Hybrid design for the world's longest span cable-stayed bridge

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Hybrid Design for the World's Longest Span Cable-Stayed Bridge

Conception hybride du pont à haubans le plus long du monde

Gemischte Bauweise für die Schrägseilbrücke mit der grössten Spannweite der Welt

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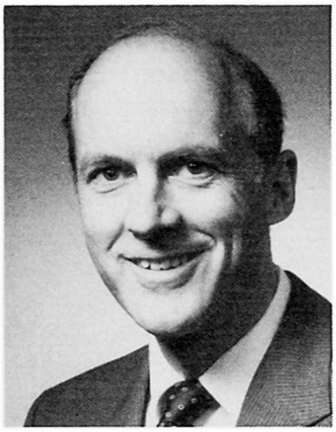

Peter Taylor received his PhD. from Bristol University in 1965. His career includes five years with Dominion Bridge Company in Montreal. He has been involved with five major cable-stayed bridges.

SUMMARY
At the design concept stage of Annacis Island Bridge, conventional structural arrangements for a steel cable-stayed bridge were disregarded and instead the simplest possible arrangement of elements capable of resisting gravity loads, fabricated from the most suitable material, were selected based on economy and simplicity of construction. Considerable analytical and testing effort was then devoted to justification of this simple conceptual design. This philosophy resulted in the original concept surviving essentially unscathed and produced a composite steel design which has no diaphragms, no bracing, no bearings, no box girders and no orthotropic deck.

RESUME
Lors de l'étude du pont Annacis Island, le projet conventionnel pour un pont haubanné en acier a été écarté. Pour des raisons d'économie et de simplicité de construction, un projet extrêmement simple a été retenu, avec des éléments capables de résister aux charges de gravité, et fabriqués avec les matériaux les plus appropriés. De nombreux analyses et essais ont permis de justifier ce concept simple. Cette philosophie a eu pour résultat que le concept original a survécu, produisant un projet hybride en acier, qui est dépourvu de diaphragmes, de contreventements, d'appuis, de poutres caisson, et de tablier orthotropique.

ZUSAMMENFASSUNG
Während der konzeptuellen Konstruktionsphase der Annacis Island Brücke wurden zunächst alle konventionellen Bauweisen für Stahlschrägseilbrücken unbeachtet gelassen und anstatt dessen elementär nach der einfachsten Anordnung von Elementen und Materialen gesucht, die Schwerkräfte aufnehmen. Als Auswahlkriterien dienten die Wirtschaftlichkeit und Einfachheit der Bauausführung. Beträchtlicher rechnerischer und experimenteller Aufwand wurde der Rechtfertigung dieses einfachen Konstruktionskonzeptes gewidmet. Dieses Vorgehen ergab, dass das ursprüngliche Konzept fast unverändert blieb und eine gemischte Stahl-Beton-Bauweise gewählt wurde, die keine Membranfelder, keine Verstrebungen, keine Kastenträger und keine orthotrope Fahrbahnplatte aufweist.

1. INTRODUCTION

1.1 Description of the Project

Annacis Bridge will span the South arm of the Fraser River at a point 19 km upstream from the mouth. The bridge, which is being constructed by the Ministry of Transportation and Highways of British Columbia, will provide a new direct highway route south from Vancouver towards the U.S. border and also a new river crossing for urban and commuter traffic between Surrey and Vancouver. It is designed to carry an initial configuration of four traffic lanes, with a later increase to six lanes when traffic volumes demand it. The bridge was also designed to carry two lanes of rail mounted Rapid Transit vehicles plus four lanes of automobiles, but installation of Rapid Transit on the bridge now appears unlikely.

Two alternative designs were commissioned for Annacis Bridge, this paper is concerned with the composite steel girder design which is now being constructed.

1.2 Features of the Site

The Fraser River at the bridge site is about 500 m wide and carries considerable marine traffic ranging up to 60,000 DWT in size. Current velocities can reach almost 2 m/s in flood. The geology of the site is highly non-uniform, see Figure 1. On the South side, dense pre-glacial gravels occur close to the surface and provide excellent bearing. On the North side, interbedded layers of alluvial deposits occur to considerable depth. The upper alluvial layers are quite loose. The site is located within 100 km of an active earthquake zone and earthquakes up to magnitude 7.1 have been experienced within the Region.

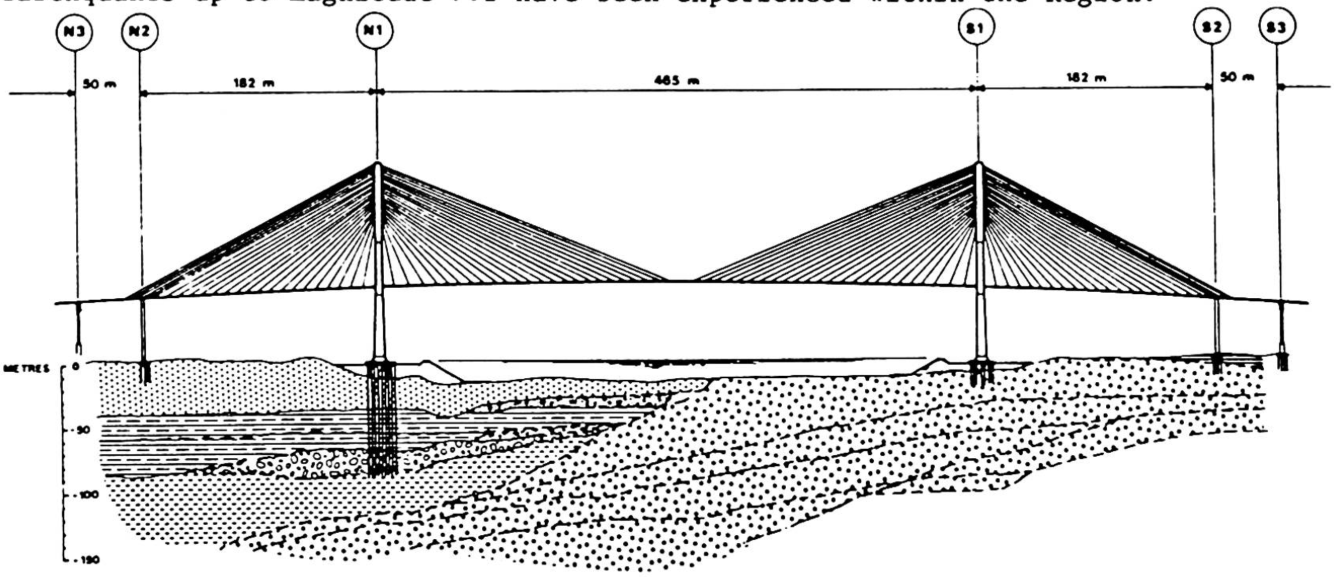

FIGURE 1 SITE GEOLOGY AND BRIDGE ELEVATION

2. DESIGN CRITERIA

2.1 Design Traffic Live Loads

At the moment, longspan bridge design traffic live loads in various countries are undergoing considerable scrutiny and revision [1]. For Annacis Bridge, the new A.S.C.E. Rules for Longspan Bridge Traffic Design Load [2] were used for loaded lengths in excess of 100 m. Locally derived truck loading data on longspan bridges was used to predict on ultimate heavy vehicle fraction of 7% and this was incorporated in the A.S.C.E. Loading. Canadian Highway Loading [3] was used for loaded lengths less than 100 m. Design loads for the six car

Advanced Light Rapid Transit trains were critical only in the design of the deck and floorbeams.

2.2 Environmental Design Loads

Static wind design forces were based on local data with a probability of occurrence of 0.01 in any year. The minimum critical wind velocity for smooth flow aerodynamic instability was also based on local data, with a probability of occurrence of 3x10-4 during the life of the bridge.
Limit state earthquake design accelerations and velocities were based on a probability of occurrence of 0.1 in 50 years with values reduced by allowance for attenuation with distance from the source.

2.3 Special Considerations

Ship Impact with bridge piers is a topic of increasing concern. The design philosophy used for Annacis Bridge [4] established the need to resist the impact of a 60,000 DWT vessel travelling at 5 m/s without damage to the piers. This requirement has been met by constructing large sand berms around the piers with rock protection on the face to prevent erosion by the river.

A further special consideration for a light flexible cable-stayed bridge is fatigue. The arrangement of cables and sidespan ratio were carefully selected to keep the live load stress range in the cables well below the cable material fatigue limit. The fatigue requirements of the British Code BS5400 were used to check the main girders and floorbeams.

3. PRELIMINARY REVIEW

3.1 Steel Cable Stayed Bridge Practice up to 1981

The bridge design was commenced in 1981 and conventional design practice then for steel cable-stayed bridges is summarized in Table 1 which shows 6 bridges designed immediately prior to that date. It can be seen that most of the bridges had large cable spacing, an orthotropic steel deck with asphalt paving, a stiff steel box girder with diaphragms, steel towers and vertical bearings at the tower portals.

Bridge	Cable Spacing	Deck	Girder Configuration	Tower Material	Bearings at Tower	Year
Kohlbrand	15 m	Orthotropic	Box	Steel	Yes	1975
St. Nazaire	15 m	"	"	Steel	Yes	1975
Luling	50 m	"	Boxes	Steel	"	1980
Duisburg-Neuenkamp	45 m	"	Box	Steel	"	1971
Kessock	8 m	"	Plate Girders	Steel	"	1977
Tjorn	40 m	"	Box	Concrete	"	1980

Table 1 Steel Cable Stayed Bridge Configurations prior to 1981

3.2 Considerations prior to start of Conceptual Design

Being in a competitive design situation, the above parameters were examined very carefully in the early conceptual design stages of Annacis Bridge. Each was evaluated in terms of the potential for design improvements, local material and labour costs, and local manufacturing and erection capabilities and preferences. This kind of site specific objective review is most important if an efficient and appropriate design is to be achieved. There is no universal optimum design solution for a particular span range, each location has its own particular set of circumstances which must be respected. All things being equal, a solution utilizing local materials is preferable to one using imported materials. While orthotropic steel decks with asphalt paving have been used successfully on a number of bridges in British Columbia, Port Mann Bridge has the first orthotropic steel deck built in North America, the cost of local skilled labour makes them expensive. Furthermore, in British Columbia, bridge deck paving using a dense concrete overlay is generally preferred to asphalt.

4. EVOLUTION OF DESIGN CONCEPT

4.1 Basic Philosophy

The basic philosophy adopted at the design concept stage was to derive a consistent arrangement of simple repetitive bridge components which together would create the most economical bridge. Obviously some engineering judgement was necessary to select appropriate member proportions, but the primary initial consideration was overall economy without bias to materials or form. Only after the most economical arrangement had been derived, by successive revisions to the conceptual design, were engineering efforts commenced to justify the concept. This approach led to some innovations and considerable cost savings.

4.2 Development of Design Concept

Design commenced at the roadway surface and worked back through the superstructure, cables, and towers to the foundations. The local preference for concrete bridge decks with dense concrete overlays was mentioned earlier. Cost comparisons showed that this system with a concrete slab about 200 mm thick spanning about 4.5 m was considerably more economical than an orthotropic steel deck with asphalt paving, even after the premium for the extra deadweight was taken into account. Precast concrete was specified for the deck to avoid expensive site formwork.

Steel plate girders provide the necessary bending stiffness at minimum initial cost and deadweight, and, when combined with a support system comprising closely spaced single cables, they can be made quite shallow. For a cable spacing of 9.0 m, consistent with floorbeams at 4.5 m, a girder depth of about 2 m is adequate. Field bolted splices provide for fast and simple connection. The splice spacing was set at 18.0 m and rigid adherence to this and other modules resulted in maximum repetition for fabricated components. One of the design conditions for Annacis Bridge required the cables to be located 600 mm outside of the 6 lane clearance at 28 m centre to centre. The most direct and preferred location for the girders was therefore on this cable alignment. This wide spacing of main girders required relatively deep (1600 mm) floorbeams which provided generous closely spaced lateral restraint to the main girders and eliminated the need for diaphragms and lateral bracing.

The superstructure cross section which emerged from the conceptual design is shown in Figure 2.

After the superstructure, the next consideration was the cable and tower configuration. A modified fan configuration of cables was used to permit space to anchor each cable separately at the tower and for ease of replacement. The A frame configuration was found to be excessively expensive for this scale of bridge and was rejected until proven necessary. The tower legs were cranked inwards slightly, see Figure 2, in order to bring all cables into a vertical plane. This avoids the necessity of dealing with compound cable angles and the associated eccentricities at each anchorage. Despite their considerably larger deadweight and associated foundation cost premium, concrete towers were estimated to be much cheaper than steel towers at this particular location. The transfer of each cable horizontal tension component through the tower, which is inconvenient in concrete, was achieved with twin structural steel channels, which also provided jacking seats for cable connection and adjustment.

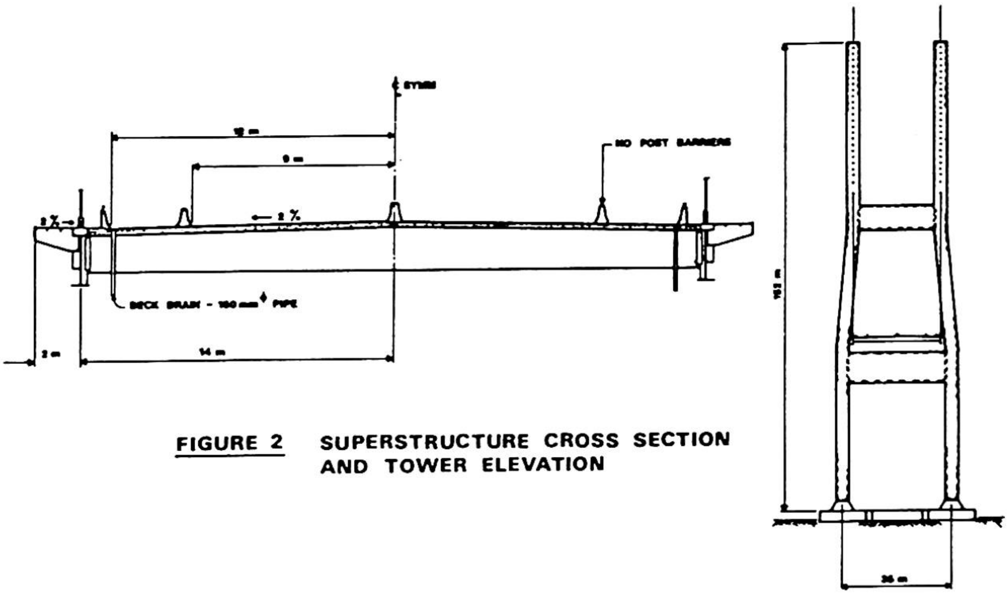

FIGURE 2 SUPERSTRUCTURE CROSS SECTION AND TOWER ELEVATION

Vertical bearings were eliminated at the towers in order to avoid the bending moment peak which they create and also to avoid the indeterminate reaction there after any time dependent strains occur in the tower or cables.

The towers were founded on steel piles, short steel H piles to bearings strata on the South side and 914 mm diameter pipe piles to dense bearing material at 90 m depth on the North side.

5. JUSTIFICATION OF THE DESIGN CONCEPT

5.1 Confirmation of the Overall Concept

The success of the overall concept hinged upon the flexural and aerodynamic behaviour of the main girders. It was essential to confirm at an early stage that the girder was deep enough to provide the necessary bending stiffness and strength, without too large an amplitude of stress reversal, while not being so deep as to create an aerodynamically unstable cross section.

Despite the generally poor aerodynamic behaviour of open plate girder sections, a careful examination of previous aerodynamic test data and prototype performance records showed that the width to depth ratio of plate girders was just as important as the torsional to vertical frequency ratio. The data indicated that there was a good chance that a bridge such as Annacis with a wide deck and shallow plate girders, could be aerodynamically stable with a torsionally flexible superstructure. Wind tunnel testing of aerodynamic sectional models was commenced early in the design process and was refined as details were developed [5].

Accurate knowledge of the torsional and vertical vibration frequencies of the bridge is critical to any aerodynamic stability assessment. The design team put a great deal of effort into creating and testing various independent analytical methods which were used to establish these variables with confidence. The principal analytical tool used was a three-dimensional computer analysis which modelled the complete superstructure including every cable, using catenary equations for initial static cable equilibrium and then cable tangent moduli at dead load tension for subsequent linear dynamic analysis.

The results of the wind tunnel testing showed that the section was indeed aerodynamically stable in smooth air flow up to a velocity of 50 m/s, provided the steel sidewalks cantilevering 1600 mm out from the main girders were present to improve airflow separation at the leading edge. These sidewalks form part of the six-lane configuration and their premature installation in the mainspan may be regarded as a premium for aerodynamic stability of the open girder section.

The three-dimensional computer model established for dynamic analysis was also used for static loading analyses for all components of the bridge. Non-linearities due to cable catenary behaviour and axial loads on the girders and towers were accounted for in all analyses, avoiding the necessity for arbitrary allowances for second order effects.

The preliminary proportions selected for the girder proved to be adequate for strength, the largest flanges required were 80 x 800 mm.

Once these two interrelated main criteria of girder bending strength and aerodynamic stability were resolved, it remained to satisfy a large number of further demands on the various components of the bridge, such as axial load sharing between the composite deck and the girder, the time-dependent effects of creep and shrinkage, shear lag in the composite deck over the tie down pier etc.

The towers are also subject to creep and shrinkage effects, but are more seriously affected by the ductility demands of seismic displacements.

6. CONCLUSIONS

6.1 General Conclusions

This paper attempts to show that, given the encouragement of an owner who recognizes the merits of alternative designs for major bridges, the bridge engineer can achieve significant capital cost economics by approaching the conceptual design of the bridge without biases of form or material, but with a single minded commitment to the most efficient combination of components for the particular set of circumstances at that location. This approach can of course lead to innovations and improvements, but it must be tempered with a very thorough checking and analysis effort to ensure that new features are thoroughly investigated before being incorporated in the final design.

7. ACKNOWLEDGMENT

This paper is published by permission of the Honourable Alex Fraser, Minister of Transportation and Highways of British Columbia.

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