects of bridges have been the subject of much discussion. A concrete bridge is predominantly an engineering structure and, while the services of an architect might be occasionally required, it remains the responsibility of the bridge engineer to produce an economical and graceful form of bridge.

The late Dr. Steinman said "The bridge designer of this era has to be an engineer and an artist combined. To a thorough understanding of structural design and function he must add a strong feeling, both innate and trained, for beauty of form, line and proportion."

Last year Congress passed the Highway Beautification Act and thus made aesthetics the law of the land. Bridges are one of the most distinctive features of our highways and cities; they are a measure of civilization. In some countries and in many of our cities, supervision of aesthetics is vested in different citizens committees, and structures have to comply with an aesthetic code as well as the construction one. There is a strong demand from our art-conscious society for more beautiful concrete bridges. Who can remain unmoved at the sight of a beautiful concrete bridge?

Because concrete can be shaped in practically any form, beauty in concrete bridges can be accomplished with very little sacrifice of economy. The modern trend is toward simplicity and more beautiful designs by developing forms that express better the qualities of concrete, especially in long-span bridges.

## WHAT OF THE FUTURE?

The introduction of the Bureau of Public Roads criteria will require additional research in order to obtain an answer to the many questions which will arise from its application. One of the big questions will be, "How will concrete bridges designed by the ultimate strength method compare with the ones designed on the basis of the working stress method?"

Despite the fact that it is easier for one to be a historian than a prophet, I would like to predict that in the not-too-distant future the ultimate strength method will find such acceptance among bridge engineers that it will become the only means for the design of all reinforced and prestressed concrete bridges.

One of the missions of ACI Committee 443 on Concrete Bridge Design is to develop a recommended practice for the design of concrete bridges based on both the working stress and the ultimate strength methods. The international acceptance of the ACI Building Code, which is used as a reference by all of the design codes in the United States, can serve as a goal for the efforts of the ACI Committee on Concrete Bridge Design. It is the desire of the members of this committee to accomplish this tedious task and to offer to the engineering profession the best possible recommendations based on all existing knowledge and experience.

# PAST AND FUTURE IN THE DESIGN AND CONSTRUCTION OF CONCRETE BRIDGES

By LEONIDAS T. DELYANNIS

The use of bridges dates from antiquity when man built rude bridges in imitation of nature, but bridge design as a science did not begin to emerge until the 17th Century. Bridge design has progressed with the development of materials, and today reinforced concrete and steel are the prime materials in bridge construction. The structural design of bridges has mainly been based on the working stress method, but there is now a trend to the ultimate strength method. One of the missions of ACI is to develop recommendations based on both methods and utilizing all existing knowledge. Codes for bridges should be precise, clear and dynamic (easy to revise as knowledge progresses). Since a bridge is a dominant part of a landscape, its appearance is important, and thus the aesthetics of bridge design must be considered along with structure and function. This requirement emphasizes one of the benefits of concrete, which is easy to shape and lends itself to beauty of design. This paper presents an historical account of the evolution in the design and construction of concrete bridges. The general philosophy of a concrete bridge code is discussed, and different standard specifications are reviewed and compared, with particular emphasis on their limitations and on what can be done in the future.

Keywords: Architecture; bridges (structures); building codes; history; precast concrete; prestressed concrete; reinforced concrete; standards; structural design; ultimate strength method (structural); working stress method (structural).

☐ Bridge building might be as old as man himself. The need of early man to cross a stream, a river or any other obstacle was second to his need for shelter. The first bridges he built were probably similar to the ones he observed in nature and his first construction materials were trees and natural stones. These bridges crossed obstacles at right angles and were used by pedestrians or horse traffic.

They had nothing in common with the modern multi-traffic-lane bridges one sees on our highways. Their designers and builders were unfamiliar with engineering knowhow and their work was not guided by something that might be called "science".

## HISTORICAL BACKGROUND

A pedestrian stone-slab bridge over the River Meles in Smyrna, Asia Minor, which according to legend was used by the ancient Greek epic poet Homer, is probably the oldest bridge in existence. In later years bridges played a great part in human life. Greeks and Romans used bridges extensively for their military conquests. Many masonry bridges of that period still stand after 2000 years. Just recently workmen repairing a street in Parma, Italy, discovered an ancient Roman bridge built under an existing street around the first century A.D. Bridge building in ancient Rome was considered so important that the head of State had adopted the title "Pontifex Maximus" (Chief Bridge Builder).

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The Middle Ages produced a number of stone and masonry arch bridges, among them the famous London Bridge. The revival of arts, letters and learning in Europe during the Renaissance period marked the transition to a more scientific approach on bridge design and construction. Galileo Galilei, the Italian physicist and astronomer, published in 1638 his "Dialoghi della Nuove Scienze," the first book on structural analysis. In 1678 Robert Hook devised the law of proportionality of stress and strain, only to be followed by Edme Mariotte and then Bernouilli, who in 1694 calculated beam deflections. A number of bridges from that period still exist in Europe. They are mostly arch type with rather heavy piers because they were constructed to support the horizontal thrust of each individual arch.

The 18th Century marked the beginning of a new era in bridge construction with the founding in 1716 of the Corps des Ponts et Chaussees under Jacques Gabriel III, and about 30 years later of the Ecole des Ponts et Chaussees in Paris, which is the first engineering school in the world.

The use of iron in the 19th Century, combined with the development of the railroad as the principal means of long-distance inland transport, stimulated a new interest in bridge design and produced the truss, the cantilever and the suspension type of bridge.

In the beginning of this century the great era of railroad building was succeeded by the highway era. The extensive use of the automobile in everyday life and the development of the modern highway networks resulted in an increased rate of construction of all types of bridges. The old construction materials, wood, stone and iron, slowly yielded to the newcomers of modern bridge construction, steel and concrete.

Three-quarters of a century ago the first two reinforced concrete bridges were built in the United States. One was a 20-ft arch at Golden Gate Park in San Francisco, built in 1889, and the other also was an arch with a span of 125 ft built in 1897 in Kansas.

The emergence of reinforced concrete as a prime bridge material marked the beginning of another era in bridge construction. Its adaptability to any architectural form and the increased efficiency in concrete construction resulted in the widespread use of reinforced concrete in bridge building.

The advantages of continuous bridges were fully materialized with the development of reinforced concrete. Built-in-place continuity was not only an inherent expression for concrete but also a basic requirement for economy.

# AESTHETIC PROBLEMS IN CONTEMPORARY CONCRETE BRIDGE DESIGN

By JULIUS G. POTYONDY

A bridge has not only a physical function but a moral, cultural, and architectural effect. It has its own style and character that contrasts or harmonizes with its surroundings. In the new era of highway complexes, the bridge is an integral part of the whole. It should be attractive when seen from any distance and also should afford an uncluttered view of the surrounding landscape to a viewer on the bridge. There are no fixed rules to guarantee a pleasing architectural appearance, but certain principles should guide every design. Members should be proportioned to suit their function and not in a manner that is structurally absurd. Simplicity of design is desirable since modern high-speed traffic does not afford opportunities to appreciate detailed ornamentation. Careful detail design will avoid discoloration of concrete surfaces by rusty drain water. To create bridges that will add beauty to the landscape, engineers should supplement structural and materials knowledge with study of architectural form and aesthetics.

Keywords: abutments; architectural concrete; architecture; bridges (structures); education; prestressed concrete; reinforced concrete; structural design.

After the introduction of reinforced and prestressed concrete in bridge construction, our technology and bridge aesthetics entered into a new period. The great advantage of concrete is that it can be cast into almost any shape by a "cold" process.

Concrete as structural and architectural material can be used most efficiently if the designer understands and can express the flow of stresses and the behavior of the structure. In modern highway and bridge design we have moved from the design of one bridge, from the design of a short highway, into the design of large complexes including a series of bridges. In this new era the bridge is an integral part of the whole project including the surroundings and landscape. Unfortunately, there are no general rules in aesthetical design of bridges, only general principles which we have to follow. Briefly, these principles are that the design should represent a clear demonstration of necessity and function, should be a truthful expression of material and structure, and should display consistency between details and harmony in the whole project. In recent years many good examples of these principles were produced where the swinging line of highways and bridges gave movement and rhythm to our construction materials. This rhythm is what we call modern engineering style.

## THE CHARACTER OF BRIDGES

In the past sixty years bridge engineering has progressed exceptionally by using new materials and new constructional procedures and by introducing new design methods. The gigantic spans of recently built bridges and the resulting public responsibility required great courage from bridge designers. Bridges are built for long time;

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they represent one of the most important engineering creations and they are the index of progress and civilization.

In our modern life we rarely appreciate the individual value of a product created by man, such as bridges, which stand so open and are used so much by everybody in daily life. Nobody can imagine a full impression of Paris, London, Rome, New York, or Montreal without bridges.

The bridge is not only a physical connection between two separated areas but also has beyond its physical function a moral, a cultural and an architectural effect. A bridge, like a composition, has its own style, its character, rhythm, contrast, and harmony. The composers who should exploit these values of attractiveness are the bridge designers, the engineers, and the architects.

## THE ENGINEER-ARCHITECT-CONTRACTOR RELATION

Until the 19th century the function of the engineer, the architect and the contractor were combined in one person. When steel and concrete were introduced, the design work required more and more basic study of the behavior of materials, and a science of engineering was created. This led to the division between the architect and the engineer. At the beginning of this century the separation of the designer and the contractor took place. Obviously, further disintegration developed between these three parties in the practical field as well as in the educational level. This necessary disintegration had, however, a certain disadvantage, mainly on the higher level of engineering design.

In our civil engineering curriculum, art and aesthetics are replaced increasingly by scientific subjects. This might be the only right answer to the tremendous demand from the industry, and so probably affords the right education for the average designer and engineer. We need high-level creative and imaginative civil engineer leaders with this intense technical background but at the same time they should be capable of creating not only with the slide rule but with their individual taste for beauty, aesthetics and imagination. A bridge designer with these combined qualities will dissolve the argument about the individual importance of the architect, the artist or the engineer in many civil engineering projects. Great bridge designers such as Robert Maillart, Luigi Nervi and Riccardo Morandi are well known internationally. They created a new art by using new structural methods in bridges and buildings because they are not only engineers but also excellent creating architects and in certain cases they even represent the contractor.

I believe that the structural engineer who is taking further studies in the field of architecture, or an architect who is spending his late hours by taking extra structural engineering studies, are broadening their knowledge, not to compete with the "opposite side," but to fulfill their own professional requirements. Le Corbusier explains this:

"The engineer, inspired by the law of economy and governed by mathematical calculations, puts us in accord with universal law," and, "Our engineers produce architecture, for they employ a mathematical calculation which derives from natural law and their works give us the feeling of harmony. The engineer, therefore, has his own aesthetics, for he must, in making his calculations, qualify some of the terms of his equations and it is here that taste intervenes."

Along the same line, Professor Nervi concludes in the following form: "The true essence of the good design consists in the full satisfaction of functional, statical, constructional and economic means, and the creation of a well balanced arrangement; a project which satisfies these conditions may be aesthetically significant or expressively beautiful but will never be aggressively annoying. Otherwise, the engineering design can represent an architecturally pleasing work if the engineer has sufficient creative qualities" (Fig. 2-1).

## PRINCIPLES OF AESTHETICAL DESIGN OF BRIDGES

Recently, in many countries the appearance of bridges has been given much more attention and in some cases all important works are submitted to a special Commission for approval or criticism. This results in a great improvement in design, selection of type, in new arrangements and appearance.

Unfortunately, it is not possible to suggest a formula which will ensure that all designs are beautiful, but there are certain basic principles which must be followed for any structure if it is to be aesthetically satisfying. To design an aesthetically satisfying structure involves a great deal more than rigidly following a set of rules. The rules are a minimum requirement, but they do not alone guarantee success. Artistic appreciation is involved and, like all things pertaining to art, there is a wide range of opinion and taste.

To satisfy the aesthetic principle, the design should not conceal the type of structure being employed; joints and hinges, whether in arches or beams, should not be hidden; a hinged arch should not be designed to look like a fixed arch. A good example of correct expression of structural behavior is the bowstring bridge (Fig. 2-2). The arch and floor system of this bridge are the integral parts of the structure. The vertical members are designed simply to resist tension. In other bridges these members are dimensioned like compression members supporting the arch above the roadway, which is structurally absurd; they should have been designed to look like what they are; that is, tension members transferring the load from the deck to the arch. In Fig. 2-3 the arrangement is opposite, the vertical members are in compression.

We have recently available excellent materials and construction techniques, such as prestressed concrete, where the designer should emphasize the great advantages of the material in his structural concept. Many designers look on concrete as a substitute for stone or brick and in style and dimensions adhere to the past experience with these materials. Reinforced concrete, compared with brick or stone, is light and strong, and should be designed to look slender, not heavy and massive, as would be necessary in a stone structure. Failure to observe this principle is a common fault in many modern reinforced concrete bridges. Many bridges built on this continent in the 50's from prestressed concrete are proportioned almost the same as if they were built from ordinary reinforced concrete.

In modern high-speed traffic the automobile driver or passenger has no time to observe small decorations, but he may expect to understand visually all of our engineering projects. To create something which a viewer can understand from the window of a moving car requires simplicity in design and appearance of our structures. This can be achieved by harmonizing all such bridge and highway elements as signs, fences, handrails and bridges to give a full impression of unity. The sil-

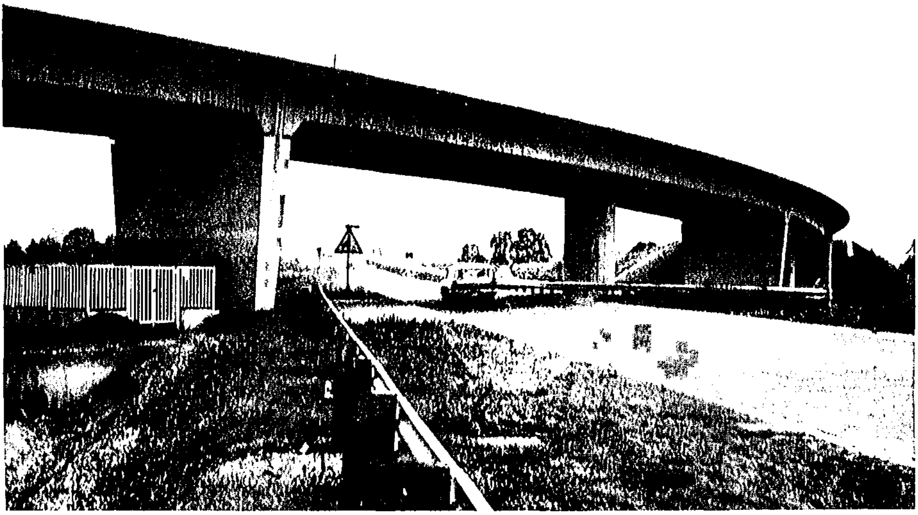

Fig. 2-1 - Examples of Functional Appearance Design

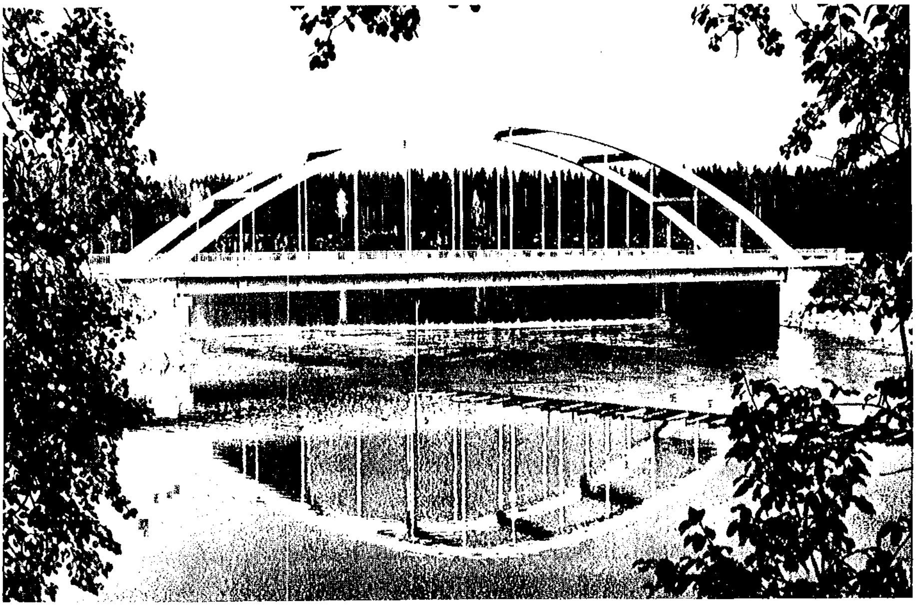

Fig. 2-2 - Bowstring Bridge with Slender Vertical Tension Members

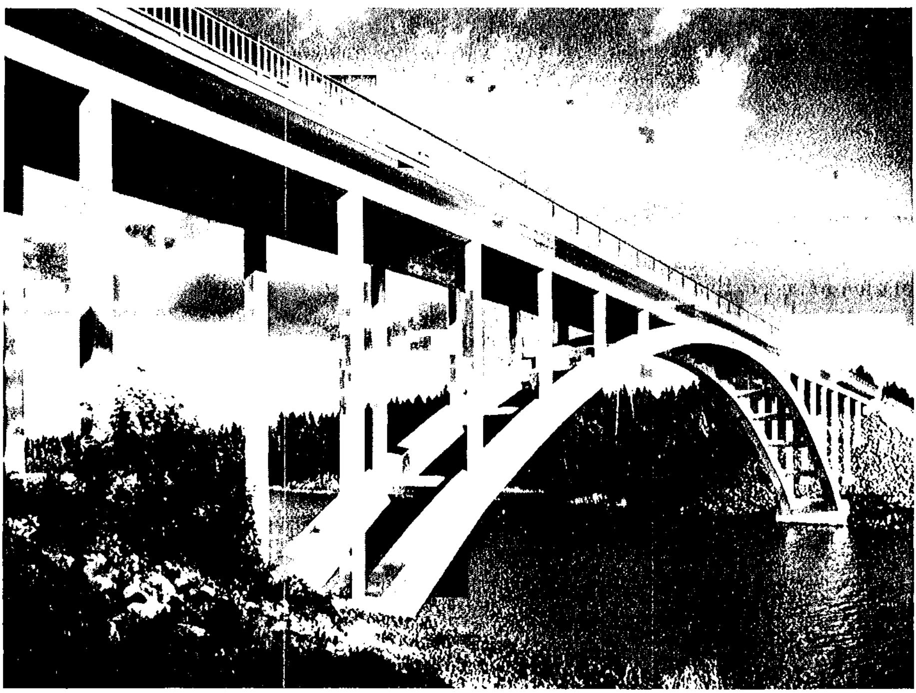

Fig. 2-3 - Arch Bridge with Vertical Compression Members