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Optimum Design of Cable Stayed Bridges Due to a Various of Loads

Youssef Agag[1], Mohamed Abou El-Saad[2], Mohamed El-Madawy[3], Mohamed El-Saman[4]

[1,2]Prof. of Structural Engineering Department, Mansoura University, Faculty of Engineering, Mansoura, Egypt
naguib2005[at]yahoo.com
[3]Dr. of Structural Engineering Department, Mansoura University, Faculty of Engineering, Mansoura, Egypt
m_tantawy77[at]yahoo.com
[4]Mansoura University, Department of Structural Engineering, M. Sc. In civil Engineering, Mansoura, Egypt
m.el_saman[at]yahoo.com

Abstract: ***This research includes the optimal design of cable stayed bridges using the Parameter Space Investigation (PSI) method combined with LPτ generator and the corresponding finite element program for design cable stayed bridge that meets the requirements of AISC "American Institute of Steel Construction" under the terms of strength, general and local buckling and develop a procedure for making optimal decisions on the Pareto set. The main research objective is to decrease the weight and the cost of bridge construction. Also, derive a main program to accelerate automation of calculations based on modern Finite Element software products. The study includes a comparison between four types of longitudinal ribs used in orthotropic steel deck. Many factors affect the optimization of bridges are taken into considerations. it was the number of ribs and floor beams, variations of rib thicknesses and floor beams, steel plate thickness and pylon thickness. The static analysis for each case due to self-weight of bridge elements and equivalent uniform traffic loads is carried out.***

Keywords: Cable-Stayed Bridge, Finite Element, Orthotropic bridges, Pareto set, parameter space investigation (PSI) method

1. Introduction

Cable-stayed bridges have become very common in recent decades compared to suspended bridges, because of the aesthetic appearance, efficient use of structural materials, low design and maintenance costs. In the case of long spans, the orthotropic steel decks are incorporated with the bridge to reduce the total dead load carried by the main superstructure elements and substructure.

Construction of modern large spans cable-stayed bridges would be unthinkable without the use of steel orthotropic deck, which need today for bridge construction using lighter structures. In the modern bridges are used not only simple open orthotropic plate, but as complex closed orthotropic plate. During operating these structures are exposed to various types of loads (permanent and temporary loads).

The main goal of optimal design of cable-stayed bridges is to reduce the weight and cost of the bridge. In general, there are many parameters should be considered when designing cable-stayed bridges including pylon height, the length of the stay cables, the arrangement of stay cables and the type of deck. For optimal design, it's necessary to create software tools that enable designers to browse a variety of solutions and choose the best, guided by a number of restrictions. [1]

A design program is prepared by connecting to finite element program (CSI-Bridge Software) [2], which has the ability to analyze many cases of the cable-stayed bridge and give the results in excel sheet. Then the results are subject to a set of constraints to get the optimal solution. This program is called as “CBridge 2017”.

2. Description of Bridge Model

All the studied bridges have an interior span of 300 m, length and two equal exterior spans of 150 m each. Which are symmetric and composed of three major elements: steel deck, two concrete pylons, and the cables [3].

The deck was taken as steel orthotropic plate with open and closed ribs. It is assumed that the deck has two traffic lanes. The total width of the steel deck is B = 10 m. The spacing between ribs, a, ranges between 0.3 to 0.4 m. Also, the spacing, s, between floor beams has a range of (1.5 - 3.5) m for open ribs. Similarly, for closed ribs, the spacing, a, between ribs is ranging (0.6 - 0.7) m, and the floor beams spacing, S, ranges between (2 - 4.5) m.

In order to take into account, the influence of rib type as shown in **Figure1-II**. The considered rib types are:

a) The open type ribs which are used in the model as inverted tee cross section. The rib height (h_R), web thickness (t_{WR}), flange width (b_{FR}) and flange thickness (t_{FR}) are considered as the design variables of rib dimensions for case (**A**).

b) The open type ribs which are used in the model as angle cross section. The rib height (h_R), web thickness (t_{WR}), leg width (b_{LR}) and leg thickness (t_{LR}) are considered as the design variables of rib dimensions for case (**B**).

c) The open type ribs which are used in the model as flat cross section. The rib height (h_R) and web thickness (t_{WR}) are considered as the design variables of rib dimensions for case (**C**).

d) The closed type ribs which are used in the model as trapezoidal cross section. The rib height (h_R), rib thickness

(t_R) and top width (b_{TR}) are considered as the design variables of rib dimensions for case (**D**).

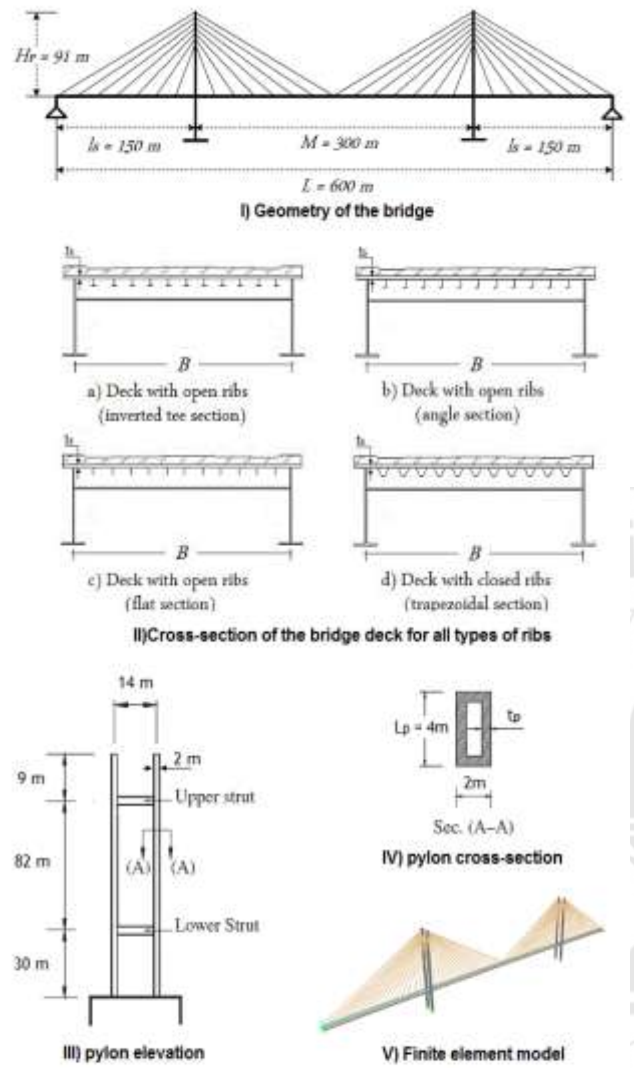

Figure 1: The geometry of cable-stayed bridge, and cross sections

The concrete pylons are designed as hollow rectangular cross section, the dimensions of the pylon cross section are L_P = 4 m, B_P = 2 m and pylon thickness (t_P) is considered as the design variable. It is assumed that the pylons are fixed at supports and its height (H_P) relative to the mid span of the bridge which (H/L) of 0.3 (H_P = 91 m). The upper and lower strut cross section dimensions of 2.5*2.5 m.

A two plane of cables was arranged in a semi-fan system. It was considered to be the best arrangement for long span cable stayed bridges by Sarhang [4]. The cables connected by the pylon distributed at equal distance with total of 8m has also equally distributed at floor beams Related to the deck.

The number of cables at one side of pylon for each plane varies between 14 and 16. The cables used in model are galfan coated steel full locked strand type vvs-3 and the initial tension is about 0.15 of the breaking load. The properties of cables and other materials properties used in the bridge model are given in Table 1.

Table 1: The properties of materials used in the bridge model

Materials	Parameter	Properties
Steel	Unit weight (γs)	7.85 t/m^3
	Modulus of elasticity (Es)	2100 t/cm^2
	Poisons ratio (υs)	0.3
	Yield strength (Fy)	3.6 t/cm^2
Concrete	Unit weight (γc)	2.5 t/m^3
	Compressive strength (fc)	3569 t/m^2
	Modulus of elasticity (Ec)	245.75 t/cm^2
	Poisons ratio (υc)	0.2
Cables	Modulus of elasticity (Esc)	1700 t/cm^2
	Dimeter (d)	14 cm
	Metallic area	0.0139 m^2
	Weight	0.1129 t/m
	Breaking load	1236.83 ton
Asphalt	Unit weight (γ)	2.3 t/m^3
	Thickness	0.11 m
Water proofing layer	Unit weight (γ)	1.8 t/m^3
	Thickness	0.01 m

The static analysis for each case is carried out due to self-weight of bridge elements and equivalent uniform traffic loads.

3. Formulation of the Optimization Problem

The main stages in the solution of the optimization problem structure, optimal solutions are sought on the admissible set solutions that must meet all the requirements on the construction, stress and deflection limitations.

3.1 Parameter Variables

The parameter variables describe dimensions of cross section for bridge elements and the geometric configuration for cable stayed bridge as follows:

-N_C is the number of cables at one side of pylon for each single plane based on the spacing between cables and the spacing between floor beams.

-Nr is the number of longitudinal ribs based on the rib spacing.

-Nx is the number of floor beams based on the floor beams spacing.

-Main girder dimension: height ($\mathbf{h_M}$), web thickness ($\mathbf{t_{WM}}$), flange width ($\mathbf{b_{FM}}$), and flange thickness ($\mathbf{t_{FM}}$).

-Floor beams dimension: height ($\mathbf{h_X}$), web thickness ($\mathbf{t_{WX}}$), flange width ($\mathbf{b_{FX}}$), and flange thickness ($\mathbf{t_{FX}}$).

-ts is the thickness of steel plate in orthotropic deck.

-tp is the thickness of H-shaped pylon.

-Rib dimension: height ($\mathbf{h_R}$), web thickness ($\mathbf{t_{WR}}$), flange width ($\mathbf{b_{FR}}$), and flange thickness ($\mathbf{t_{FR}}$) in case using inverted tee section as in **Figure 2**.

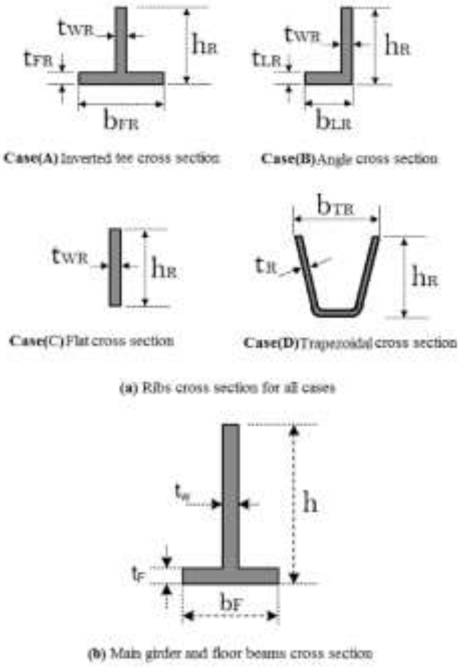

Figure 2: The parameter variables of cross section

3.2 Lower and Upper Bounds for Parameter Variables

In this study, the limitations of parameters are taken from previous studies on cable stayed bridges taking into account the limitations of parameters as stated in AISC [5] design manual for orthotropic deck bridges.

Table 2: The lower and upper limits for common parameter variables in all cases

Case	Parameters	Upper limit	Lower limit
All cases	N_C	16	14
	h_M	2.5 m	1 m
	t_{WM}	0.022 m	0.01 m
	b_{FM}	0.6 m	0.4 m
	t_{FM}	0.025 m	0.012 m
	h_X	0.8 m	0.6 m
	t_{WX}	0.012 m	0.008 m
	b_{FX}	0.3 m	0.2 m
	t_{FX}	0.014 m	0.01 m
	ts	0.022 m	0.014 m
	tp	0.6 m	0.4 m
Case (A)	**Nr**	31	23
	Nx	401	171
	h_R	0.3 m	0.1 m
	t_{WR}	0.01 m	0.007 m
	b_{FR}	0.12 m	0.06 m
	t_{FR}	0.01 m	0.007 m
Case (B)	**Nr**	31	23
	Nx	401	171
	h_R	0.3 m	0.1 m
	t_{WR}	0.01 m	0.007 m
	b_{LR}	0.1 m	0.04 m
	t_{LR}	0.01 m	0.007 m
Case (C)	**Nr**	31	23
	Nx	401	171
	h_R	0.3 m	0.1 m
	t_{WR}	0.01 m	0.007 m
Case (D)	**Nr**	16	12
	Nx	241	133
	h_R	0.35	0.2
	t_R	0.012	0.008
	b_{TR}	0.38	0.29

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3.3 Automation of Calculation and Design Procedures

In the process of automating calculations and further design optimization, you need to create FE-model for each combination of parameters by a script-language program. the acceleration of the parametric analysis allows you to explore the influence of various parameters on the structure, the sequence of steps is summarized as:

1. Assigning the design variable parameters.
2. Generation of combinations using LPτ – sequence generator by the excel sheet.
3. The design variable table obtained is transferred to external software (the present program) to run analysis of bridge model by CSiBridge [2].
4. Export the obtained results to MS Excel. Next the results obtained are checked according to AISC [5] requirements.
5. Recording results for all the combinations in Excel table with section properties.
6. Check stresses and deflection on the results to obtain the table of acceptable values.
7. Make a trade-off between acceptable values to get the best values.

3.4 Design Constraints

The selection of the design constraints functions based on the AISC [5] code. The constraint for each components of cable-stayed bridge can be written as follows:

3.4.1 Stay Cables

The stay cables resist only axial tensile forces. Therefore, the following conditions have to be written as follows:

$$T_{m\ cable} - 0.25T_{b\ cable} \leq 0 \quad (1)$$

Where $T_{m\ cable}$ is the maximum tensile force in the stay cables , $T_{b\ cable}$ is the breaking force of the stay cables.

3.4.2 Orthotropic Steel Deck

(a) Check Slenderness Coefficient C_s for Longitudinal Ribs

- For Flat Rib

$$C_s = \frac{d}{15t_w} + \frac{a}{12t_s} \quad (2)$$

- For Tee or Angle

$$C_s = \frac{d}{1.35t_w + 0.56r_y} + \frac{a}{12t_s} \quad (3)$$

Where:

$$-C_s \leq \left\{ \frac{0.4}{\sqrt{fy/E}} \right\} \quad for \quad f_{\max .comp} \geq 0.5Fy$$

$$-C_s \leq \left\{ \frac{0.65}{\sqrt{fy/E}} \right\} \quad for \quad f_{\max .comp} \leq 0.5Fy$$

- d : rib depth, a: spacing of ribs, t_w: rib thickness as in **Figure 3**.

- r_y : radius of gyration of ribs about axis normal to plate without the effective width of plate.

- ts : plate thickness.

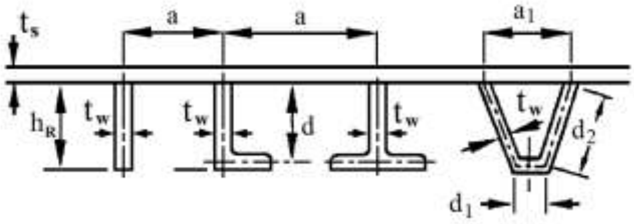

Figure 3: The geometry of longitudinal ribs

(b) Bending Stresses in Longitudinal Ribs and in Transverse Beams

$$f_{b\ rib} + f_{b\ floor\ beams} \leq 0.55Fy * 1.25 \quad (4)$$

Where:

- $f_{b\ rib} \leq 0.55Fy$, $f_{b\ floor\ beams} \leq 0.55Fy$.

- $f_{b\ rib}$: bending stresses in longitudinal ribs.
- $f_{b\ floor\ beams}$: bending stresses of the floor beams.

(c) Check on Stress Superposition " System I+II "

(1) <u>Case of maximum compression stress at maximum positive moment of main girder:</u>

$$f'_{bc} + f''_{bc} \leq f_{all} \quad (5)$$

f'_{bc} : compression stress in main girder at lower fibers of ribs due to maximum positive moment "system I".
f''_{bc} : compression stress at lower fibers of longitudinal ribs due to negative moment "system II".

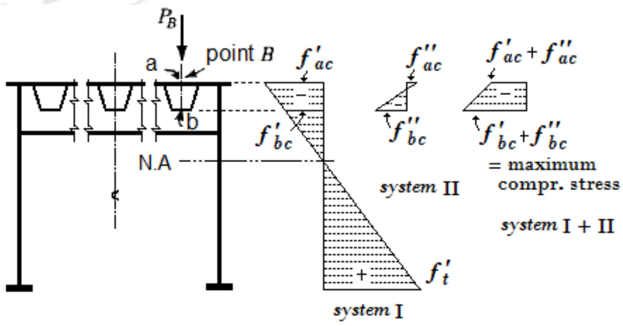

Figure 4: Case of maximum compression stress

(2) <u>Case of maximum tension stress at maximum negative moment of main girder:</u>

$$f'_{bt} + f''_{bt} \leq f_{all} \quad (6)$$

f'_{bt} : tension stress in main girder at lower fibers of ribs due to max negative moment "system I".
f''_{bt} : tension stress at lower fibers of longitudinal ribs due to positive moment "system II".
f_{all} : Allowable stress according AISC [5] specification.

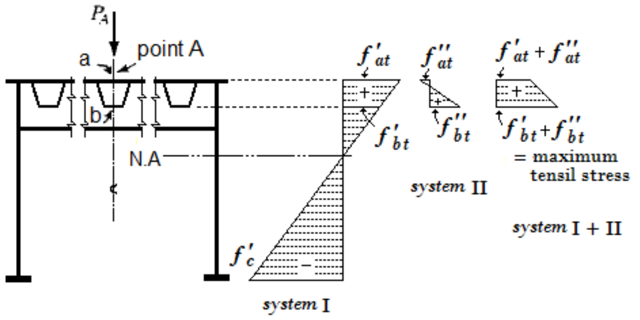

Figure 5: Case of maximum tension stress

3.4.3 Check deflection

$$\delta \leq \frac{L}{1000} \quad (7)$$

Where:

- δ : Maximum deflection at mid span of the bridge due to live load including impact.
- L : The span of interior panel of the bridge

4. Output Results

A five hundred combination trails are tested for four types of ribs. The obtained results are optimized to obtain the pareto optimal set. All four considered cases are summarized as:

1- **case A**, which has inverted tee ribs, the five hundred combination trails are filtered to 129 combination trails satisfying all design constraints. An eight pareto optimal solutions are determined and recorded in **figure 6**. The preference is given to solution having a series number of 105, that has the minimum self-weight with limited allowable required deflection.

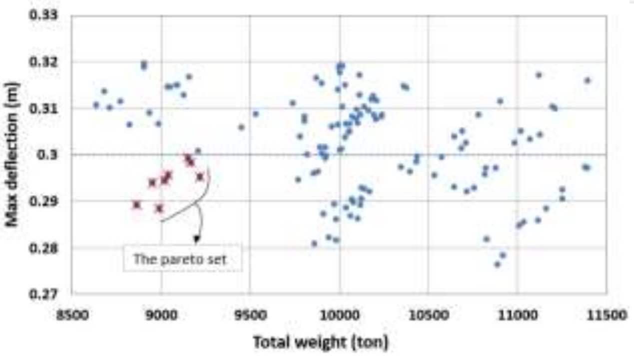

Figure 6: Relation between total weight and maximum deflection for case A, with tee ribs

2- **case B**, which contains an angle cross section ribs (open type), the 500 combinations are decreased to 114 only, these satisfied all design requirements. A six pareto optimal solutions are drawn in **figure 7**. The preference is given with solution titled of number of 364, which having a minimum self-weight.

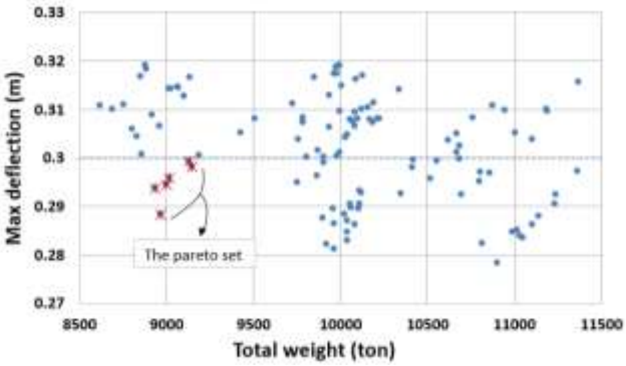

Figure 7: Relation between total weight and maximum deflection for case B, with angle ribs

3- **case C**, which has flat ribs, the five hundred combination trails are filtered to 64 combination trails satisfying all design constraints. A two pareto optimal solutions are determined and recorded in **figure 8**. The preference is given to solution having a series number of 169, that has the minimum self-weight with limited allowable required deflection.

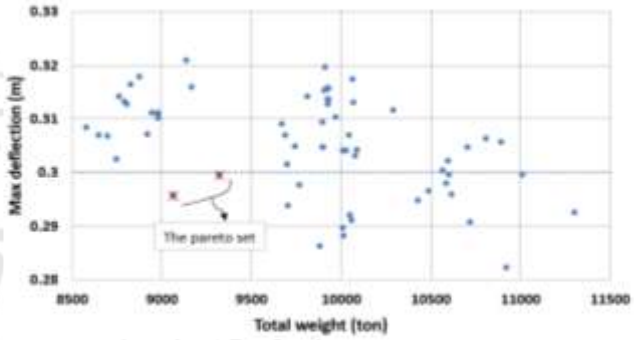

Figure 8: Relation between total weight and maximum deflection for case C, with flat ribs.

4- **case D**, which contains a trapezoidal cross section (closed type), the 500 combinations are decreased to 177 only, these satisfied all design requirements. A nine pareto optimal solutions are drawn in **figure 9**. The preference is given with solution titled of number of 212, which having a minimum self-weight.

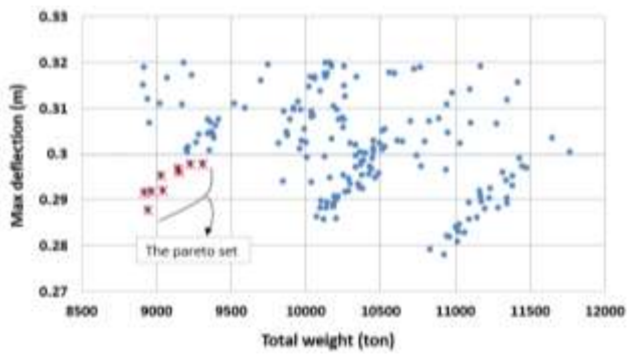

Figure 9: Relation between total weight and maximum deflection for case D, with trapezoidal ribs.

Table 3: The final values for the parameter variables used in all cases

arameters	Case A	Case B	Case C	Case D
Total weight (ton)	8861.164	8937.8	9064.93	8920.236
Maximum deflection (δ)	0.29	0.294	0.296	0.292
N_C	16	16	16	16
Nr	27	23	27	12
Nx	201	201	201	133
h_M	1.36	2.239	2.025	1.4277
t_{WM}	0.015	0.111	0.011	0.0125
b_{FM}	0.427	0.4426	0.4226	0.443
t_{FM}	0.0155	0.0164	0.0236	0.015
h_X	0.717	0.6347	0.7758	0.7867
t_{WX}	0.0097	0.0099	0.0113	0.009
b_{FX}	0.263	0.2197	0.2871	0.2332
t_{FX}	0.0117	0.0119	0.01395	0.0137
ts	0.016	0.014	0.018	0.016
tp	0.4	0.4	0.4	0.4
Rib dimension				
Tee ribs	**h_R**		0.1172	
	t_{WR}		0.00735	
	b_{FR}		0.0755	
	t_{FR}		0.00735	
Angle ribs	**h_R**		0.2425	
	t_{WR}		0.00894	
	b_{LR}		0.0875	
	t_{LR}		0.00894	
Flat ribs	**h_R**		0.1523	
	t_{WR}		0.0098	
Trapezoidal ribs	**h_R**		0.25	
	t_R		0.008	
	b_{TR}		0.31325	
	Bottom width		0.165	

The study also included the effect of the pylon thickness on total weight and maximum deflection at each number of cables used considering number of cables, N_C, **figure 10** to **figure 21** contains a significant case having the four cases with variable number of cables.

1- For the number of cables, N_C = 14

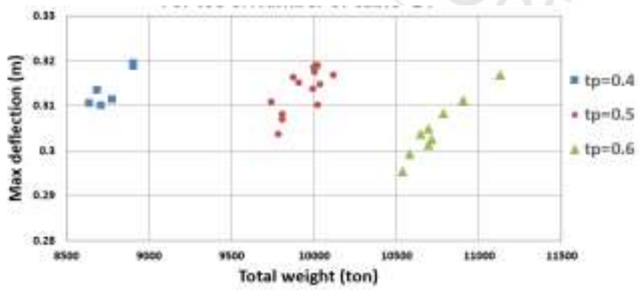

Figure 10: Case (A), with tee ribs.

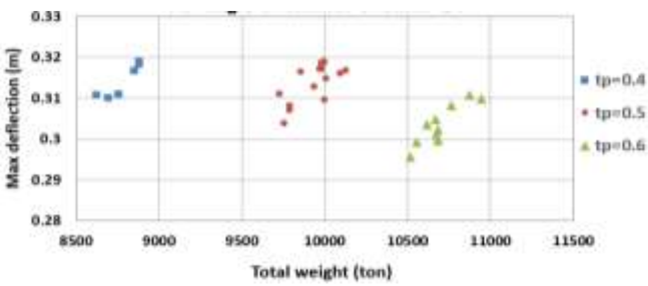

Figure 11: Case (B), with angle ribs.

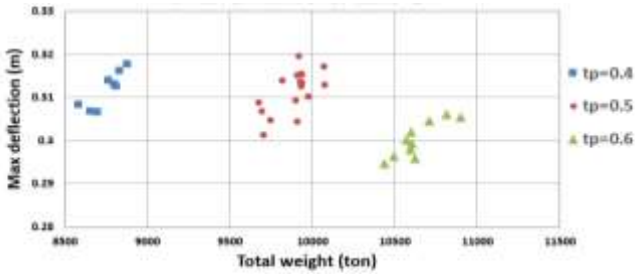

Figure 12: Case (C), with flat ribs.

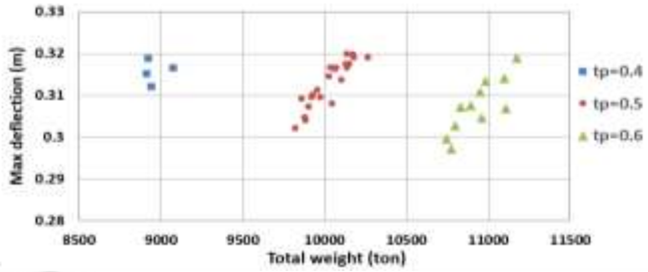

Figure 13: Case (D), with trapezoidal ribs.

2- For the number of cables, N_C = 15

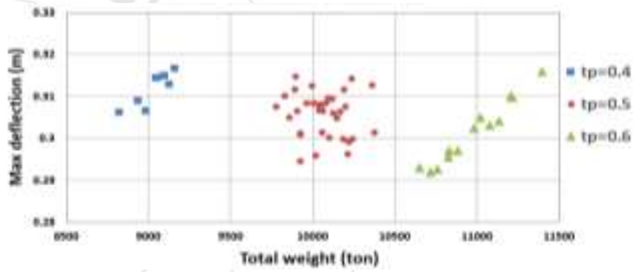

Figure 14: Case (A), with tee ribs.

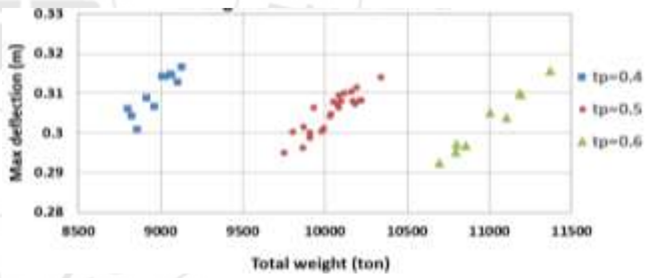

Figure 15: Case (B), with angle ribs.

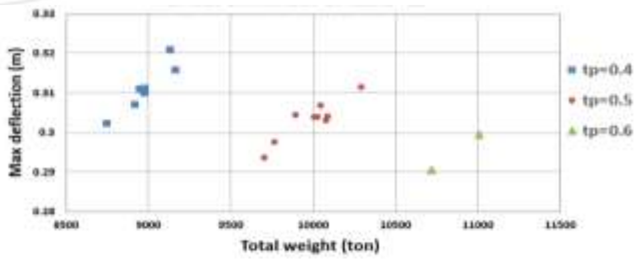

Figure 16: Case (C), with flat ribs.

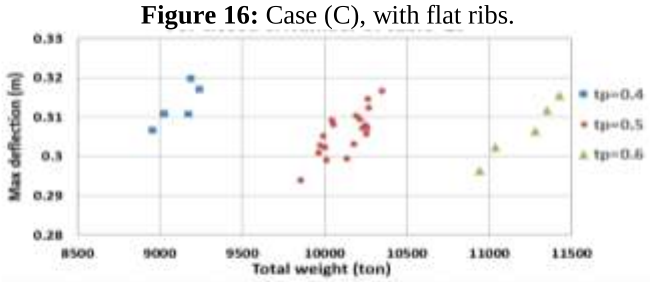

Figure 17: Case (D), with trapezoidal ribs.

3- For the number of cables, $N_C = 16$

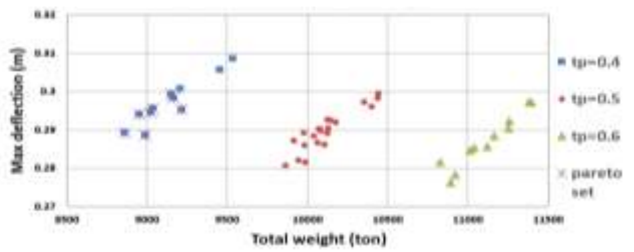

Figure 18: Case (A), with tee ribs.

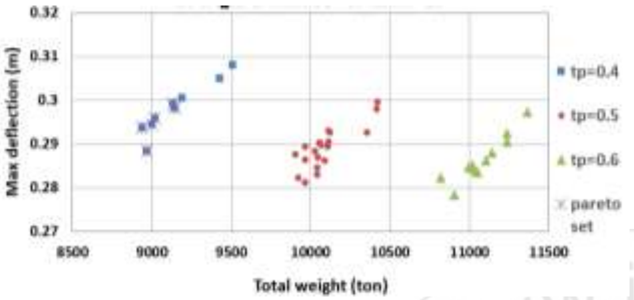

Figure 19: Case (B), with angle ribs.

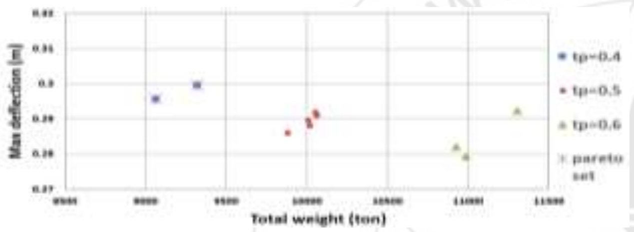

Figure 20: Case (C), with flat ribs.

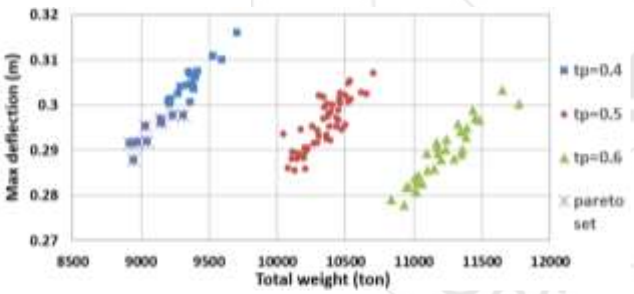

Figure 21: Case (D), with trapezoidal ribs.

From the previous graphs, the total weight increases significantly by increasing the pylon thickness and increasing the number of cables. By contrast, the maximum deflection decreases when pylon thickness and the number of cables increase.

5. Parametric Study on Flat Ribs

We have studied the effect of the most effective variables on the behavior of the bridge using a flat cross section type of rib. From the previous results, the pylon thickness has a significant effect on the deflection and total weight of the bridge and therefore the study will address the effect of the number of cables, number of floor beams and number of longitudinal rib on the following:

5.1 Deflection and Total Weight of the Bridge

The relation between total weight of the bridge and maximum deflection is recorded in **figure 22** for flat ribs. The obtained results showed that, an increasing of number of cables causes a decrease of maximum deflection, and increase the total weight.

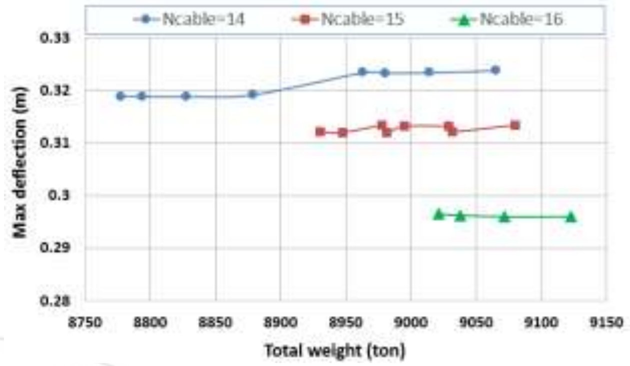

Figure 22: Total weight with maximum deflection

The effect of the number of ribs and floor beams on the total weight is recorded in **figure 23,** and **figure24** respectively. For each number of floor beams, increasing the number of ribs leads to the increase of total weight. But the effect of the number of floor beams on the total weight is related to the number of cables, increasing the number of floor beams at each number of cables causes the increase of total weight.

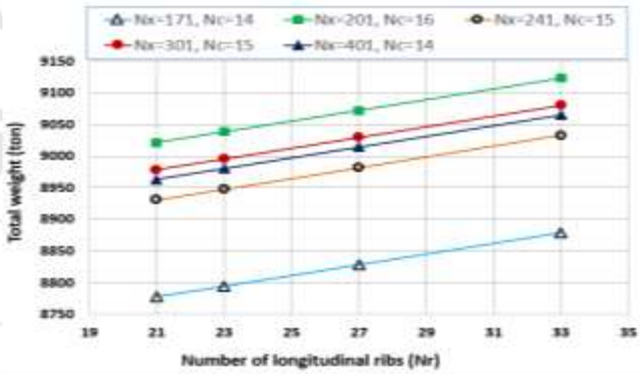

Figure 23: Total weight with number of ribs

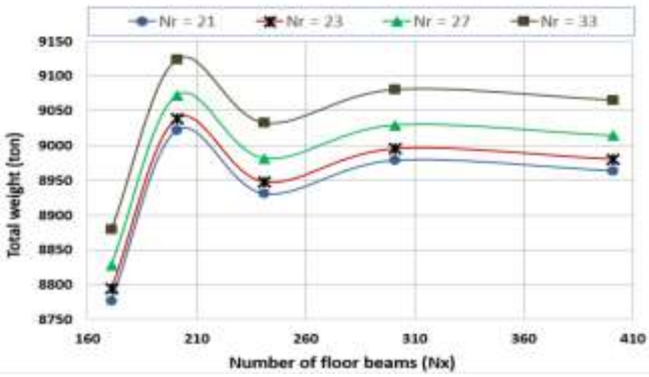

Figure 24: Total weight with number of floor beams

In addition, the effect of the number of ribs and floor beams on the maximum deflection is recorded in **figure 25,** and **figure26** respectively. For each number of floor beams, it is not noticeable the effect of the number of ribs on the maximum deflection. As mentioned earlier the effect of the number of floor beams is linked to the number of cables, increasing the number of floor beams at each number of cables leads to the increase of maximum deflection.

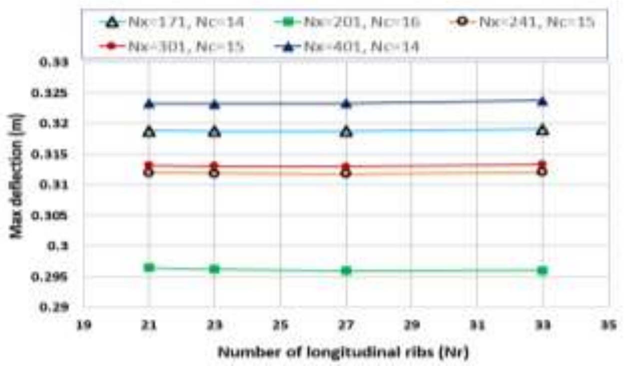

Figure 25: Maximum deflection with number of ribs

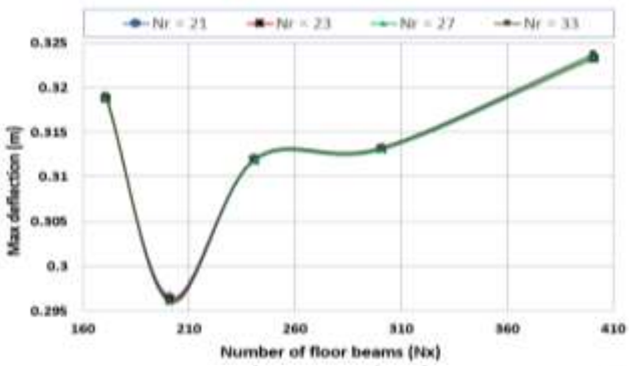

Figure 26: Maximum deflection with number of floor beams

5.2 Positive and Negative Moment of Main Girder

Figure 27 and **figure 28** contains the relation between number of ribs, number of floor beams with the positive moment in the main girder respectively. Increasing both the number of ribs and the number of floor beams cause a decrease of the positive moment in the main girder linked to the number of cables, which increases with increasing the number of cables.

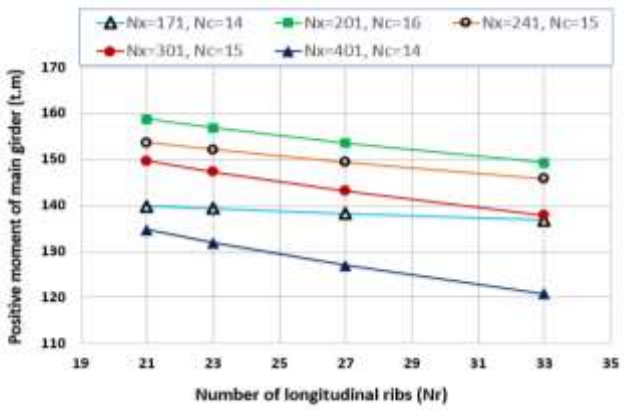

Figure 27: Moment of M.G (+) with number of ribs

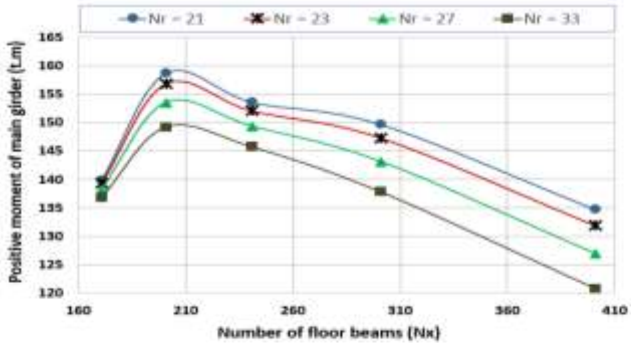

Figure 28: Moment of M.G (+) with number of floor beams

Also, the effect of the number of ribs and floor beams on the negative moment in the main girder at **figure 29,** and **figure 30** shows the increase of the negative moment in the main girder by increasing both the number of ribs and the number of floor beams, which linked to the number of cables, but depends clearly on the number of floor beams.

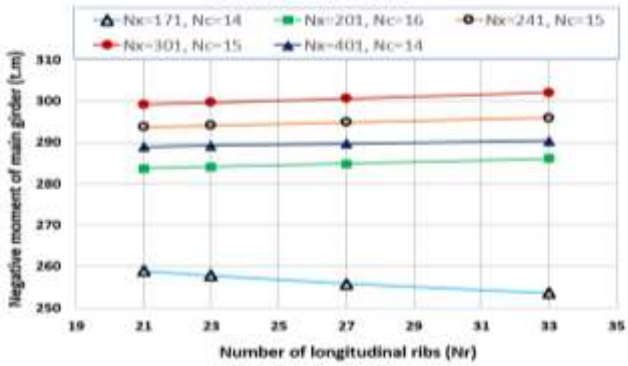

Figure 29: Moment of M.G (-) with number of ribs

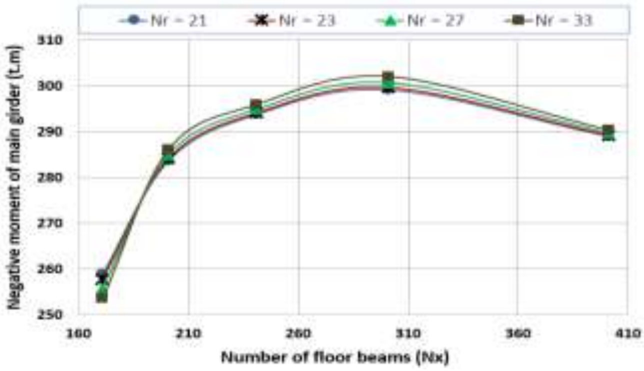

Figure 30: Moment of M.G (-) with number of floor beams

5.3 Moment of Floor Beams

The relations between number of cables, the number of floor beams and the moment in the floor beams are recorded in **figure 31,** and **figure 32** for flat ribs. For each number of cables, increasing both the number of ribs and the number of floor beams leads to the increase of the moment in the floor beams, but it decreases with increasing the number of ribs.

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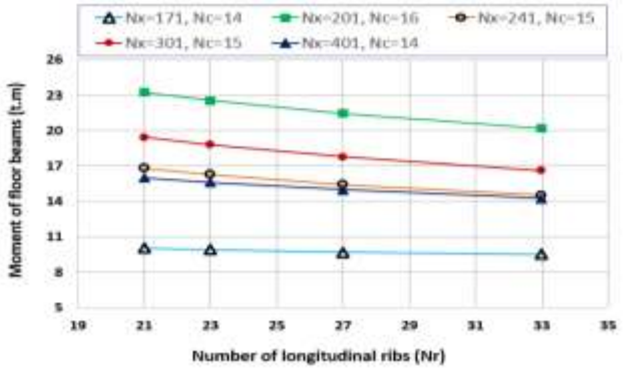

Figure 31: Moment of F.B with number of ribs

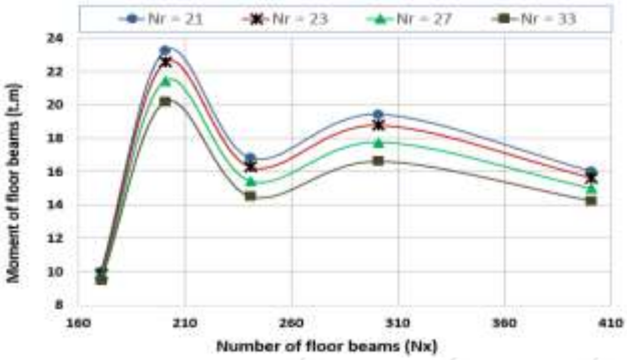

Figure 32: Moment of F.B with number of floor beams

5.4 Moment of pylon

The moment of pylon increases with increasing the number of ribs as in **figure 33** with constant number of floor beams. But decreases as the number of cables increases as in **figure 34**. For each number of cables, the moment of pylon decreases when increase the number of floor beams.

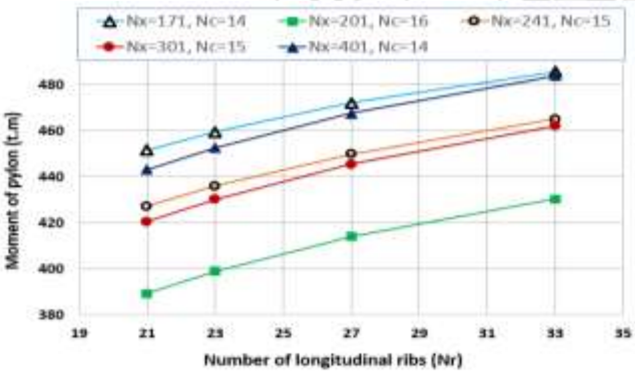

Figure 33: Moment of pylon with number of ribs

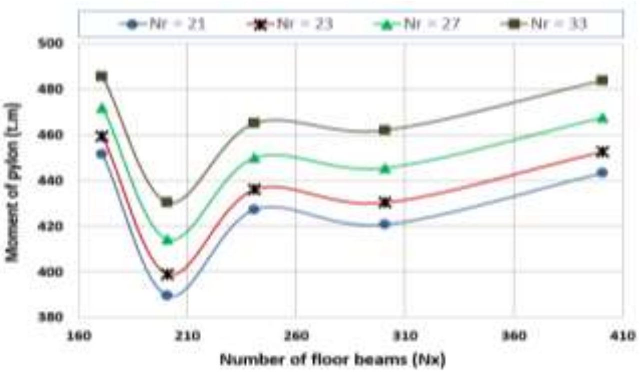

Figure 34: Moment of pylon with number of floor beams

5.5 Maximum forces in the stayed cables

The maximum forces in cables increases with increasing the number of ribs as in **figure 35** with constant number of floor beams. Also the maximum forces in cables increases with increasing number of floor beams as in **figure 36** with constant number of cables, but decreases with increasing number of cables.

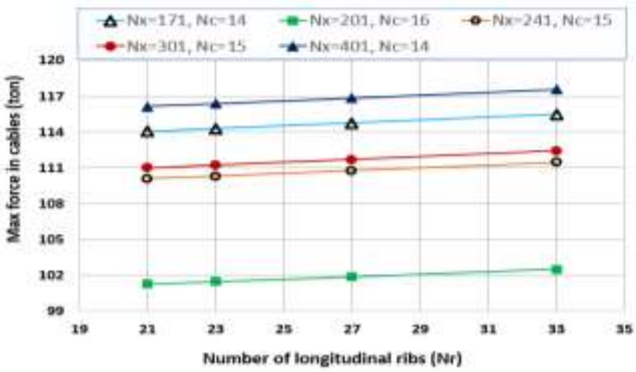

Figure 35: Maximum forces in cables with number of ribs

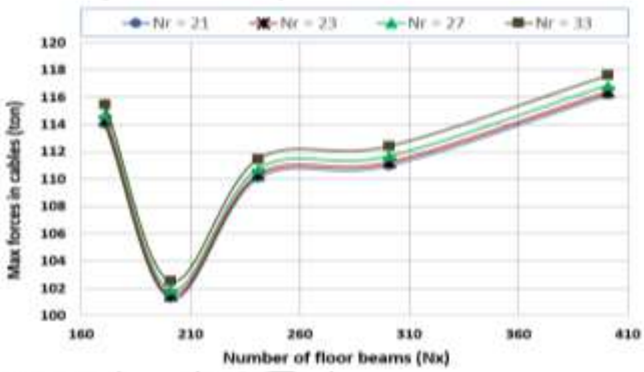

Figure 36: Maximum forces in cables with number of floor beams

6. Conclusion

- This study enables the designer how to deal with such types of bridges and decks. It is clear from the study that the optimal total weight of the bridge ranges from 8,500 to 9,500 tons with acceptable deflection values.
- The effect of the number of floor beams depends on the number of cables. When the number of cables is 14, the distance between the cables allows the number of floor beams to be 171 and 401.
- The preferred rib type is the closed shape, where it gave more results accepted. While the second one is the inverted tee cross section then angle cross section.

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