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Comparative Study of Aluminum and Steel Bridges

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Abstract— ***Aluminum alloys have been used in bridge since 1933, when the first aluminum bridge deck was used to replace an earlier steel and wood deck on Pittsburgh's Smithfield Street Bridge in order to increase its live-load carrying capacity. Aluminum alloys have much to offer for bridges, because of their light weight, high strength-to-weight ratio, and excellent corrosion resistance. The most famous aluminum alloys that used for bridges are 5086-H116, 5456-H116, 6061-T651, 6061-T6, 5083- H321 and 6063-T6 as given in AAHSTO 2012. In Egypt we have neither aluminum bridges nor researches about them so; in this research aluminum bridges will be studied. Structural analysis, design and comparison between three variants of bridges having the same geometric dimensions are implemented. Variant one consists of steel girders and concrete deck slab. The second variant consists of aluminum girders and aluminum deck. The third variant consists of steel girders and aluminum deck. Loading and design of the three variants are according to American Specifications (AASHTO LRFD Bridge 2012). Flexural, shear, torsional buckling and deflection were verified to produce safe sections. Parametric study is performed for aluminum bridges (variant two and three). The bridges are simply supported with spans 30 and 40 m and have the same cross section. It is concluded that Aluminum Bridge (variant two) is a good competitor for steel bridge because of its excellent corrosion resistance and light weight of super structure. It saves about 80% of the composite bridge weight of superstructures (variant one) and saves 25% of variant three. Replacing the concrete deck (variant one) with aluminium deck (variant three) saves about 75% from the weight of the superstructures.***

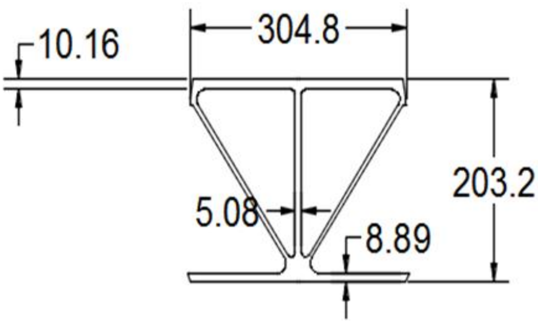
Index Terms— **bridges, aluminum, steel, structural behavior**

I. INTRODUCTION

Aluminum alloys have been used in bridges from 1933 in U.S.A. Some countries in Europe, America and China have different styles of aluminum bridges[5]. Nine bridges were built in North America with aluminum beams and girders between 1946 and 1963[10]. Many researches had been worked to study the behavior of aluminum deck experimentally and numerically. These researches demonstrated that aluminum deck is a feasible alternative to RC decks from the standpoint of stiffness, strength, weight and load carrying capacity. T.Höglund [1] studied replacing damaged concrete decks with aluminum extrusions deck theoretically and experimentally. Kurt P. Thompson [8] investigated different types of aluminum bridge decks rehabilitated in the last decades. Tomasz W. Siwowski [6] investigated the use of aluminum decks for replacing deteriorated RC deck experimentally. Jeffrey M. Dobmeier et al. [2] and Paul C. Misch et al. [3] studied aluminum deck panel made of 6063-T6 alloy with dimensions (2.74 m x 3.66 m) experimentally and numerically as the first phase while the second phase of this study was two field tests that performed to evaluate bridge static and dynamic response. Ichiro Okura et al.[11] studied the connection of aluminum decks to steel girders. Viami International Inc. and the Technology Strategies Group[10] investigated the use of aluminum for the repair and rehabilitation of structurally deficient bridges in Eastern Canada and the North Eastern United States in future. Qinghai and Yangon [7] investigated the analysis of aluminum half-opened bridge under live load. Aluminum Association in Germany [4] celebrates with golden jubilee for Germany's first aluminum road bridge. Scott Walbridge et al. [9] investigated in their search the past use of aluminum in vehicular bridges, the available codes for designing aluminum structures and bridges, properties of aluminum alloys, the use of aluminum for retrofitting of existing bridges and the opportunities for aluminum use in new bridge construction.

II. VERIFICATION OF ALUMINUM DECK

Jeffrey M. Dobmeier et al. [2] tested experimentally one aluminum deck which was fabricated from 6063-T6 aluminum alloy and has tensile yield strength of 172.4 MPa and ultimate strength of 206.8 MPa. Fig.1 represents the cross section of the aluminum deck with vertical stiffener, boundary conditions and load configuration. They measured the deflection at six points at the bottom deck. Tomasz W. Siwowski [6] tested another aluminum deck as shown in Fig.2 which was fabricated from Aluminum alloy AW 6005A-T6 and has tensile yield strength of 250.74 MPa and ultimate strength of 280.42 MPa. Four different load cases and boundary conditions were tested. He measured the deflection at the mid span of the bottom deck for each load case. Numerical models for the two decks with the same dimensions, materials, boundary conditions and load configurations are performed using SAP2000 v14.2 program. Shell element is used to simulate the deck. The results of the numerical models and the experimental tests are given in Fig.3 and Fig.4 which show a good convergence.



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a- Cross-section of the Aluminum deck, Dimensions in mm

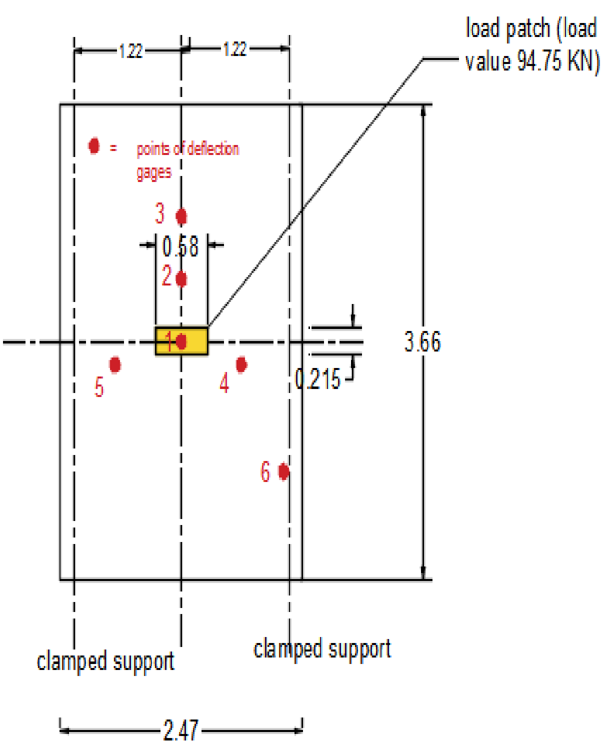
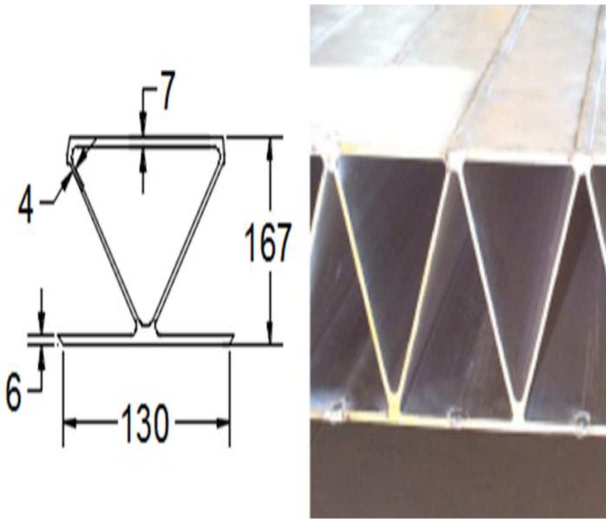


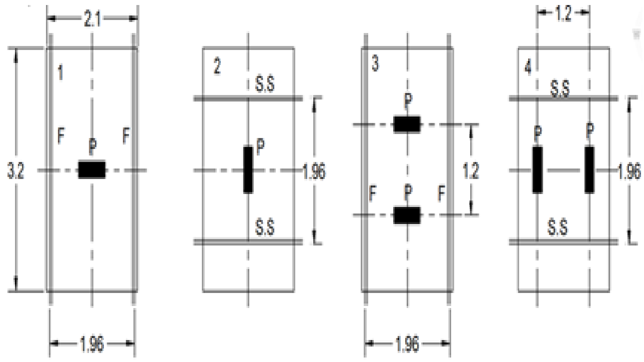
Fig.1 Aluminum Deck by Jeffrey [2]

b- Boundary Conditions and Load Configuration, Dimensions in m



a- Cross-Section of the Aluminum Deck Panel, Dimensions in mm

b- Boundary Conditions and Load Configurations, dimensions in m



(F: Fixed, S.S: Simply Supported, P =150KN)

Fig.2 Aluminum Deck by [6] Tomasz deck

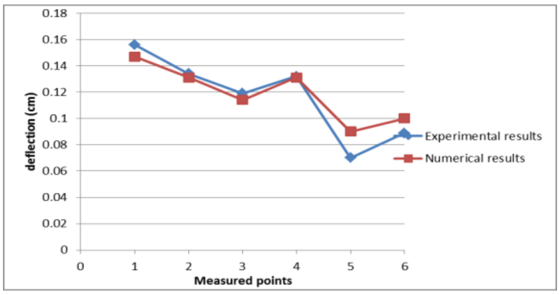


Fig.3: Comparison of Numerical and Experimental Results for Jeffrey deck [2]

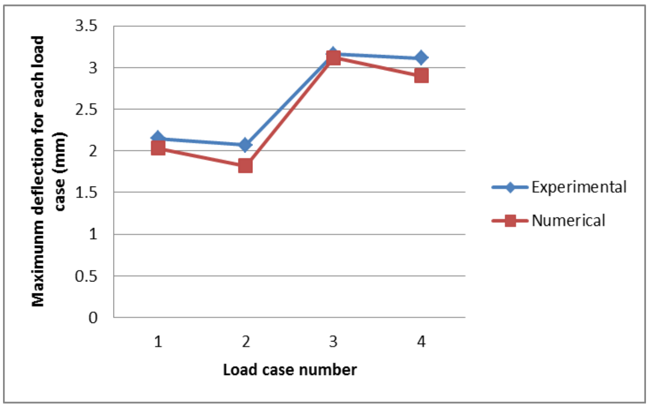


Fig.4: Comparison of Numerical and Experimental Results for Tomasz deck [6]

III. NUMERICAL ANALYSIS

Three variants of bridge have five main girders with 20 m simply supported span and spacing 2 m with different decks are modeled.

The three bridges have the same plane and cross section and boundary conditions as shown in Fig.5 (a,b and c). They differ in materials of elements as shown in Table1. The cross section of girders is I-beam as shown in Fig.6 and the

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dimensions are listed in Table 2. In this research, SAP2000 v14.2 program is used because it is easy in handling and gives the design forces (moment and shear) and deflection for different load cases and load combinations which are required in design. Shell elements are used to simulate decks and frame element for girders. The applicable live loads are AASHTO trucks.

Table 1 : Material of The Three Bridge Elements

	Deck	Girders
Variant one	20 cm Concrete f'_c = specified compressive strength of concrete= 28 MPa	Steel (Modulus of elasticity = 210000 MPa and Yield stress = 360 MPa)
Variant two	Aluminum alloy 6061-T6 has Modulus of elasticity, = 69589 MPa (as in Fig.2 (a))	Aluminum alloy 6061-T6
Variant three	Aluminum alloy 6061-T6 (as in Fig.7)	Steel (Modulus of elasticity = 210000 MPa and Yield stress = 360 MPa)

Table 2 : Dimensions of Girders Cross Section in mm

	Variant one		Variant two		Variant three	
	Main girder	Cross Girder	Main girder	Cross Girder	Main girder	Cross Girder
bft	400	150	480	390	260	190
tft	29	8	34	20	15	9
dw	1120	864	1480	1130	1500	1134
tw	11	7	17	10	13	8
bfb	300	150	480	390	260	190
tfb	14	8	34	20	15	9

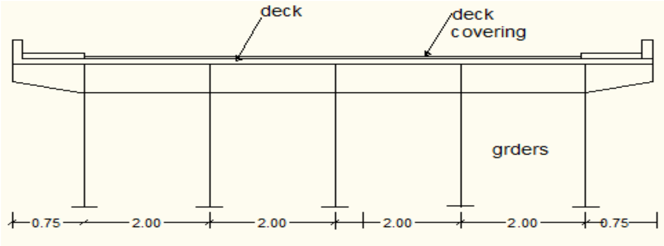

Fig.5a : Cross Section of the Bridge

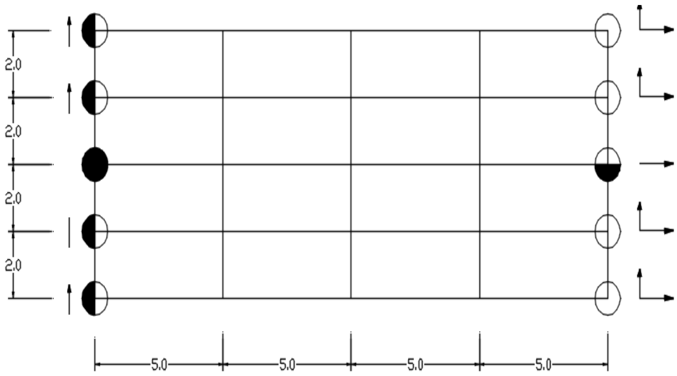

Fig.5b: Plan of the Bridge Dimensions in m

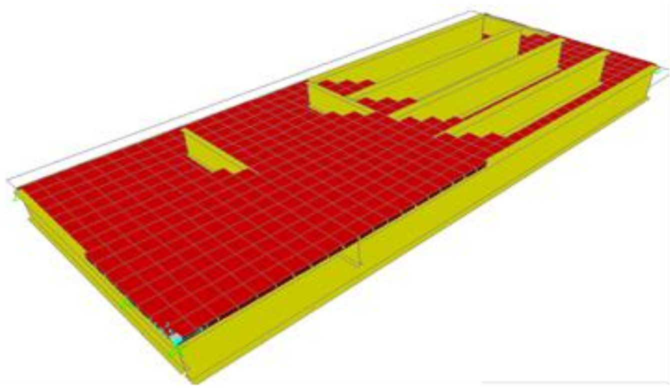

Fig.5c: 3-D Model on SAP2000

Fig.5: Genera Layout of the Studied Bridges

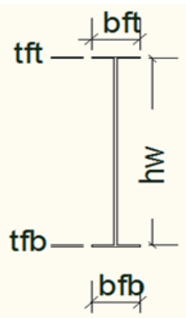

Fig.6: Dimensions of Main and Cross Girder for Variant One, Dimensions (mm)

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IV. DESIGN OF BRIDGES

A. Variant One (Reinforced Concrete Deck and Steel Girders)

resistance		Value	unit	article number in AASHTO	Actual		achieved Limit state
Name	type				name	value	
Fr	Flexural stress	282.14	MPa	7.11.1	σt	70.43	Strength I
Fr	Flexural stress	360.9	MPa	7.11.3	σc	70.43	Strength I
Fr	Flexural stress	275.6	MPa	7.11.3.7	σw	67.34	Strength I
Frb	Flexural stress	223.1	MPa	7.11.3.2.2	σc	70.43	Strength I
Fr	Shear stress	124	MPa	7.11.4.2	τ	44.6	Strength I
(ΔF)n	Fatigue stress	34.9	Mpa	7.6.1	γ(Δf)	15.8	Fatigue II
Δ allowable	deflection	25	mm	2.5.2.6.2	Δ max	24.1	service II

Table 3: Design of Variant One Bridge

Design of this bridge is according to AASHTO (LRDF) 2012, section six as composite bridges. Table (3) gives the actual straining actions (internal forces) and deflection compared with the resistance actions.

Where:

Mr **:** flexural resistance

Mu : factored moment force at strength I load combination

Vn: nominal shear resistance

Vu : factored shear force at strength I load combination

(ΔF)n : nominal fatigue resistance

B. Variant Two (Aluminum Deck and Aluminum Girders)

Design of this bridge was according to AASHTO (LRDF) 2012, section seven. Table 4 gives the actual stresses and deflection compared with the resistance ones.

Table 4: Design of Variant Two Bridge

Resistance		Value	unit	Article number in AASHTO	Actual		achieved Limit state
Name	type				name	value	
Mr	flexural	7905	KN.m	6.10.7	Mu =Σγi.Mi	1654	Strength I
Vn	shear	1364	KN	6.10.9	Vu=Σγi.Vi	649.5	Strength I
(ΔF)n	stress	55.03	Mpa	6.6	γ (Δf)	11.03	Fatigue II
Δ allowable	deflection	25	mm	2.5.2.6.2	Δmax	24	service II

Where

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σc : Stress on compression flange at strength I load combination

Table 5: Design of Variant Three Bridge

resistance		value	unit	article number in AASHTO	Actual		achieved Limit state
Name	Type				name	value	
$\emptyset f * F_{nc}$	flexural	360	MPa	6.10.8.1.1	$f_{bu} + \frac{1}{3} fl$	205.3	Strength I
Vn	shear	2800	KN	6.10.9	Vu=Σγi.Vi	1195	Strength I
(ΔF)n	stress	55.03	MPa	6.6	γ (Δf)	44.5	Fatigue II
Lp	L.T.B	4203	mm	6.10.8.2	Lb	3000	____
Δ allowable	deflection	25	mm	2.5.2.6.2	Δ max	24.1	service II

σw : Stress on web at strength I load combination

	Variant one	Variant two	Variant three
Steel	27.65	_	29.7
Aluminum	_	25.9	4.23064
Concrete	95	_	_
Asphalt	33.44	_	_
Epoxy	_	2.85	2.85
Total Weight (Ton)	156.09	28.75	37.9

Table 6: Sub Structures Design Variables and Cost

Fr : factored stress resistance

σt : Stress on Tension flange at strength I load combination

Frb : factored stress resistance against local buckling

τ :Shear Stress

C. Variant three (Aluminum Deck Deck and Steel Girders)

Design of this bridge was according to AASHTO (LRDF) 2012, section six, Article 6.10.8 as non-composite bridge. Table 5 gives the actual stresses and deflection compared with the resistance ones.

Element	Variant One				Variant Two and Three			
	cross section		length	volume	cross section		length	volume
Cross Beam	2	1.5	9.5	28.5	1.6	1.2	9.5	18.24
Column	2	1.2	5.5	13.2	2	1	5.5	11
Pile Cap	5	5	1.5	37.5	3.5	3.5	1	12.25
PileS	Four piles with diameter = 1 m		20	251.2	Four piles with diameter = 0.6 m		20	90.432
Total Volume				330.4				131.922
Total Cost				293688				117264

Table 7: Weight Point of View in (tons)

Where

$\O f$: Resistance factor for flexure

F_{nc}: Nominal flexural resistance of the compression flange

f_{bu} : flange stress calculated without consideration of flange lateral bending determined as the largest value of the compressive stress throughout the unbraced length in the flange under consideration.

f_l : flange lateral bending stress

Lb : unbraced length

Lp : limiting unbraced length

L.T.B : lateral torsional buckling

From **Table 5**, the deflection governs the design where the flexural and the shear are very safe and the deflection is just safe.

V. BRIDGE SUBSTRUCTURES

Due to saving in the weight of super structure there will be saving in substructure, therefore reinforced concrete beams and columns supporting the girders are designed and also the foundations for the three types of bridges . The amounts and price of reinforced concrete for the sub structure elements are listed in Table 6. The variant two and three have the same substructure dimensions. the cost of reinforced concrete per cubic meter Equals 889 dollars.

VI. WEIGHT AND COST COMPARISON

After designing the three variants, weights and costs of each variant are given in Table 7 and Table 8**.**

Number of important notes can be observed. Firstly, a significant reduction in the weight of the bridge is achieved by replacing the concrete deck with an aluminum one. Comparing the weights of the Variant one and three, Variant three weighs 0.24 of variant one. This reduction of weights leads to save in columns and foundations. Variant two weights 0.18 of variant one. From Studying costs of the three variants for life cycle in Table 8, it is observed that variant two and three will be more economic than variant one where they cost nearly 0.628 and 0.562 relative to variant one respectively.

VII. PARAMETRIC STUDY

The parametric study is performed for variant two and variant three with simply supported spans 30 and 40 meter. The two variants have the same cross section arrangement of the previous variants. Structural analysis and design are performed for the parameters. Dimensions of the main girders of the four bridges are listed in Table 9. Weights of the bridges are listed in Table 10.

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Table 8: Costs Point of View (long term study) in U.S Dollars

Elements	unit cost	Variant1		Variant 2		Variant 3	
		quantity	Cost	quantity	Cost	quantity	Cost
Steel (ton)	2222	27.65	61444	_	_	29.7	66000
Aluminum(ton)	4444	_	_	25.9	115111	4.230`1	18802
Concrete (m^3)	888	38	33777	_	_	_	_
Asphalt (m^2)	111	190	_	_	_	_	_
Epoxy (m^2)	77	_	_	190	14777	190	14777
Protection for One Ton	155	27.65	4301	_	_	29.7	4620
Foundation and Sub Structures			293688		117264		117264
Total			3932212		247152		221464
Percentage of Cost Reduction			1		0.628		0.562

Table 9: Dimensions of Cross Section of Main Girders in mm

Parameter	span 30 m		span 40 m	
	variant two	Variant three	variant two	Variant three
b_{ft} (mm)	670	450	750	470
t_{ft}(mm)	36	20	45	31
d_w(mm)	1760	1660	2230	2038
t_w(mm)	23	17	25	22
b_{fb}(mm)	670	450	750	470
t_{fb}(mm)	36	20	45	31

For span 30 total weight of variant two compared with variant three equals 0.66 and for span 40 m, Variant two weights 0.62 compared with variant three. When plotting the weight per unit area of variants two and three for spans 20 , 30 and 40 m in **Fig.7**, it is noticed that for each variant the unit area weight increasing as parabolic and the rate of increasing for variant three is more than of variant two. Variant two has lower rate compared with variant three.

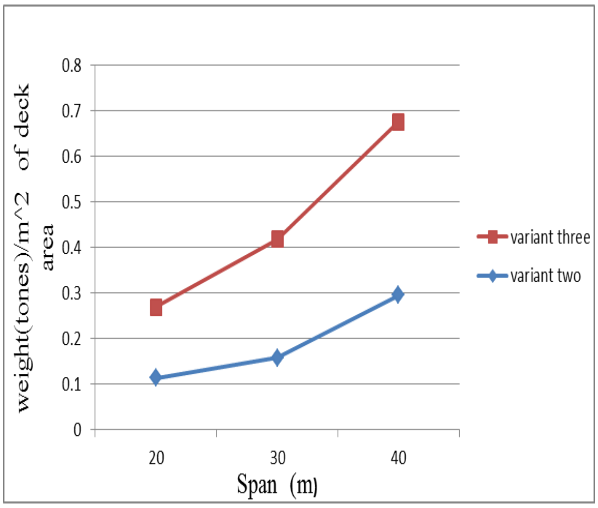

Fig.8: Weight versus Span for Variant Two and Three

VIII. CONCLUSIONS

This paper mainly gives a comparison between three variants (1-steel girders and RC deck,2- aluminum girders and aluminum deck , 3-steel girders and aluminum deck). 3D numerical models using SAP2000 were used to get design requirements. Designs according to (AASHTO LRFD 2012) was performed and several conclusions are obtained as Following:

- Aluminum has a good history for bridge girders and bridge decks.
- Number of modern codes and standards facilitate the design of aluminum vehicular bridges.
- Replacing concrete slab with aluminum one leads to

big saving in total weight by about 75% which leads to increase live load capacity and save in foundations.

- Using aluminum girders and aluminum deck leads to save 25% in total weight compared with bridges composed of steel girders and aluminum deck.
- Using aluminum girders and aluminum deck leads to save 81% in total weight compared with bridges composed of steel girders and concrete deck.
- Total cost of bridges composed of aluminum deck and aluminum girders is about 58% of that composed of steel girders and aluminum deck.
- Total cost of bridges composed of aluminum deck and steel girders is about 52% of that composed of steel girders and concrete deck
- Total cost of bridges composed of aluminum deck and aluminum girders increases by 11% that of aluminum deck and steel girders.
- Deflection governs the design for the three variants.
- Bridges composed of aluminum deck and aluminum girders weighing 0.77, 0.66 and 0.62 of the weight of aluminum deck and steel girders for spans 20, 30 and 40m respectively.
- Aluminum girders has lower weight to span ratio than steel ones.
- If the comparisons are made based on life-cycle costs, aluminum girders is a good competitor for steel ones because of its excellent corrosion resistance.

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