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Rational Procedure in the Design of Bridges Using Pre-stressed Concrete Beams — A Theoretical Practical Method in Search of Sustainable Structures

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Abstract: Currently there is not a direct procedure for the design for this system of bridges, according to methods approved by the respective authorities, the procedure is still based on trial and error, there are no studies that give us both the optimal number of girders or the other characteristics of this type of structures like the right thickness of slab or proper resistance, taking into account the concept of optimization, which supports the idea of sustainability and more environmentally friendly designs, the idea of applying this concept to the design of bridges based on pre-stressed concrete beams, which are an integral part of the road network of most countries around the world. Knowing also that concrete is the most produced material by man and that without it would be difficult to understand our current world, due to its own characteristics that make it unique if it is a matter of sustainability, however, its production requires energy and consumption of materials, that is why an optimal design of a superstructure will lead to the minimum consumption of materials while obtaining a design more friendly to nature. It is a global necessity to obtain and deliver concrete structures that meet sustainability conditions.

Key words: bridges, girders, concrete, pre-stressing, sustainability, optimization, AASHTO, live and dead loading

1. Introduction

It is true that after many years in which have been used pre-stressed concrete girders supporting a concrete slab, has not been able to establish the suitable type of girder according to the span, nor to know the maximum performance of each type of girder, giving in this way many solutions to a given problem, but none adopted in a generalized way to provide an appropriate and economical solution to the proposed array of girders, in other words, the most sustainable or optimum solution. It is shown a direct method to determine the number of girders more suitable according to the type to use.

2. Review to the Technical Literature

Recently has emerged the concept of the sustainable design of structures, which by applying it to pre-stressed concrete girder bridges, could be synthesized in the use of:

1) minimum number of line girders,
2) optimum thickness of slab over girders,
3) minimum number of columns in the case of piers
4) minimum number of intermediate spans in the bridge, which is achieved using the girders to its maximum performance.

In 1971 [1] conducted a study motivated by the need to have greater spans with the existing girder sections and to have the most suitable section for local conditions. The study gave the correct importance to the employment of segmented girders spliced in field with the application of a post-tensioning, however due to the little studies on this process is opted to find

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another solution. Although we had enough information about the types of girder sections in use, the question remained is, What it is the cheapest and practical section to be used? It was considered the following criteria:

- Practicability, realistic concrete strengths 6000 psi (42 Mpa) consistently, perhaps up to 7000 psi (50 Mpa), realistic size and weight limits for precast girders.
- Safety, the use of a single unit precast section appears desirable since it can span existing roadway without shoring. This eliminates inherent shoring hazards.
- Esthetics, it appears desirable to eliminate the stubby end blocks such as on the old AASHO sections. Also, it seems desirable to eliminate the possibility of texture blemishes that can result from field splices.
- Economy, the cost of field splicing, in all cases, appears to be an added cost that can be justified only if a single piece section cannot be hauled over-road to the site.

In terms of number of girders and their spacing, it is clear that a deep girder is capable of carrying a greater payload moment when compare to a shallow girder for a given span, this allows that greater height beams are spaced at greater distance than the shallower girders which results in fewer girders for a width of bridge, but this is reflected in a thicker deck slab with more reinforcement, on the other hand, may require greater volume of earthwork for the clearance require, Several sections and parameters were defined like, Span and girder spacing, as well as, the thickness of the slab deck. Two concrete strength in girders were defined, 6000 y 7000 psi. Live load AASHO HS20-44, Intermediate diaphragms at 12 m maximum and 20 cm thick have been proposed and using a computer program, were obtained graphs that relate the span, type of girder and cost per unit of surface, as we see in Fig. 1.

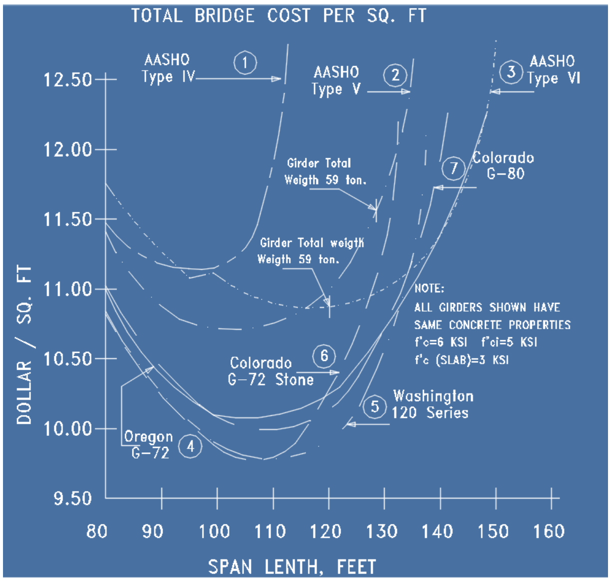

Fig. 1 Optimum girder spacing cost curves for seven stone concrete girders.

As a first conclusion of this study we can say that for a certain span, optimum spacing between girders provides more economic bridge, in this case, a spacing equal to 1.25 times the height of the girder. It is noted the concept of balanced section according to the area of lower flange compared to the top flange area.

In the report by Rabbat and Russell [2], they wanted to determine optimal designs for common girders and to analyze the potentialities of standardizing these sections as well as make recommendations for practical and economic designs. To do this we studied structural efficiency and cost-effectiveness of the best existing designs and study the impact to make some modifications to AASHTO girders, it was proposed to study the following sections shown in Fig. 2 making the following assumptions.

- Design according with AASHTO Specifications.
- Live loads consists of HS 20-44 loading.
- Girders are simply supported
- A typical interior girder is considered

Concrete deck is cast in place and acts compositely with the girder. Deck formwork is supported on the girder. In calculations of the composite section properties, the transformed area of strands is neglected. Concrete compressive strength of the deck is constant

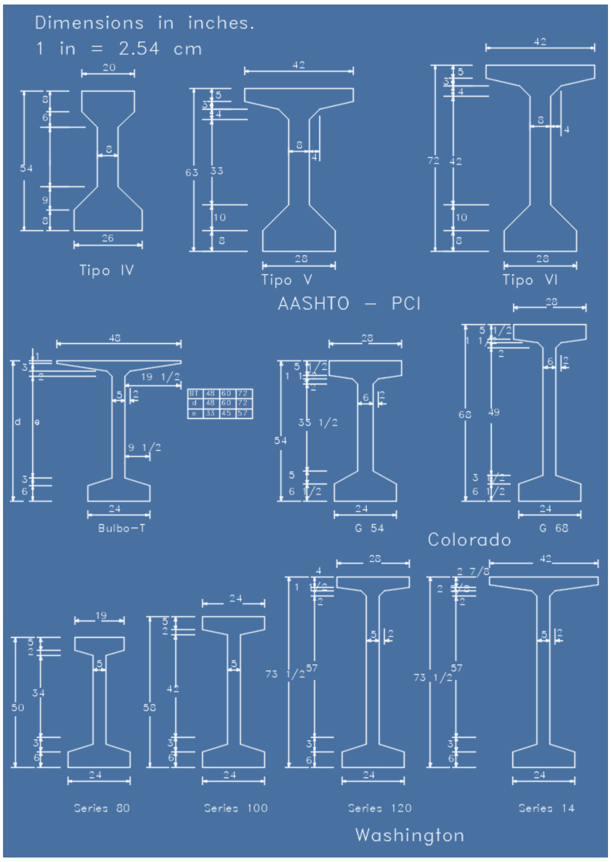

Fig. 2 Modified girder analyzed (AASHTO, Bulb T, Colorado and Washington).

and equal to 5000 psi (28 Mpa) at 28 days. Strands are Grade 270 (1,900 Mpa) stress relieved with ½ in (1.3 cm) diameter and have an idealized trilinear stress-strain curve. Total pre-stressing looses are constant and equal to 45,000 psi (310 Mpa). Initial or long term camber or sag do not govern design, because AASHTO specifications do not specify deflections limits for concrete bridges. As a result of studies in different sections of girders show that the AASHTO sections are not the most economical for the characteristics of materials, the live load applied and to the design conditions prevailing in the country, and suggests to modify the above sections to reduce cost in the work, also suggests the use of concrete in beams from 35 to 50 Mpa to increase the until span about 15%. Also suggests that the modified section "Bulb-T" is most suitable for spans from 24 to 42 meters, for greater spans it is recommended spliced sections. Intermediate diaphragms are not needed, end diaphragms are sufficient.

In 1993, Lounis and Cohn [4], defined first some of the parameters involved in the design of a bridge with girders, such as:

a) live load,

b) the type of girder,

c) the strength of the concrete slab and the strength of concrete in the girder and

d) existence or not of continuity at intermediate supports

And with the use of a computer program defined for spans and common widths, the type of girder, the minimum number for girders and the maximum spacing for girders, maximizing the performance of these elements.

3. A Practical-Theoretical Approach

Based on the study of the structures previously shown and using basic concepts of optimization, has been related numerically the different parameters involved in the design of this bridge system, defining certain parameters as is mentioned in previous reports, has been obtained an optimization constant involved in the geometry of the superstructure, this constant is an indicator which depends of the type and number of girders, so that, thickness and concrete strength of the slab over girders. At the same time that this constant produces an optimal superstructure, implicitly define the more sustainable superstructure. It has been established the following equation:

$$\frac{\eta \times K_0 \times \int_0^{h_u} dy}{(L \times B)} \longrightarrow \{K_1 \longrightarrow 0.02\} \qquad (1)$$

Were η, represents the number of girders in the superstructure.

K_0, is a constant with a value 1.0 approximately for girders with web width of 20 cm.

L, represents the span (m)

B, is the width of the superstructure (m).

K_1, is the optimization constant with a value of 0.02 approximately.

And $\int_0^{h_{tr}} dy$ represents the girder depth in the superstructure.

It has been established certain constraints:

- concrete strength in girders of f′c = 40, 45 and 50 Mpa
- two concrete strength are considered for the slab 25 and 30 Mpa
- live loading is that defined by SCT T3-S2-R4 (710 KN), which is very similar to the O.H.B.D. live loading.
- design specifications is that one given by AASHTO.
- width web is approximately 20 cm.

This is summarized in the figure below, which relates the live loads and the type of girder, obtaining the optimal ratio of the sum of the height of beams on the system, divided by the product of the span and total width of the system. The K_{xoc} factor should be close to the value of 0.02. Any system which produce a K_{xoc} factor close to this value, will produce an optimal solution.

A very remarkable feature of this factor, is that it is bidirectional, because it can be applied to both directions of the axis of the bearings.

Design Process:

- According to the live load and the girder type selected, choose the appropriate constant K_{xoc}.
- Get the product of the constant K_{xoc} times the span and the width of the superstructure.
- Choose the more appropriate girder according to its depth h_{tr}.
- Obtain the number of girders dividing the first product by girder depth, closing it to the next higher integer, obtaining this way, the real value for K_{xoc}.
- Accommodating the number of girders obtained above, we get the spacing between girders which must be within the acceptable maximum values.
- The final design of the girder will be according to the initial conditions.

Applying the formulation for the following cases, we obtain a-factor K_{xoc} equal or very close to 0.02, so reaching the optimal solution. This formulation perfectly agrees with the results given in Table 1 for the condition of single spans girder bridges. For continuous spans we can take into account only 0.85 of the length between intermediate supports. For the case of the reconstruction of the Walnut Lane bridge, we can notice that we have a $K_{xoc} = 0.0202$.

Table 1 Maximum feasible girder spacing, optimum girder spacing and optimum number of girders for single, two and three-span continuous CPCI girder bridges, Z. Lounis and M. Cohn.

Bridge width W (m)		Girder spacing and number of girders	Girder type and span length										
			CPCI 900		CPCI 1200				CPCI 1400				
			10 m	15 m	10 m	15 m	20 m	25 m	10 m	15 m	20 m	25 m	30 m
Single span girder bridges	All widths	Maximum feasible spacing (m)	3.37	2.52	3.37	3.37	2.95	1.95	3.37	3.37	3.37	3.10	2.19
	8 m	*S* (m)	2.5	2.5	2.5	2.5	2.5	1.9	2.5	2.5	2.5	2.5	1.9
		n	3	3	3	3	4	3	3	3	3	3	4
	12 m	*S* (m)	2.9	2.3	2.9	2.9	2.9	1.95	2.9	2.9	2.9	2.9	2.0
		n	4	5	4	4	4	6	4	4	4	4	6
	16 m	*S* (m)	3.1	2.2	3.1	3.1	2.6	1.95	3.1	3.1	3.1	3.1	2.2
		n	5	7	5	5	6	8	5	5	5	5	7
2&3 span continues girder bridges	All widths	Maximum feasible spacing (m)	3.37	2.79	3.37	3.37	3.1	2.19	3.37	3.37	3.37	3.30	2.33
	8 m	*S* (m)	2.5	2.5	2.5	2.5	2.5	1.9	2.5	2.5	2.5	2.5	1.9
		n	3	3	3	3	3	4	3	3	3	3	4
	12 m	*S* (m)	2.9	2.9	2.9	2.9	2.9	2.0	2.9	2.9	2.9	2.9	2.3
		n	4	4	4	4	4	6	4	4	4	4	5
	16 m	*S* (m)	3.1	2.6	3.1	3.1	3.1	2.0	3.1	3.1	3.1	3.1	2.2
		n	5	6	5	5	5	8	5	5	5	5	7

It is necessary to mention another determining factor in the cross section of the superstructure called K_{br}, which can be defined as the result of dividing the sum of the depth of the beams in the superstructure by the width of the same superstructure, as explained below:

$$0.4 < \frac{\eta \times K_0 \times \int_0^{h_{tr}} dy}{B} < 0.8 \qquad (2)$$

4. Application of the Concept of Sustainability to This Bridge Type

In summary, a sustainable design is one that is obtained at this time without compromising the ability of future generations to solve their own needs. From this definition, an engineering and sustainable project such as a bridge project based on concrete beams, is one that is conceived, designed, built, operated on, is maintained and eventually is put out of service so that these activities require as little as possible in terms of energy and material consumption in support of the community. Under this concept of sustainability, what is sought are engineering projects that have the greatest positive impact at the intersection between the interests of the people they serve, the planet in its short and long term scale and the utility for anyone involved in the life of that project as defined by the concept of Triple bottom line. A fully sustainable bridge is one that strives to serve the population for which it was made, and that its long-term cost is totally environmentally friendly. In this sense, concrete plays an important role in providing solutions to future challenges by contributing to the construction of sustainable infrastructure. With a growing population, concrete's crucial contribution is required as it supports communities in building their infrastructure to connect cities and transport people and goods. Its benefits and sustainable characteristics make concrete a unique material for a more environmentally friendly future.

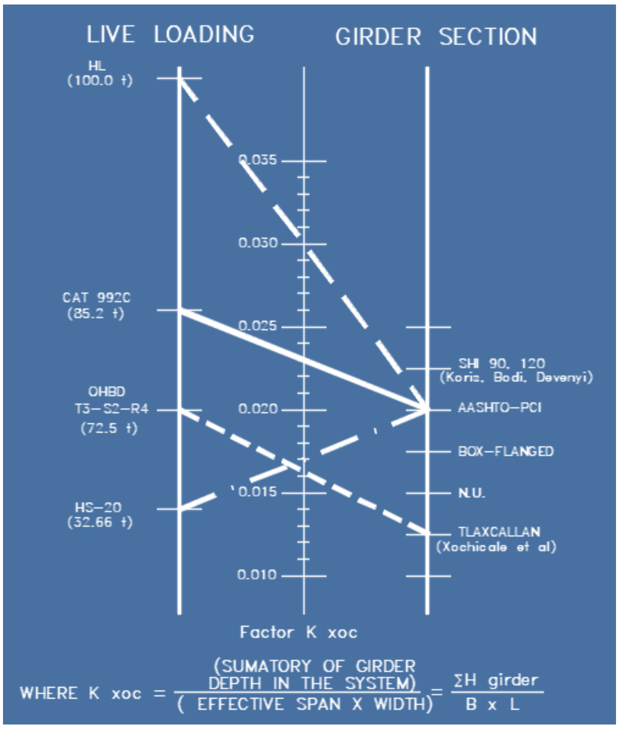

Fig. 3 Graphic definition of K xoc, according to live loading and girder type.

Fig. 4 Definition of sustainability triple bottom line.

5. Application to A Current Project in Mexico

Applying these concepts to a current project to be built in Mexico, in the state of Michoacán, we can see the advantage of applying the concepts of optimization and sustainability to this type of structure. This is a road distributor which consists of a series of 13 spans of 34.0 meters, in which 80 AASHTO type V beams are used, and 19 spans of 29.0 meters, in which 99

AASHTO type IV beams are used, meaning the following report in terms of material consumption, Each span contains 5 beams spaced at 150 cm. and is reduced to 4 beams spaced at 200 cm. in its modified semi-optimized version in which it has a K_{xoc} closer to 0.02. The final version is the optimized one and shows the lowest consumption of materials whose K_{xoc} factor is even lower than 0.02.

It is noted that with the application of the optimization criterion it is possible to reduce quantities of materials by 20% and with it the total costs of the work, having this way a structure that fulfills the aspects of sustainability.

Table 2 Study case to show the K xoc factor and the relation between the number of girders and the consumption of materials.

Identification	Number of AASHTO girders in superstructure	Quantities			Optimization factor K_{xoc}
		Concrete f′c = 45 Mpa m^3	Reinforcement steel fy = 420 Mpa ton	Pre-stressing steel fy = 1900 Mpa ton	
Initial project	99 girders type IV	1427.0	167.6	97.9	0.0294
	80 girders type V	1812.0	247.8	105.5	0.0297
Modified project (Semi-optimized)	78 girders type IV	1123.0	132.0	79.6	0.0235
	63 girders type V	1427.0	195.1	101.1	0.0238
Optimized project (Tlaxcallan girders)	59 girders type 140-080	1020.0	102.0	82.8	0.0185
	49 girders type 180-120	1239.0	123.1	97.1	0.0199

6. Materials Savings

In general terms it can be seen that for the mentioned project it is possible to save up to 980 m^3 of concrete and up to 214 tons of steel, this represents to avoid up to 340 tons of CO_2 in the production of the cement, knowing in addition that at the moment up to 75% of the steel is recycled in the construction, it is immediately noticeable that an optimal design leads to a sustainable design since it means savings in materials and the reduction of pollutants, in addition to other expenses as they are the transfer of equipment, personnel and other materials.

7. Conclusions

The shown method has given very successful solutions and it is recommended in the development of new projects. Once defined the type and the number of beams by use, spacing is defined at the same time, respective calculations done can proved the convenience of using each type of girder that fits its height to the closest value to the factor $K_{xoc} = 0.02$. In addition, as can also be seen, this value leads to economic and rationally designed solutions including sustainability features, among which can be mentioned, the reduction in the consumption of natural resources, the reduction of pollutants emitted into the environment and the possibility of recycling the materials used.

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