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Sustainable Design of a Composite Bridge: A Comparison Between Normal and Green Concrete Composite Slab

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***Abstract*- Bridges are among the most essential structures in engineering. There are different types of bridges among them is the composite bridge. Composite bridges consist of two different materials that act together: concrete slab and steel girders. Sustainability in composite bridge design could be achieved by reducing the material amount as well as incorporating sustainable material such as green concrete. This study evaluates the design of a single-span composite bridge of 30 meters span and 19.2 meters width with eight steel I-girders spaced 2.4 m apart. The design was performed using the American Association of State Highway and Transportation Officials (AASHTO) and Load and Resistance Factor Bridge Design (LRFD) Specifications. Two types of concrete were used for the slab which are the normal concrete and the green concrete. In addition, two types of steel sections were used for the girders, namely, W33 x 221 (W840 x 329) and W33 x 201 (W840 x 299). The comparison between the resulted four designs shows that the design that consists of green concrete slab and the lighter steel girder is the best design accomplishing our aspect of sustainable bridge design.**

Keywords—Sustainability, Composite Bridge, Steel I-Girder, Green Concrete, Normal Concrete, AASHTO-LRFD, Bridge Design.

I. Introduction

Bridges are among the most essential structures in engineering due to their relatively high cost, which makes designing these structures challenging. The design process should consider a holistic approach, integrating environmental, social, and economic considerations to create a sustainable bridge that positively contributes to the surrounding ecosystem and society as a whole [1]. The best design of steel-concrete composite I-girder bridges according to AASHTO LRFD Bridge Design Specifications standard is examined in this research.

Steel-concrete Composite bridges are more lightweight and easy to construct in comparison to other bridges, such as concrete bridges [2]. Since they integrate the structural advantages of steel and concrete, composite bridges are a preferred worldwide investment solution. The steel structure of a composite floor system is primarily deployed to resist tension and shear, which is placed below the concrete slab in these bridges. While the concrete slab serves as a compression component. To ensure that steel and concrete operate together under the applied loading and deflection, certain studs are welded from one edge on the girder's top flange, while the other edges are anchored in the concrete slab. Shear connections are utilized in such structures to accomplish an effective composite function, which allows for the most beneficial usage of both materials, resulting in greater stiffness and strength[3].

The aim of this study is to determine the most sustainable vehicular composite bridge according to AASHTO – LRFD bridge design specification, taking into account various factors, primarily concrete characteristics, since concrete components, production, and construction impose pollution and CO2 emissions. As a consequence, a comparison of normal concrete and green concrete was undertaken in the design of the composite bridge for several environmental and economic aspects in order to achieve the most sustainable design. The following sections illustrate and compare the designs in further depth.

II. Bridge Geometry & Loading

In this study, a single-span composite bridge with a 30 m (1181 in) length span, 19.2 m (756 in) width, and 5.5 m (216.5 in) height as well as eight steel I girders with a 2400 mm (94.5 in) spacing between them, in addition to the 1.2m (47.2 in) overhang distance that is carrying the concrete traffic barrier, has been conducted. The bridge cross section is shown in 'Figure 1".

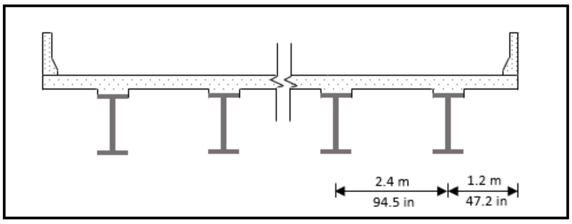

Figure 1: Composite Bridge Cross Section

A. Dead Loads

Loads that remain constant throughout time, such as the bridge's self-weight, traffic barrier load, and future wearing surface, are considered dead loads. Bridge materials are not considered dead loads until they are placed permanently. The weights of the deck slab and its supporting girders are used to determine these loads. The dead load of a component, on the other hand, may be computed using its section characteristics and the unit weight of its materials [4].

The dead load on the composite bridge superstructure is categorized into two groups. Group 1, the weight of all structural components and nonstructural attachments (DC), which affects non-composite sections, is applied prior to concrete placement.

$DC = DC_{slab} + DC_{haunch} + DC_{steel} + DC_{mics.} + DC_{stay\text{-}in\text{-}place}$

Group 2, wearing surface and utility weight (DW), which influences the composite section. It is applied after placing the concrete. It takes into consideration the pavement weight, traffic barrier, and asphalt thickness.

$DW = (w_{fws} * \text{roadway width})/(\text{no. of girders})$

Bending moments and shear forces were computed after calculating the dead loads [5].

B. Live Loads

Live loads play a crucial role in providing the structural integrity and safety of composite bridges. The AASHTO - LRFD specifications provide guidance on determining the live load requirements for composite bridges.

The term "live loads" refers to the moving or transitory loads that a bridge is expected to come across over its service life. These loads include vehicle traffic, pedestrians, and any other dynamic loads acting on the bridge [6]. Because trucks are often responsible for the largest loading on highway bridges, the truck system used in this study is HL-93 according to AASHTO – LRFD Specifications.

This design truck has three axles, one front and two rear, with the front axle weight (35 kN) and the rear axles weighing (145 kN). To produce the worst design force, the distance between the front and rear axles is 4.3m, and the distance between the two rear axles can be changed between 4.3m and 9.0m. In any axle, the tire to tire distance is 1.8m. [7]

Effective factors on determination of live load include the number of axles, weight of axles, and distance between axles. Here, live loading model HL-93 is used. The weight of the track is 450 kN that has three axles with 1.5 m distances. The weight of each axle is 150 kN, and the weight of each tire is 75 kN. The distance between the tires is 2 m. A uniform load of 5 kN/m2 also affects the bridge [7]. “Figure 2” illustrate AASHTO design vehicle (HL-93).

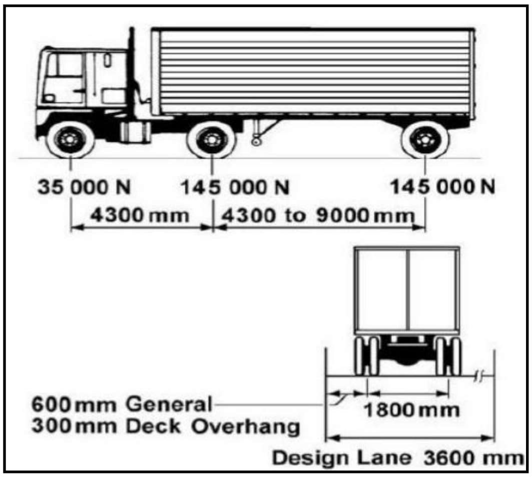

Figure 2: AASHTO design vehicle (HL-93) [7]

In order to calculate the effective force on the internal and external girders according to AASHTO - LRFD requirements and static rules, concrete slab sets on girders are considered as simply supported, and then the quantity of the support reaction is calculated. This reaction in the supports is equally applied on the girder[6].

For design, first a section is considered and then stresses on concrete and steel are examined. These stresses must not exceed the permitted limits.

III. SLAB DESIGN

The slab deck is a bridge's surface and a structural component of the superstructure. It is constructed out of concrete, steel, open grating, or wood. The deck is often covered by a railway bed and track, asphalt pavement, or a different type of surface to facilitate vehicle crossing [8].

The concrete bridge slab is covered with asphalt pavement and supported by steel girders within this study. The slab was designed in accordance with the AASHTO-LRFD design specification. The slab thickness was assumed to be 200mm (7.87 inch), and the bridge's dead load, which represents the slab's self-weight, future wearing surface, and traffic barrier load, as well as the live loads on the bridge caused by moving vehicles (HL-93), and the moments that occurred as a result of these loads, were calculated first. Following that, an adequate rebar diameter and spacing must be chosen for maximum moment and verified for flexural resistance and cracking control. The empirical design method was used in designing the slab.

A. Empirical Design Method

AASHTO - LRFD Bridge Design Specifications allow for the use of the empirical deck design method. Since it does not involve structural analysis to determine load effects, the empirical design technique is significantly simpler than the traditional design method. The empirical deck design method also has criteria for slab thickness, transverse span-to-depth ratio, transverse span, and diaphragms. Furthermore, as compared to the empirical deck design method, adopting the traditional method (flexural approach) in design lead to excessive usage of steel reinforcement and redundant conservatism. The empirical deck method will not only minimize the amount of reinforcement requisite as compared to the traditional method, but it will also simplify the design and construction, resulting in significantly decreased related costs while achieving service and strength limit states. As a result, utilizing the empirical design method in accordance with AASHTO's current restrictions is an important aim towards attaining sustainability by reducing the consumption of materials and, hence, negative impact [9].

As the depth of a concrete deck should not be less than 175 mm (7 in), the assumed slab thickness t = 200mm (7.87 in), was examined for the two concrete types evaluated in this study.

B. Normal Concrete vs. Green Concrete

As stated earlier, this study will test the normal and the green concrete, to set the most sustainable type for the bridge design.

Normal concrete is the traditional building material made from Portland cement, aggregates, and water. On the other hand, Green Concrete is a sustainable building material made from eco-friendly ingredients and utilizes different construction waste that reduce its carbon footprint.

Referring to the literature done, it shows that the green concrete having reduced environmental impact with reduction of the concrete industries CO2 commissions by 30%. In addition, green concrete is having good thermal and fire resistant [10].

In terms of manufacturing, green concrete consists of waste material utilized such as ceramic wastes, aggregates, thus increased concrete industry use of waste products by 20%. Accordingly, green concrete consumes less energy and becomes economical. In structures, green concrete reduces the dead weight of a facade from 5 tons to about 3.5 tons. It reduces crane age load, allow handling, lifting flexibility with lighter weight. As well as, it has good thermal and fire resistance, sound insulation than the traditional granite rock, improve damping resistance of building and speed of construction leading to shorten overall construction period [11]. "Table I" clarifies the parameters of both types as well as the price in BHD/m^3 for each type, which verifies that the green concrete considered more economical since its price is less by more than 70 BD/m^3 [10].

Table I: Characteristics of Normal Concrete and Green Concrete

Parameter	Concrete Strength, f'c		Concrete Unit Weight, wc		Price*
Unit	Kips/in^2	Mpa	lbf/ft^3	Kg/m^3	BHD/m^3
Normal Concrete	4	28	150	2400	662.6
Green Concrete	5	34	99	1590	590.4

*[10]

By applying the empirical method, the results show that both of the tested concretes (Normal and Green) are satisfied in terms of sustainability and could be applicable accordingly. Even though the unit weight of green concrete is lighter compared to normal concrete by around 810 kg/m^3.

IV. COMPOSITE GIRDER DESIGN

A. Steel I-Girder

A girder is a type of structural member commonly used in bridge construction. The primary function of a steel girder is to transfer load to the columns on which it rests [12].

One of the biggest advantages of steel is weight savings, which means lower erection costs, since the bridge pieces can be handled with lighter equipment. In addition, for the same span and load, a steel girder requires less depth than a concrete girder, which can be helpful when constrained by vertical clearance requirements. In construction phase, steel components are made to closer tolerances, which often translates into faster erection. Furthermore, if the substructure and superstructure are designed properly, the lighter weight of steel will allow lighter foundations than for concrete[13].

Generally, it's easier to make spans continuous for both live and dead loads and to develop composite action with steel designs rather than with concrete ones. As the principal ingredient of the raw material for steel bridges is scrap steel, rolled shapes and angles are virtually 100% reclaimed steel from scrap. Plates are about 75% recycled steel. For that reason, steel considered as the most environmentally friendly material used in bridge construction [14]. Many steel I-girder sections have been evaluated throughout the implementation. Despite this, the study offers the comparison for the smallest two steel I-girder sections that satisfied the design requirements. "Figure 3" identifies the parameters of an I-girder section.

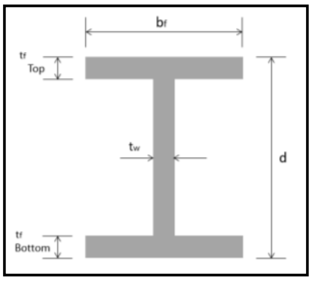

Figure 3: I-Girder Cross Section Parameters

The parameters of the selected two sections is represented in "Table II".

Table II: Steel I-Girder Sections Dimension

Parameter \ Unit	W 33 x 221		W 33 x 201	
	in	m	in	m
tf top	1.28	32.5	1.15	29.2
tf bottom	1.28	32.5	1.15	29.2
bf	15.8	401	15.7	399
tw	0.775	19.7	0.715	18.2
d	33.9	861	33.7	856
ws (lb/ft)	221		201	

B. Design of the Composite Girder

Utilizing W 33 x 221 (W 840 x 329) and W 33 x 201 (W 840 x 299) steel sections as a 200 mm (7.87 inch) thickness of concrete slab, different designs for the bridge are compared by testing these sections on normal concrete and green concrete. The designs were examined according to AASHTO specifications for service 1 limit state, service 2 limit state and fatigue 2 limit state. The criteria of each check in addition to its satisfactory is summarized in "Table III" below for the first section (W33 x 221).

Table III: Composite Girder Design for (W 33 x 221)

W 33 x 221						
Design			A		B	
Concrete type			Normal		Green	
Girder location			Int.	Ext.	Int.	Ext.
Service 1 limit state	Girders flexure	Fy < 70 ksi	ok	ok	ok	ok
		(D/tw) < 150	ok	ok	ok	ok
		(2Dcp/tw) ≤ (3.76 * ((E/Fyc)^0.5))	ok	ok	ok	ok
		Mu+1/3*fl*Sxt ≤ Φf *Mn	ok	ok	ok	ok
	Shear resistance	Vu ≤ Φv Vn	ok	ok	ok	ok
Service 2 limit state	Top flange	ff ≤ 0.95 Rh Fyf	ok	ok	ok	ok
	Bottom flange	ff + (fl/2) ≤ 0.95 Rh Fyf	ok	ok	ok	ok
Fatigue 2 limit state		γ(Δf) ≤ (ΔF)n	ok	ok	ok	ok
		Vu ≤ Vcr	ok	-	ok	-
Weight of the design (kips)			631.3341		448.3564	
Weight of the design (Ton)			286.368		203.371	

In order to determine more sustainable design for the composite bridge, a smaller section was examined. “Table IV” shows the results of implementing (W33 x 201) section, in addition to the satisfactory of each criteria.

Table IV: Composite Girder Design for (W 33 x 201)

W 33 x 201							
Design				C		D	
Concrete type				Normal		Green	
Girder location				Int.	Ext.	Int.	Ext.
Service 1 limit state	Girders flexure	Fy < 70 ksi		ok	ok	ok	ok
		(D/tw) < 150		ok	ok	ok	ok
		(2Dcp/tw) ≤ (3.76 * ((E/Fyc)^0.5))		ok	ok	ok	ok
		Mu+1/3*fl*Sxt ≤ Φf *Mn		ok	ok	ok	ok
	Shear resistance	Vu ≤ Φv Vn		ok	ok	ok	ok
Service 2 limit state		Top flange	ff ≤ 0.95 Rh Fyf	ok	ok	ok	ok
		Bottom flange	ff + (fl/2) ≤ 0.95 Rh Fyf	ok	Not ok	ok	ok
Fatigue 2 limit state		γ(Δf) ≤ (ΔF)n		ok	ok	ok	ok
		Vu ≤ Vcr		ok	-	ok	-
Weight of the design (kips)				614.5906		431.6129	
Weight of the design (Ton)				228.774		195.776	

V. RESULTS

Using AASHTO - LRFD requirements, the impact of the normal concrete -its unit weight is 2400 kg/m^3 (150 lb/ft^3)- and the green concrete – which has a unit weight of 1590 kg/m^3 (99 lb/ft^3) – alongside multiple steel I-girder sections on the design of a sustainable composite bridge has been examined from several aspects, both economically and environmentally. Based on the research, green concrete has more sustainable characteristics in terms of weight; green concrete weighs less than normal concrete. This weight reduction decreases carbon dioxide emissions as well as the overall weight by 810 kg/m^3 (51 lb/ft^3) as mentioned earlier.

In addition to the reasonable price of the green concrete in comparison to the normal concrete, the green concrete has a lower price by 72 BHD/m^3. In addition, green concrete is considered as environmentally friendly, since it is composed of waste used in construction, which is one of the main causes of the spread of pollution around the world. The utilization of this waste in such a significant component -concrete- used around the world helps in achieving sustainability. There were several steel sections tested to conduct the sustainable design. However, the outcome of the smallest two sections is further explained in this paper. First, W33 x 221, which has a unit weight of 221 lb/ft (329 kg/m). The second section is W33 x 201, which has a unit weight of 201 lb/ft (299 kg/m).

As for the concrete, there were two types of concrete in this study, which are the normal concrete and the green concrete. The estimated slab thickness for both types is 200 mm. The empirical design method was used to configure the satisfactory of the slab’s design for the utilized concrete. In examining the identified steel sections, four designs for the bridge were conducted. First, Design A, which has a normal concrete with W33 x 221 I-girder, it fulfills the criteria and has a weight of 631.33 kips (286.37 ton). Secondly, design B, that has the same steel section, and utilizes green concrete. This design meets the criteria as well, and its weight 448.36 kips (203.37 ton). Since it utilizes green concrete instead of the normal concrete, its overall weight has been reduced.

As for Design C, it was created out of normal concrete and W33 x 201 steel. This design will be eliminated as it is failed to meet the condition related to service 2 limit state. Finally, Design D, which preforms the green concrete with W33 x 201 for the steel girder. This design has the least weight, i.e. 431.61 kips (195.78 ton). Due to the fact that the steel section utilized in this design has the least weight, in addition to the concrete used is the green concrete, this design is selected as the most achievable composite bridge.

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VI. CONCLUSION

In this study, a sustainable design of a composite bridge was designed in accordance with the AASHTO - LRFD specifications. The bridge geometry and loading were computed, and the results of the analysis are then used in the design of the bridge components; the slab and the girder. All conditions and constraints were met. Beginning with the slab design, with a thickness of 200 mm assumed. The dead loads (slab self-weight, barrier, future wearing surface) and live loads (design truck HL-93) were computed, and the moment caused by these loads was estimated. Following that, all necessary checks were performed, which verified to be satisfactory according to the empirical design method, for both, normal concrete and green concrete. Following that, the girder design was performed for both concrete types by examining two steel I-girder sections, i.e. W33 x 221 and W33 x 201. Accordingly, there were four designs (A,B,C &D) to be examined to conduct the sustainable design of the bridge. Therefore, the composite designs A,B & D confirmed to be adequate. While design C was eliminated since one of the criteria related to bottom flange in service 2 limit state found to be unsatisfactory. In comparison of the accepted designs, design D was the most sustainable design of a composite bridge. This bridge (design D) has a slab of green concrete, which is the eco-friendly concrete, and (W 33 x 201) girder, which is the smaller and lighter steel section. Also, it has the lightest weight, compared with the remaining accepted designs.

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