4e Conférence spécialisée en génie des structures
de la Société canadienne de génie civil

4th Structural Specialty Conference
of the Canadian Society for Civil Engineering

Montréal, Québec, Canada
5-8 juin 2002 / *June 5-8, 2002*

DESIGN ECONOMICS OF HPC GIRDER BRIDGES PRESTRESSED WITH CFRP TENDONS

Mostafa A. Hassanain, Ph.D., P.Eng.[A], Mahmoud M. Reda Taha, Ph.D., P.Eng.[B]
A Edwards and Kelcey, Inc., Minneapolis, Minnesota, USA
B Stantec Consulting Ltd., Calgary, Alberta, Canada

ABSTRACT: Surveys have indicated that between 30% and 40% of all bridges in North America are in urgent need of replacement or rehabilitation. New materials such as HPC and FRP could play a major role in the renewal of North America's bridges. Despite the potential benefits from the use of these materials, most designers and precasters are still reluctant to use them. This may be due to the increased initial cost and quality control required to produce these materials. It is unlikely that HPC and FRP will gain wide acceptance without a clear economic incentive. This paper presents a rigorous and systematic procedure using optimization techniques for the design of slab-on-girder bridges. The procedure is used to develop an optimization system that can be utilized to carry out cost effectiveness studies of the use of HPC and FRP prestressing tendons in the production of standard CPCI I-girders, and to develop preliminary design charts according to the CHBDC provisions.

1. INTRODUCTION

According to the National Research Council's Institute for Research in Construction, about 40% of all bridges operating in Canada are older than 30 years, and most are in urgent need of replacement or rehabilitation. In the United States, almost 30% of all bridges are rated structurally deficient or functionally obsolete by the Federal Highway Administration. New construction materials such as high-performance concrete (HPC) and fibre-reinforced polymers (FRP) could play a significant role in the renewal of North America's bridge infrastructure.

For many years, the most common application of HPC has been in the building industry where concrete strengths of 100 MPa and more have been frequently used in the lower columns of high-rise buildings. In comparison, strengths of about 60 MPa have been considered the maximum achievable in the precast, prestressed concrete industry; this appears to be very timid especially considering that several research studies have indicated that the potential advantages from the use of HPC with its increased strength and improved durability for precast, prestressed highway bridges are quite promising. Hassanain and Loov (1999), for example, have shown that it is more economical to use fewer HPC girders than a larger number of normal-strength girders. This economic advantage of using HPC becomes more apparent for longer spans. A major benefit from the use of HPC is that it allows significant increases in span lengths. When span lengths increase, the number of piers and foundations can be reduced in multi-span bridges, or they can even be entirely eliminated. This, in turn, reduces the cost of the substructure. Another benefit from the use of HPC is that it allows the use of a shallower girder cross-section for a given span length compared to the girder depth required with normal-strength concrete. The resulting increase in vertical clearance may significantly reduce the amount of earthwork associated with bridge construction, which usually constitute a major portion of the bridge cost. Due to its dense microstructure, HPC exhibits excellent durability, which translates into a longer service life, fewer repairs, higher sustainability, and reduced life-cycle costs (Rejj *et al.* 1995).

Another newly emerging technology, with potential applications in prestressed concrete, consists of prestressing bars and tendons made from FRP composites. FRP products are typically made of high-performance fibres, resin, fillers, and additives. The fibres, which are made of aramid, carbon, or glass, provide high stiffness and tensile capacity. The resin, which could be of the polyester, vinyl ester, or epoxy groups, protects the fibres and binds them into a firm matrix. The fillers serve to reduce cost and shrinkage. The additives help to improve the mechanical and physical properties of the composites, in addition to their workability. All FRP bars and tendons are produced through a pultrusion process that involves a continuous pulling on the fibre strands through a resin bath, and then into a heated die. The elevated temperature of the die cures the composite matrix into a constant cross-section structural shape.

The applicability of FRP reinforcement to concrete structures as a substitute for steel bars and prestressing tendons has been studied by numerous researchers (e.g. Arockiasamy *et al.* 1996, Balázs *et al.* 2000, Burke and Dolan 2001, Dolan *et al.* 2001, Fam *et al.* 1997, GangaRao and Faza 1992, Grace 1999 and 2000, Lu *et al.* 2000, Mahmoud *et al.* 1999, Michaluk *et al.* 1998, Park and Naaman 1999, Saadatmanesh and Tannous 1999, Tannous and Saadatmanesh 1998, and Yamaguchi *et al.* 1997). This is because FRP reinforcement, in comparison to conventional steel reinforcement, offers some excellent advantages including non-corrosive, non-magnetic, non-conductive, high-strength, and lightweight properties. Of particular importance are the non-corrosive properties of FRP reinforcement. With corrosion decay being a continued challenge for bridge engineers, FRP reinforcement provides the promise for more durable concrete bridge infrastructure.

Despite the potential advantages from the use of HPC and FRP reinforcement for the design and construction of highway bridges, the higher initial cost and/or the increased quality control requirements associated with the production of these materials seem to deter designers and precasters from implementing them more widely. Although HPC is slowly gaining more acceptance in the precast, prestressed concrete industry as evidenced by the increasing number of HPC bridges constructed all over North America, the same is not true for FRP reinforcement. A limited number of experimental precast concrete bridges prestressed with FRP tendons have been built in Canada (Rizkalla 1998, Rizkalla *et al.* 1998, and Shehata *et al.* 1997), the United States (Dolan 1999), Japan (Fukuyama 1999), and Europe (Burgoyne 1998) to showcase the advantages of the material. In addition, several code committees and other research groups have recommended design guidelines for structural concrete reinforced with FRP reinforcement (e.g. ACI Committee 440 1996 and 2000, BRI 1995, CSA 2000, and ISIS Canada 2001). It is unlikely, however, that FRP will gain wide acceptance in the precast, prestressed concrete industry without a clear economic incentive.

The objective of this paper is to investigate the economic benefits from the use of HPC and FRP prestressing tendons for the design and construction of continuous, precast, pretensioned slab-on-girder bridges (Figure 1). These were chosen because they represent the most common type of prestressed concrete bridges constructed in North America over the past 50 years. The paper introduces a rigorous and systematic procedure for the design of slab-on-girder bridges; the problem is formulated as an optimal design problem (Hassanain and Loov 1999). The procedure is used to develop an optimization system that can be utilized to carry out cost effectiveness studies, and to develop preliminary design charts and guidelines according to the provisions of the Canadian Highway Bridge Design Code (CHBDC) (CSA 2000). The intent of the study presented herein is to look beyond current precast, prestressed concrete production capabilities, and bridge analysis, design, and construction methods. Although current practice is considered as the basis for the assumptions made in developing the optimization system, it is not used as a means to restrict potential applications of HPC and FRP in precast, prestressed concrete slab-on-girder bridges.

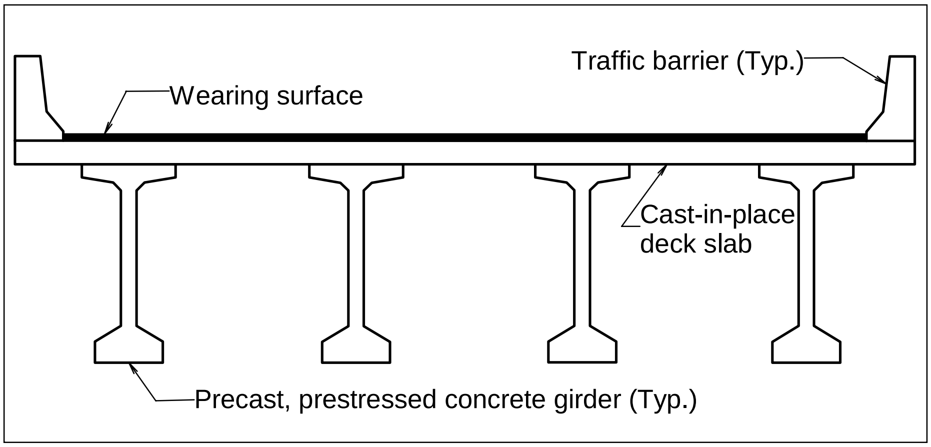

Figure 1. Cross section of a typical slab-on-girder bridge.

2. FRP FOR PRESTRESSING APPLICATIONS

As indicated in the previous section, different types of FRP materials are manufactured; these include aramid FRP (AFRP), carbon FRP (CFRP), and glass FRP (GFRP). There is general agreement that CFRP materials are superior to aramid and glass fibres in strength and durability (Tannous and Saadatmanesh 1998). Therefore, CFRP prestressing tendons are used in this study. An understanding of the properties of FRP constituent materials would help in understanding the behaviour of FRP under different states of stress. A review of FRP properties, and a comparison to steel properties have been presented elsewhere (ACI Committee 440 1996, and Schupack 2001). Only those properties that affect the performance of prestressing tendons are briefly discussed hereafter. These properties include FRP strength, stress-strain, creep, and fatigue performance.

Being a product of high-modulus fibres, FRP tendons tend to have high tensile strength in the same range or slightly higher than that of steel tendons. This is because the strong, bundled, parallel fibres dominate the tensile strength of an FRP tendon. However, the strength of FRP is considerably reduced when its size increases. This size effect of an FRP tendon is attributed to the limited shear capacity of its resin matrix (GangaRao and Faza 1992). The low shear strength of FRP materials results also in the difficulty encountered in anchoring FRP tendons. Anchors that are usually used with prestressing steel tendons dig into the sensitive surface of FRP tendons, resulting in premature failure (Nanni *et al.* 1996). A number of new anchors especially made for FRP tendons have been developed (e.g. Kerstens *et al.* 1998, and Reda Taha and Shrive 2001). The low fatigue capacity of concrete elements reinforced or prestressed with FRP is only a concern when GFRP bars or tendons are used. CFRP tendons have been reported to exhibit excellent fatigue performance (Saadatmanesh and Tannous 1999).

Most FRP tendons have an elastic modulus that is lower than that of steel tendons. An important mechanical property of an FRP material is its lack of yield. Being a polymer-based material, no dislocation movements can take place, and therefore, the material behaves in a linear manner up till failure. This would reduce the deformability of concrete members prestressed with FRP tendons if a design philosophy similar to that used with prestressed steel tendons were adopted for prestressed FRP structures. Not only does FRP have a linear behaviour up till yield, but also most FRP tendons would have a limited failure strain compared to that of steel tendons. The absence of yield and the limited failure strain require establishing different design criteria to ensure the satisfaction of ductility requirements. Special provisions to guarantee acceptable deformability and ductility are therefore necessary when FRP is used in prestressed concrete structures (CSA 2000 and ISIS Canada 2001). Recently, Newhook *et al.* (2002) have suggested a modification to the concept of deformability given in the CHBDC (CSA 2000). They showed that when, in addition to the crack control requirement, an upper limit is imposed on the cross-sectional area of the FRP, no calculations will be necessary to check the deformability.

FRP tendons experience a creep problem that has never been observed in steel tendons. That is the creep-rupture phenomenon which is exhibited by the disability of a material to sustain a load lower than its ultimate capacity over a long period of time (Dowling 1993). This results in the need to limit the FRP stress below a specific ratio of its ultimate strength. Therefore, creep-rupture would be a significant concern when FRP is used in prestressing applications as it imposes a new stress limit on the stresses in the tendons (CSA 2000). CFRP tendons are reported to have the best creep-rupture performance while GFRP have the lowest ratio of all tendons (Yamaguchi *et al.* 1997). The creep-rupture phenomenon of FRP tendons results also in a limitation on the FRP stress when draping (i.e. harping) of the tendons takes place in a prestressed girder. This is because at these points of stress-concentration, creep-rupture can result in failure of the FRP tendons.

It is important to emphasize that, despite the aforementioned limitations of FRP materials, an attractive feature of FRP is their good chemical stability in hostile environments. Superior durability performance of CFRP tendons has been reported in several studies (e.g. Tannous and Saadatmanesh 1998). Only limited durability problems with GFRP have been reported in alkaline environments. Newly developed GFRP products have good alkaline resistance that allows their use in concrete structures (ISIS Canada 2001).

3 FORMULATION OF THE OPTIMAL DESIGN PROBLEM

3.1 General

Most structures are designed on a trial-and-error basis. A preliminary design is estimated and analyzed. If it is satisfactory, it is considered a feasible design. If the trial design is not satisfactory, the designer has to change it and repeat the analysis until a feasible one is obtained. Usually, there are an infinite number of feasible designs, and designers strive to find the best (optimal) within the time they have available.

Mathematical optimization techniques provide systematic procedures by which optimal designs can be obtained with substantially less time and effort. The formulation of an optimal design problem requires identification of a set of design variables that describe the structure, an objective function that measures the merits of alternate designs, and design constraints that must be satisfied (Arora 1989). The objective function and constraints must be functions of the design variables. Prestressed concrete design optimization problems, in general, are nonlinear because the objective function and/or most of the constraints are nonlinear functions of the design variables; thus, requiring nonlinear programming procedures to be used (Hassanain and Loov 1999).

3.2 Design Variables

The design of a structure can be completely described by a set of pre-assigned parameters, and a set of design variables. Only the design variables are modified during the optimization process. For standard precast I-girders, cross-sectional dimensions are known and become pre-assigned parameters. In this study, Canadian Prestressed Concrete Institute (CPCI) girders are investigated. Design variables include the required prestressing force, the tendon profile defined by its eccentricities at and near girder mid-span, and at its ends, and the required amounts of non-prestressing flexural reinforcements in the girders and deck slab. Moreover, the girder concrete compressive strength at 28 days is also taken as a design variable. In addition, because composite action of the precast girders and cast-in-place deck slab was assumed, the slab thickness is taken as a design variable.

3.3 Objective Function

The relevant objective function in the design of bridges with a fixed number of spans is the minimum superstructure cost / deck area. This assumes that the cost of piers, abutments, and approaches is relatively unaffected by changes in the number of girders. The superstructure includes the deck and the girders. The objective (cost) function includes the material (concrete and CFRP) costs plus overhead and waste, in addition to the labour, transportation, and erection costs. Items with fixed costs do not need to be included in the cost function because they are included in all alternative feasible designs and, therefore, have no effect on the optimal design. Examples of such items are the wearing surface, traffic barriers and guardrails, drains, lighting, and signs.

3.4 Design Constraints

The cost function is minimized under all relevant constraints according to the CHBDC provisions (CSA 2000). A synthesis of the design provisions of the CHBDC for fibre-reinforced structures has been presented by Bakht *et al.* (2000) and Tadros (2000). In addition to the flexural constraints at serviceability limit states, and at ultimate limit states, several other constraints pertaining to deformability, creep-rupture, fatigue, and redundancy have to be considered. Moreover, practical constraints, which constitute limits for the design variables, have to be included. Other constraints (e.g. shear and deflection) could be added. However, in general, they have marginal effect on the design and were left to be checked at the final design stage. It is clear that the design constraints for a precast girder prestressed with CFRP tendons are very much different from those for a girder prestressed with steel tendons. The relatively large number of constraints associated with the application of FRP materials in concrete structures makes the traditional design approach of trial and error extremely tedious and time consuming. This is why it would be logical to use design optimization techniques for this type of problems.

3.5 Solution of the Optimal Design Problem

Once the design optimization problem has been formulated, it is transcribed into the following standard nonlinear constrained optimization model: Find the set of n design variables contained in the vector {b} that will minimize the objective function

[1] $$f(\{b\}) = f(b_1, b_2, ..., b_n)$$

subject to the constraints

[2] $$h_i(\{b\}) = 0, \qquad i = 1, ..., k$$

[3] $$g_i(\{b\}) \le 0, \qquad i = 1, ..., m$$

[4] $$b_i^l \le b_i \le b_i^u, \qquad i = 1, ..., n$$

where k is the number of equality constraints, m is the number of inequality constraints, b_i^l and b_i^u are the lower and upper bounds on the ith design variable, respectively.

Many numerical methods have been developed to solve nonlinear constrained optimization problems. The methods start from an initial design provided by the user, which is iteratively improved until the optimum is reached. In this study, the sequential quadratic programming (SQP) method (Arora 1989) is used to solve the nonlinear constrained optimization problem. The use of this method is justified because an extensive comparative study of nonlinear programming methods presented by Schittkowski (1980) determined that the SQP method is superior in performance to other classes of optimization algorithms. The SQP method generates a sequence of quadratic programming sub-problems that are to be solved sequentially (Arora 1989). The method requires the first-order partial derivatives of the objective function and all constraints with respect to the design variables. Analytical expressions for such partial derivatives are generally difficult to obtain for practical engineering problems, and are, thus, usually calculated numerically using the finite difference method. The SQP method is incorporated into several general-purpose design optimization software packages that are available commercially (e.g. GENESIS and IDESIGN), or available in the public domain.

4 DESIGN EXAMPLE

4.1 Assumptions

The following assumptions were made in developing the optimization system:

1. Materials
- Concrete compressive strength at transfer is on average 70% of 28-day strength (PCI 1997).
- The specified concrete compressive strength of the deck slab is fixed at 35 MPa.
- 12-mm-diameter Leadline^{TM} CFRP bars having a guaranteed tensile strength of 2250 MPa are used for the precast, pretensioned girders. 10-mm-diameter Leadline^{TM} CFRP bars are used for the cast-in-place reinforced concrete deck slab. It should be noted that the ultimate tensile strength of CFRP reinforcement is usually higher than the guaranteed value reported by the manufacturer (Shehata *et al.* 1997). The effective stress in the pretensioned bars is taken as 45% of the tensile strength.
- Tendons are draped at the third-points of the span.
- The effective prestressing force after losses is 80% of the prestressing force at the time of transfer. Although stress relaxation of a CFRP tendon is higher than that of a steel tendon, the elastic modulus of the former is smaller than that of the latter. This decreases the effect of the other components of prestress loss due to concrete deformation (i.e. creep, shrinkage, and elastic shortening) on the CFRP tendon, and provides more favourable conditions compared to the effects on the steel tendon. Therefore, the fact that a CFRP tendon undergoes greater stress relaxation than a steel tendon does not necessarily mean that the overall prestress loss will be greater (BRI 1995). The assumed value for prestress loss used in this study (20%) is typical for steel tendons.

2. Loading
- A future wearing surface having a thickness of 75 mm will be placed on top of the concrete deck as shown in Figure 1.
- Each traffic barrier has a cross-sectional area of 0.3 m^2. This load is distributed equally among the girders.
- CL-625 vehicular live load is used (CSA 2000).

3. Analysis
- Structural analysis of the bridge system is carried out using the semicontinuum method (Jaeger and Bakht 1985), which is recognized by the CHBDC (CSA 2000) as a refined method of analysis.

4. Design
- Design conforms to the CHBDC provisions (CSA 2000) except where otherwise noted.
- Flexure governs the design of girders. Flexural design of the girders is based on strain compatibility, and the material characteristics of concrete and CFRP tendons.
- Unshored, composite construction. Interface surfaces between the cast-in-place deck slab and precast girders are intentionally roughened for proper shear transfer.

4.2 Case Study

To illustrate the application of the developed optimization system, a representative continuous I-girder bridge is selected. The bridge consists of two equal spans of 40 m each. It has three traffic lanes with an overall width of 12 m, carried by four CPCI Type 1900 girders spaced at 3 m. The girder cross-section is shown in Figure 2. The properties of this section are as follows: $A = 0.544\ m^2$, $y_b = 0.940$ m, $I = 0.268418\ m^4$, $S_t = 0.279464\ m^3$, $S_b = 0.285696\ m^3$, and $J = 7.033\times10^{-3}\ m^4$. Note that A is the cross-sectional area of the girder, y_b is the distance from centroid of the girder cross-section to the extreme bottom fibre, I is the moment of inertia of the girder, S_t and S_b are the girder cross-section moduli with respect to its top surface and bottom surface, respectively, and J is the Saint-Venant torsional constant of the girder. In this study, design of this bridge implies finding the optimal values for the design variables.

The cost function requires unit costs for material, labour, and construction costs. Because girder concrete strength is a design variable that could change at each iteration of the design optimization process, it is

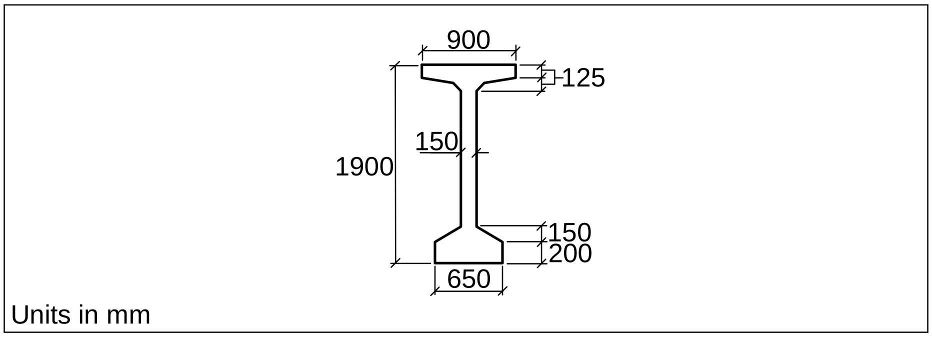

Figure 2. CPCI girder Type 1900.

necessary to have a continuous function for the concrete mix cost. Hassanain and Loov (1999) presented such a function. It relates the cost of any concrete mix to the cost of a 40-MPa mix by a ratio defined as

$$[5] \qquad \mathrm{CMCR} = 0.936 + \left(\frac{f'_c}{100\ \mathrm{MPa}} \right)^3$$

where CMCR is the concrete mix cost ratio, and f'_c is the concrete compressive strength at 28 days. CMCR can be obtained from the above equation for any level of concrete strength, and then multiplied by the cost of a 40-MPa concrete. In the present study, the cost of a 40-MPa mix is assumed to be $Cdn 115/m^3 including an overhead rate of 18%. In addition, labour and curing have been estimated to cost an additional $41/m^3. 12-mm-diameter Leadline$^{\mathrm{TM}}$ CFRP bars cost on average $70/m, while 10-mm-diameter Leadline$^{\mathrm{TM}}$ CFRP bars cost on average $60/m.

A detailed approach for estimating transportation and erection costs for the precast girders is presented by Hassanain and Loov (1999), and is not included here because of space limitations.

At the optimal point, the following values for the design variables pertaining to the girders were obtained:

- The initial prestressing force in each girder is 7.55 MN, i.e. the effective prestressing force after losses is 6.04 MN.
- Tendon eccentricity at and near girder mid-span is 822 mm, and eccentricities at girder's ends are 38 mm each.
- No positive moment reinforcement is needed in the girders, i.e. the girders are fully prestressed.
- Girder concrete compressive strength at 28 days is 74 MPa.

Final value of the cost function at the optimal point is $1100/m^2.

4.3 Discussion

Current initial costs of FRP materials are significantly higher than those of conventional materials. In addition, costs associated with the activities that bring these new materials from the research laboratory to full acceptance by the construction industry (known in the literature as new-technology introduction (NTI) costs) (Ehlen and Marshall 1996) can be significant. Examples of these costs include full-scale testing and non-destructive evaluation of demonstration projects. This cost premium is the main economic barrier preventing the use of FRP on a wide scale in the precast, prestressed concrete industry. This, in turn, hinders the build-up of adequate experience in FRP, which would help increase production and thereby, reduce costs. To break this cycle of high initial costs, lack of experience, and small-scale production of FRP, it is important to realize that FRP materials provide clear life-cycle benefits that could make them financially viable even if they cost more initially (Nystrom *et al.* 2002). Due to their favourable properties, especially their non-corrosive properties, FRP reinforcement could reduce bridge life-cycle costs, which include maintenance, inspection, repair, disposal, and replacement. Moreover, FRP could incorporate fibre optic sensors for structural monitoring, which would lead to increased structural sustainability.

Current FRP technologies and practices vary significantly, however, and these products are in the introductory phase of the product life cycle (Nystrom *et al.* 2002). Thus, it may be difficult to quantify the life-cycle cost benefits of FRP materials with great level of precision except for a specific project (Ehlen 1997). However, generalizations can be made despite the uncertainties involved.

Ehlen and Marshall (1996) analyzed the cost effectiveness of FRP bridge decks relative to reinforced concrete decks. They concluded that, once FRP composites begin to be applied and accepted, their life-cycle costs will diminish, making them more cost competitive with conventional materials. This happens for three reasons. First, spreading the NTI costs of a composite bridge over multiple bridges of similar design can significantly reduce the life-cycle cost per bridge. Second, NTI costs diminish over time as the behaviour and performance of the material and/or design become more certain, and users accept it, thereby reducing the cost of material testing. Third, as large-scale production occurs with increasing applications and increased demand for the material, and as the number of competing material's manufacturers and suppliers increases, the cost of FRP itself will be reduced.

The same logic could be applied to the use of CFRP tendons in precast HPC bridge girders. The basic optimization system presented in this paper is currently being expanded to include life-cycle cost parameters. The resulting system would provide a tool that can be used to evaluate the life-cycle cost effectiveness of CFRP tendons in relation to steel tendons. The optimization system would also be used to develop preliminary design charts and guidelines for precast HPC girder bridges prestressed with CFRP tendons according to the provisions of the CHBDC (CSA 2000).

5. CONCLUSION

New construction materials such as HPC and FRP could play a significant role in the renewal of North America's bridge infrastructure. It is unlikely, however, that these materials will gain wide acceptance in the precast, prestressed concrete industry without a clear economic incentive. Moreover, the relatively large number of new design constraints associated with the application of FRP materials in concrete structures makes the traditional design approach of trial and error extremely tedious and time consuming, and my prevent designers from selecting these materials.

This paper introduced a rigorous and systematic procedure using mathematical optimization techniques for the design of HPC slab-on-girder bridges prestressed with CFRP tendons. The procedure was used to develop an optimization system that can be utilized to carry out cost effectiveness studies, and to develop preliminary design charts and guidelines according to the CHBDC provisions. The importance of considering life-cycle costs in the economic evaluation of girder bridges prestressed with CFRP tendons was discussed. Currently, the aforementioned optimization system is being expanded to include life-cycle cost parameters.

6. REFERENCES

ACI Committee 440 (1996) *State-of-the-Art Report on Fiber Reinforced Plastic (FRP) Reinforcement for Concrete Structures*, American Concrete Institute, Farmington Hills, Michigan, USA.

ACI Committee 440 (2000) *Guide for the Design and Construction of Concrete Reinforced with FRP bars*, American Concrete Institute, Farmington Hills, Michigan, USA.

Arockiasamy, M., Shahawy, M.A., Sandepudi, K. and Zhuang, M. (1996) Application of High Strength Composite Tendons in Prestressed Concrete Structures, *Proceedings of the First International Conference on Composites in Infrastructure: Fiber Composites in Infrastructure*, University of Arizona, Tucson, Arizona, USA, 520-535.

Arora, J.S. (1989) *Introduction to Optimum Design*, McGraw-Hill, Inc., New York, New York, USA.

Bakht, B., Al-Bazi, G., Banthia, N., Cheung, M., Erki, M., Faoro, M., Machida, A., Mufti, A.A., Neale, K.W. and Tadros, G. (2000) Canadian Bridge Design Code Provisions for Fiber-Reinforced Structures, *Journal of Composites for Construction*, ASCE, 4(1): 3-15.

Balázs, G.L., Borosnyói, A. and Almakt, M.M. (2000) Future Possibilities in Using CFRP Tendons for Prestressed Pretensioned Girders, *Proceedings of the Bridge Engineering Conference 2000: Past Achievements, Current Practice, Future Technologies*, Egyptian Society of Engineers, Sharm El-Sheikh, Egypt, 8 pp. (CD-ROM).

BRI (1995) *Design Guidelines for FRP Prestressed Concrete Members* (in Japanese), FRP Reinforced Concrete Research Group, Building Research Institute, Japanese Ministry of Construction, Tokyo, Japan.

Burgoyne, C.J. (1998) Advanced Composites – The Challenge to Bridge Designers, *Proceedings of the Fifth International Conference on Short and Medium Span Bridges*, Canadian Society for Civil Engineering, Calgary, Alberta, Canada, 1: 73-86.

Burke, C.R. and Dolan, C.W. (2001) Flexural Design of Prestressed Concrete Beams Using FRP Tendons, *PCI Journal*, 46(2): 76-87.

CSA (2000) *Canadian Highway Bridge Design Code* (CAN/CSA-S6-00), CSA International, Toronto, Ontario, Canada.

Dolan, C.W. (1999) FRP Prestressing in the U.S.A., *Concrete International*, 21(10): 21-24.

Dolan, C.W., Hamilton III, H.R., Bakis, C.E. and Nanni, A. (2001) *Design Recommendations for Concrete Structures Prestressed with FRP Tendons*, Federal Highway Administration, Washington, D.C., USA.

Dowling, N.E. (1993) *Mechanical Behavior of Materials: Engineering Methods for Deformation, Fracture, and Fatigue*, Prentice Hall, Inc., New Jersey, USA.

Ehlen, M. (1997) Life-Cycle Costs of New Construction Materials, *Journal of Infrastructure Systems*, ASCE, 3(4): 129-133.

Ehlen, M.A. and Marshall, H.E. (1996) *The Economics of New-Technology Materials: A Case Study of FRP Bridge Decking*, Report No. NISTIR 5864, Office of Applied Economics, Building and Fire Research Laboratory, National Institute of Standards and Technology, U.S. Department of Commerce, Gaithersburg, Maryland, USA.

Fam, A.Z., Rizkalla, S.H. and Tadros, G. (1997) Behavior of CFRP for Prestressing and Shear Reinforcements of Concrete Highway Bridges, *ACI Structural Journal*, 94(1): 77-86.

Fukuyama, H. (1999) FRP Composites in Japan, *Concrete International*, 21(10): 29-32.

GangaRao, H.V.S. and Faza, S.S. (1992) *Bending and Bond Behavior of Concrete Beams Reinforced with Plastic Rebars*, Technical Report, Phase I, West Virginia University, Morgantown, West Virginia, USA.

Grace, N.F. (1999) Continuous CFRP Prestressed Concrete Bridges, *Concrete International*, 21(10): 42-47.

Grace, N.F. (2000) Transfer Length of CFRP/CFCC Strands for Double-T Girders, *PCI Journal*, 45(5): 110-126.

Hassanain, M.A. and Loov, R.E. (1999) Design of Prestressed Girder Bridges Using High Performance Concrete – An Optimization Approach, *PCI Journal*, 44(2): 40-55.

ISIS Canada (2001) *Reinforcing Concrete Structures with Fibre-Reinforced Polymers* (ISIS-M04-00), The Canadian Network of Centres of Excellence on Intelligent Sensing and Innovative Structures (ISIS Canada), University of Manitoba, Winnipeg, Manitoba, Canada.

Jaeger, L.G. and Bakht, B. (1985) Bridge Analysis by the Semicontinuum Method, *Canadian Journal of Civil Engineering*, 12(3): 573-582.

Kerstens, J.G.M., Bennenk, W. and van de Camp, J.W. (1998) Prestressing with Carbon Composite Rods: A Numerical Method for Developing Reusable Prestressing Systems, *ACI Structural Journal*, 95(1): 43-50.

Lu, Z., Boothby, T.E., Bakis, C.E. and Nanni, A. (2000) Transfer and Development Lengths of FRP Prestressing Tendons, *PCI Journal*, 45(2): 84-95.

Mahmoud, Z.I., Rizkalla, S.H. and Zaghloul, E.R. (1999) Transfer and Development Lengths of Carbon Fiber Reinforced Polymers Prestressing Reinforcement, *ACI Structural Journal*, 96(4): 594-602.

Michaluk, C.R., Rizkalla, S.H., Tadros, G. and Benmokrane, B. (1998) Flexural Behavior of One-Way Concrete Slabs Reinforced by Fiber Reinforced Plastic Reinforcements, *ACI Structural Journal*, 95(3): 353-365.

Nanni, A., Bakis, C.E., O'Neil, E.F. and Dixon, T.O. (1996) Performance of FRP Tendon-Anchor Systems for Prestressed Concrete Structures, *PCI Journal*, 41(1): 34-44.

Newhook, J., Ghali, A. and Tadros, G. (2002) Concrete Flexural Members Reinforced with Fiber Reinforced Polymer: Design for Cracking and Deformability, *Canadian Journal of Civil Engineering*, 29(1) 125-134.

Nystrom, H.E., Watkins, S.E., Nanni, A. and Murray, S. (2002) Financial Viability of Fiber-Reinforced Polymer (FRP) Bridges, *Journal of Management in Engineering*, ASCE, in press.

Park, S.Y. and Naaman, A.E. (1999) Shear Behavior of Concrete Beams Prestressed with FRP Tendons, *PCI Journal*, 44(1): 74-85.

PCI (1997) *Bridge Design Manual*, First Edition, Precast/Prestressed Concrete Institute, Chicago, Illinois, USA.

Reda Taha, M.M. and Shrive, N.G. (2001) Concrete Anchors for Post-Tensioned CFRP Structures, *Proceedings of the Second International Conference on Engineering Materials*, San Jose, California, USA, 10 pp.

Rejj, A.W.F., Hordijk, D.A. and Krielaart, G.H. (1995) High-Strength Concrete Bridge Design: a Contribution to Sustainable Development?, *Proceedings of the IABSE Symposium: Extending the Lifespan of Structures*, San Francisco, California, USA, 73/2: 811-816.

Rizkalla, S. (1998) Advanced Composite Materials for Bridges, *Proceedings of the Fifth International Conference on Short and Medium Span Bridges*, Canadian Society for Civil Engineering, Calgary, Alberta, Canada, 1: 49-57.

Rizkalla, S., Shehata, E., Abdelrahman, A. and Tadros, G. (1998) The New Generation: Design and Construction of a Highway Bridge with CFRP, *Concrete International*, 20(6): 35-38.

Saadatmanesh, H. and Tannous, F.E. (1999) Relaxation, Creep, and Fatigue Behavior of Carbon Fiber Reinforced Plastic Tendons, *ACI Materials Journal*, 96(2): 143-153.

Schittkowski, K. (1980) Nonlinear Programming Codes: Information, Tests, Performance, *Lecture Notes in Economics and Mathematical Systems*, Vol. 183, Springer-Verlag, New York, New York, USA.

Schupack, M. (2001) Prestressing Reinforcement in the New Millennium, *Concrete International*, 23(12): 38-45.

Shehata, E., Abdelrahman, A., Tadros, G. and Rizkalla, S. (1997) FRP for Large Span Highway Bridge in Canada, *Proceedings of the US-Canada-Europe Workshop on Bridge Engineering: Recent Advances in Bridge Engineering*, EMPA Switzerland, Dubendorf and Zurich, Switzerland, 247-254.

Tadros, G. (2000) Provisions for Using FRP in the Canadian Highway Bridge Design, *Concrete International*, 22(7): 42-47.

Tannous, F.E. and Saadatmanesh, H. (1998) Durability and Long-Term Behavior of Carbon and Aramid FRP Tendons, *Proceedings of the Second International Conference on Composites in Infrastructure: Fiber Composites in Infrastructure*, University of Arizona, Tucson, Arizona, USA, 2: 524-538.

Yamaguchi, T., Kato, Y., Nishimura, T. and Uomoto, T. (1997) Creep Rupture of FRP Rods Made of Aramid, Carbon, and Glass Fibers, *Proceedings of the Third International Symposium on Non-Metallic (FRP) Reinforcement for Concrete Structures*, Japan Concrete Institute, Sapporo, Japan, 2: 179-186.