

# Span Increment Possibility of Self-Anchored Suspension Bridge

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**Abstract** - This paper aims to indicate the behavior of self-anchored suspension bridge (Pylon-Girder and Cables) for prestressed concrete girder type when the main span increases from 160 meters up to 500 meters while monitoring the impact of this increase on the bridge components, the increment process is done using scaling method as all of the bridge geometrical properties and components dimensional properties are selected relative to the bridge main span which allow for feasible comparison, bridge reference model has been selected in accordance of other bridges geometries which are implemented of the same type and initial calculation was done for the components cross sections to eliminate the possibility of selection errors and choose the most proper sections, the results clarify that the bridge components behavior under dead and live load is linear with increasing the span which mean that the validated dimensions proved to be efficient, the prestressing system is important in order to control the stresses at girder and keep them at allowable range which indicated the difficulty of reaching this limit of spans using a reinforced concrete girder.

**Keywords:** Self-Anchored Suspension Bridge, Scaling Method, Reference model, Validation, prestressed.

## I. INTRODUCTION

The construction of suspension bridges spread out all over the world as this type achieve to reach large spans which weren't accessible before, however with reviewing the suspension bridges that have been implemented, we will see that the conventional suspension type (earth anchored) has been adopted almost entirely when it require having large spans which is reflected at the large number of earth anchored type compared to self-anchored type.

John A. Ochsendorf, David P. Billington [2] review the self-anchored suspension bridge future development and outline the advantage and disadvantage of this bridge type, a comparison between results for deflection and bending

moment by analysis using the deflection theory and the FEM is also illustrated.

The self-anchored bridge type analysis has a main difference from the bridge boundaries as the main cable is anchored directly to the bridge deck which expose the deck to the forces analyzed from the cable tension force (up lift component and compression component), both of these force shall be considered at the self-anchored analysis unlike the conventional type which uses external system (anchorage system) to transfer the cable forces completely outside the bridge system with no effect on the bridge deck.

David van Goolen [3] has studied the possibility of increasing the self-anchored suspension bridge span for steel material composing the main bridge components, the effect of construction methodology in determining the span limit also was studied.

Wenliang Qiu<sup>1\*</sup>, Meng Jiang<sup>1</sup> and Zhe Zhang<sup>1</sup> [4] tried to determine a formula for the maximum span limit according to the materials properties and sag to span ratio which are considered to identify the bridge parameters.

The effect of fixing the cables to the deck isn't just limited to the need to study the impact of these components on the deck section but also it causes a fundamental change to the method of construction.

This paper will review the results of self-anchored bridges after the construction stage for both dead and live loads with taking the cables pretensioning into consideration.

The reference model geometrical properties was chosen in the light of implemented cable stayed bridge called "4 de April" which is located at Catumbela -Angola and the purpose of choosing that bridge is that its properties were almost identical to the required reference model with the necessary change required to correspond the nature of the structure and also to give other researchers the ability to use these results to make a comparison between using these two

different types on the level of (ease of construction-economical level).

**a) Theory of analysis**

Two theories have been followed on the analysis process of the self-anchored suspension bridge over years which are the elastic theory and the deflection theory and these theories take into consideration the following assumption.

- 1) The loads are distributed uniformly on the bridge deck
- 2) The tension loads of the hangers considered as uniform load
- 3) The dead load is completely transferred to the cables

**Elastic Theory**

This theory gives the moment of girder at any point through the equation no (1).

$$M = M^{\setminus} - HY \quad \text{EQ(1)}$$

Where:-

$M^{\setminus}$  → Live load component moment of unsuspended girder

$H$  → Horizontal component of cable tension occur due to live load

$Y$  → Ordinate of main span cable

This is the original theory for analyzing these type of bridges which consider that the loads acting on the bridge is distributed between both of the cables and girder.

**Deflection Theory**

This theory could be considered as an extension of the elastic theory as it take into consideration the moment occur due to the deflection of the main cable due to live load so it reduced the moment in the girder by another amount , the moment in the girder given by the equation no (2).

$$M = M^{\setminus} - HY - (H + h)v \quad \text{EQ (2)}$$

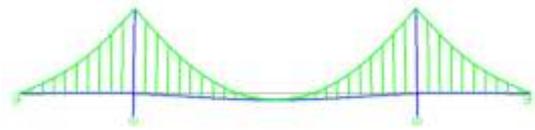
Where:-

$H + h$  → Horizontal components of the cable tension occur due to live load and dead load

$v$  → The deflection occur to the bridge

The equation above is the equation which may be used for the conventional suspension bridge so for the self-anchored type a little modification should take place as follow

$$M = M^{\setminus} - HY - (H + h)v + (H + h)v \quad \text{EQ (3)}$$



**Figure 1: Effect of the Axial Force at the Girder Deflection**

The last additional term has been added as a result of the acting compression force at the deck which cause additional moment at the girder and as per shown at figure (1).

Equation (3) is equal the original elastic theory which allow engineers to use the elastic theory for the self-anchored bridge analysis.

The simple elastic theory may be used for self-anchored suspension bridge with spans up to 200 meters but for larger spans the deflection theory give more precise results, and using nonlinear finite element model is far better.

**b) Reference Model Properties**

The material and specification of each of the bridge component shall be sufficient for achieving the structure requirements.

**Girder**

Prestressed concrete box girder is selected for this study as per figure (2).



**Figure 2: Concrete Box Girder Cross Section**

**Pylon**

Reinforced concrete square cross section will be considered for the pylon section.

Table (1) indicates the mechanical properties for both of the girder and the pylon.

**TABLE 1  
Mechanical Properties of Concrete**

<b>Concrete Description</b>	C 35/45
<b>Concrete Density</b>	25 KN/m <sup>3</sup>
<b>Compressive Strength (Cube)</b>	45 N/mm <sup>2</sup>
<b>Young's Modulus, E</b>	29500 N/mm <sup>2</sup>
<b>Passion Ratio, v</b>	0.20
<b>Shear Modulus, G</b>	12300 N/mm <sup>2</sup>

**Cables**

For both of the main cable and the hangers parallel bundled wires is been used for the cables material.

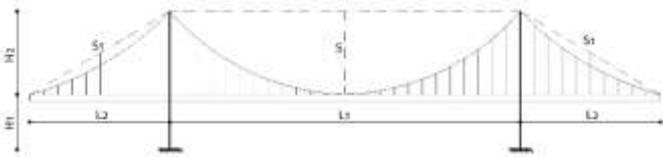
Table (2) clarifies the mechanical properties of the cables (main cable & hangers).

**TABLE 2**  
**Mechanical Properties of Cable Steel**

Cable Description	Parallel bundled wires
Steel Density	78.50 KN/m <sup>3</sup>
Yield Strength	1180 N/mm <sup>2</sup>
Tensile Strength	1770 N/mm <sup>2</sup> (High Strength Steel Wires)
Modulus of Elasticity	205000 N/mm <sup>2</sup>

For the purpose of scaling, reference model shall be identified and ensure its validation for ultimate (Resistance-Shear-Torsion) and serviceability (stress-deformation-stability) limit states.

Figure (3) shows the bridge geometrical properties which will be scaled with the same ratios at all of the scaling models.



**Figure 3: Reference Model Geometrical Properties**

Table (3) illustrates the indicated reference model geometrical and dimensional properties which have been valid for Euro Code validation criteria [13] → [21].

**TABLE 3**  
**Reference Model Properties**

Properties	Self-Anchored Bridge
Main Span (L1)	160 m
Side Span (L2)	64 m
Clear Height (H1)	10.10 m
Pylon Height (H2)	38 m
Main Span Sag (S)	38 m
Side Span Sag (S1)	6.08 m
Carriage Way Width	24.50 m
Pylon Dimensions	2.00*2.00 m
Girder Depth	2.28 m
Main Cable Diameter	240 mm
Hanger Diameter	55 mm

The indicated properties at table (1) are the validated properties of reference model which were chosen according to a full parametric study which showed that these properties are

the optimum dimension based on the components material and characteristics.

**II. MODELS GEOMETRICAL PROPERTIES**

As the reference model properties succeeded to be verified so following the same values and ratio should lead to another acceptable value as long as the bridge has a linear behavior.

- Bridge Width (Fixed =24.5 meters)

The bridge width of the bridge will be kept fixed on 24.5 meters as it was indicated on the carriageway requirement.

The fixation of the bridge width will make the increment of loads due to the span increase only without additional loads on the bridge section regarding bridge width.

- Slenderness Ratio ( $\lambda = \frac{1}{70}$ )

The girder height was determined by a ratio between it and the span length, so this ratio will remain constant to avoid any influence on the behavior of the girder.

- Sag to Main Span Ratio ( $\frac{1}{4.2}$ )

As the sag mainly controls the determination of the value of the bridge angles as well as the value of the horizontal component acting on the girder so the ratio indicated will be adopted.

- Side Span to Main Span ( $\frac{1}{2.5}$ )

The side span length according to the main span should be considered to ensure that the girder is not affected by the possible change in the level of axial force or bending moment diagram.

Failure to maintain this ratio may cause changes to the girder behavior especially at the different loading cases.

- Hangers Spacing to Main Span ( $\frac{1}{25}$ )

The hangers spacing affecting the behavior of transferring the loads from the bridge deck to the main cable.

Maintaining this ratio will avoid the girder from the exposing to additional deformation and bending moment.

- Pylon Height

The pylon height was determined based on the sag to span ratio so with increasing the span the sag will be increased with the same ratio which will lead to increase in pylon height as

well. The increase in the pylon height will appear on the height of the above deck only with maintaining the pylon height above the channel (under deck) as 10.1 meters.

- Pylon Dimension to Main Span ( $\frac{1}{80}$ )

The increase of bridge span will lead normally to other increases, including horizontal and vertical cable components which will be carried by at the top of the pylon so this ratio will prevent any deviation of the stress exposed to the pylon due to the increase of the vertical component.

- Main Cable to Main Span ( $\frac{3}{2}$ )

As calculating the horizontal component of tension in the main cable could be done through equation with the main span length so the increase of the span will have a major effect on increasing the tension force in the main cable. The area of the cable shall be increased based on the same increase on the span to maintain the stress limit in the cable and the load distribution ratio between cable and girder.

- Hangers to Main Span ( $\frac{11}{32}$ )

The hanger spacing to main span will be a fixed ratio which will display the hangers to additional loads from the deck weight. The hangers diameter shall be increased with the same ratio for different models to ensure the ability of the hangers for transferring the loads from deck surface to the main cable.

- Total Prestressing Force to Main Span ( $\frac{60000}{160}$ ) = 375

The prestressing force has to be relative to the span length so as it is included at the analysis of the models so it should be indicated in relative to the bridge span as other bridge properties.

The main properties for different self-anchored bridges models are illustrated at table (4).

**TABLE 4**  
**Bridges Models Main Properties**

Main Span(m)	Side Span(m)	Sag(m)	Hangers Spacing(m)	Prestressed Force (KN)
160	64	38	6.40	60000
200	80	47.50	8	75000
250	100	59.375	10	93750
300	120	71.25	12	112500
350	140	83.125	14	131250
400	160	95	16	150000
450	180	106.875	18	168750
500	200	118.75	20	187500

### III. LOADING CASES

For the analysis of the bridge, the loads to be studied shall be identified taking into consideration the different traffic loading cases.

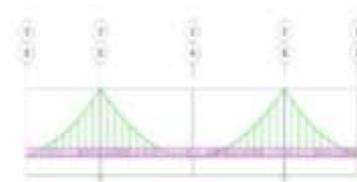
This study will take the following loads into consideration

1. Dead Loads (Self-Weight & Wearing Surface)
2. Live Loads ( Moving Trucks & Pedestrian)

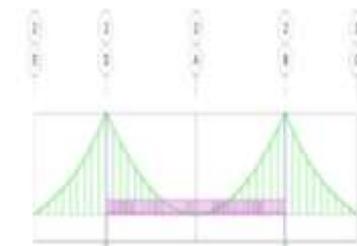
Knowing that the cables under pretensioning (dead loads completely transferred from the girder to the main cable) is the govern condition.

The prestressed system is considered at the girder according to the values at table (4) with taking anchorage losses, elastic, creep, shrinkage and steel relaxation at the modeling process.

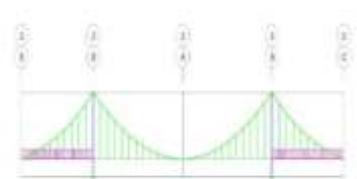
Figure (4) indicate the symmetrical possible traffic loading cases over the bridge longitudinal length.



“Full Loading Case” Live Loads distributed on the full width of the deck along the entire bridge length



“Main Span Loading Case” Live Loads distributed on the full width of the deck along the entire length of main span only



“Side Span Loading Case” Live Loads distributed on the full width of the deck along the entire length of side spans only

**Figure 4: Symmetrical Traffic Loading Cases**

Live loads along the full length of the bridge (case 1) are considered at the span increase study.

For validation process at least these three loading cases shall be considered for find out the worst loads at each of the verified section for any of the bridge components.

#### IV. RESULTS AND DISCUSSIONS

The spanning process results will be previewed using graphs for each of the bridge components individually in order to clarify the components behavior by the change occurring on its own in order to create a comprehensive view of the bridge as a whole unit.

During the modeling process the initial forces at cables is generated based on number of iterations considering a displacement of girder under permanent loads to reach the lowest value possible which express that all of the permanent loads is transferred as axial force at the bridge cables.

The comparison between initial main cable tension force at main span of manual calculations and computer model (CSI Bridge analysis) has been indicated at table (5).

TABLE 5

Comparison between Manual Calculations and Computer Model

Main Span (m)	Horizontal Force (KN)		Tension Force (KN)	
	Manual	Iteration	Manual	Iteration
160	14211.58	14360.85	19602.19	19348.03
200	20448.68	20699.25	28205.1	27878.53
250	29639.14	30023.60	40881.61	40498.06
300	40313.29	40891.30	55604.58	55211.84
350	53251.12	54070.17	73449.88	73064.72
400	67692.11	68809.66	93368.50	93037.62
450	84298.62	85813.52	116274.05	116090.90
500	102241.45	103987.70	141022.80	140744.40

The manual calculations of the main cable force were done based on the parabolic shape of the cable according to the following equations

$$H = \frac{wL^2}{8f} \text{EQ (4)}$$

$$V = \frac{wL}{2} \text{EQ (5)}$$

$$T = \sqrt{H^2 + V^2} \text{EQ (6)}$$

Where:-

$H \rightarrow$  Main cable horizontal component (Minimum tension force)

$V \rightarrow$  Vertical component of the main cable tension force

$T \rightarrow$  Maximum tension force at main cable

$w \rightarrow$  Dead Load (Self weight-Wearing Surface)

$L \rightarrow$  Bridge main span length

$f \rightarrow$  Sag at main span

The iteration process tried to reach the lowest values of bending moment and deflection of the girder as reducing these actions to zero isn't predictable.

#### Girder Preview

The girder properties for each of the models at different spans is given by table (6)

TABLE 6  
Girder Properties

Main Span (m)	Girder Height (m)	Web & Slab Thicknesses (mm)	Area (m <sup>2</sup> )	$I_x$ (m <sup>4</sup> )	$I_y$ (m <sup>4</sup> )
160	2.28	250	12.09	11.29	512.40
200	2.86	280	13.97	20.63	597.79
250	3.57	312.5	16.20	37.18	700.09
300	4.29	340	18.30	60.28	798.49
350	5.00	370	20.64	91.32	907.76
400	5.71	395	22.82	130.20	1011.08
450	6.43	420	25.10	179.40	1120.16
500	7.14	440	27.18	236.74	1220.71

#### a) Bending Moment

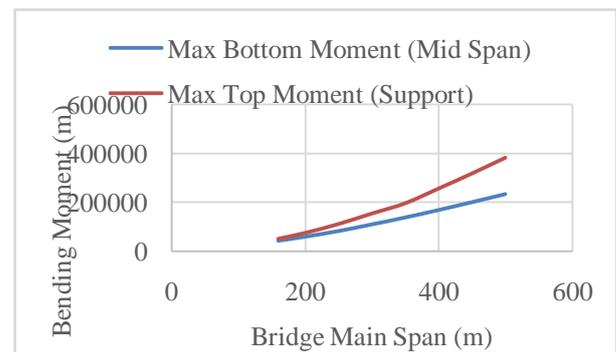
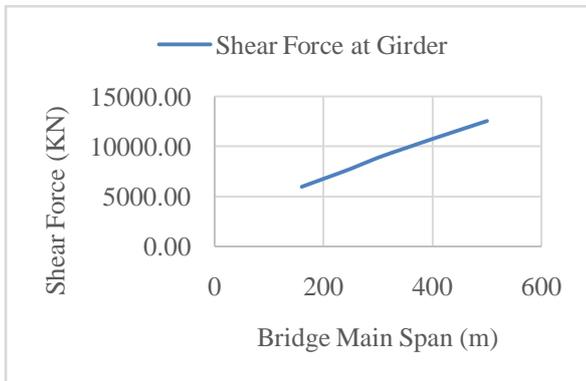


Figure 5: Bending Moment at Girder

The bending moment values at mid span showed a linear increase to the main span from span 160 to span 500 meters.

The bending moment at support considered as a linear increase divided into two parts from span 160 to span 350 the increase at moment happened but with limited values compared to the values from span 350 m to span 500 m.

**b) Shear Force**



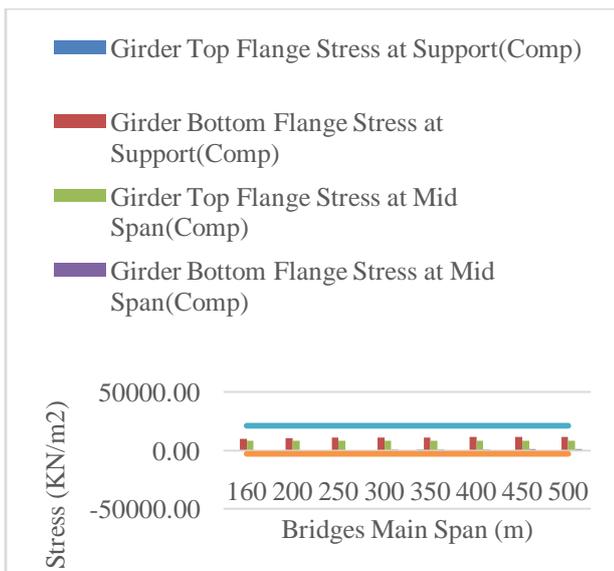
**Figure 6: Shear at Girder**

The shear force acting at the girder at support location is increasing linearly with increasing the bridge span.

Increasing the girder web is necessary in order to increasing the cross section shear resistance and also achieving requirement of shear reinforcements.

As the reference model has proved its efficiency to resist the shear it's expected that other bridges span will do so but at shear check a better resistance than the reference model was indicated due to the large increase in web thicknesses and cross section depth compared to the increase occurred to the acting shear on the girder.

**c) Stress at Flanges**



**Figure 7: Stress at Girder**

The increase at the stresses in general could be observed to be very limited or even constant. Although the bending

moment is increased the stresses at top and bottom flanges wasn't affected by that increase and keep constant.

They showed stress valued is due to the slenderness chosen for the girder which was able to handle the stress. The prestressing system has the upper hand in maintaining the stress limit at allowable range with no significant increase.

The girder top and bottom flanges stresses clarify that the girder section at all of the span limits met the allowable stress range for both of compression and tension.

**d) Girder Deformation**



**Figure 8: Girder Deformation**

The increase at girder deformation occurred with little values which could be explained due to the adopted slenderness ratio of the girder which led to maintain the girder stiffness.

In general the occurred girder deformation at different spans stay at allowable limits which is concluded as a factor of the span length ( $\Delta$ ) = L/250

The actual deformation of the girder compared to the allowable range considered small which refer to the stiff behavior of the girder based on the chosen section.

**Girder Results**

The study done on the girder shows that there are no actions contrary to the expected behavior and that the changes occurring at all levels of comparison occurred linearly and within the permissible range.

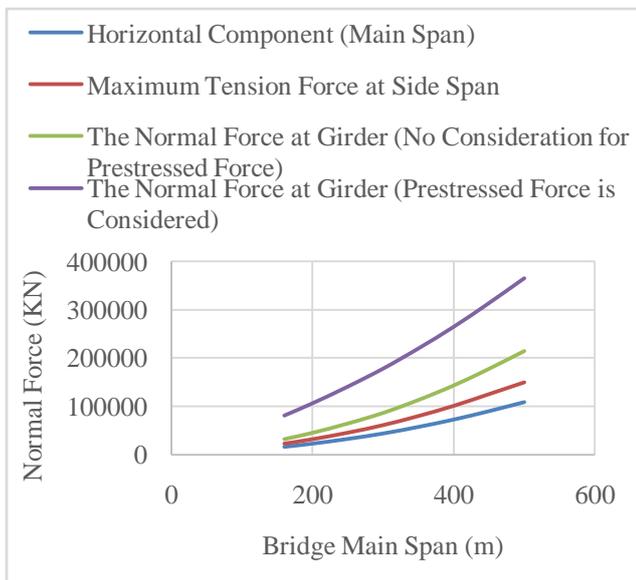
**Cables Preview**

The cables properties for main cable and hangers are configured according to the main verified specifications and are given by table (7).

**TABLE 7**  
Cables Properties

Main Span (m)	Main Cable Diameter (mm)	Main Cable Area (mm <sup>2</sup> )	Hanger Diameter (mm)	Hanger Area (mm <sup>2</sup> )
160	240	45238.93	55.00	2375.83
200	300	70685.83	68.75	3712.23
250	375	110446.62	85.94	5800.70
300	450	159043.13	103.13	8353.34
350	525	216475.37	120.31	11368.24
400	600	282743.34	137.50	14848.93
450	675	357847.04	154.69	18793.79
500	750	441786.47	171.88	23202.81

**e) Normal Forces**



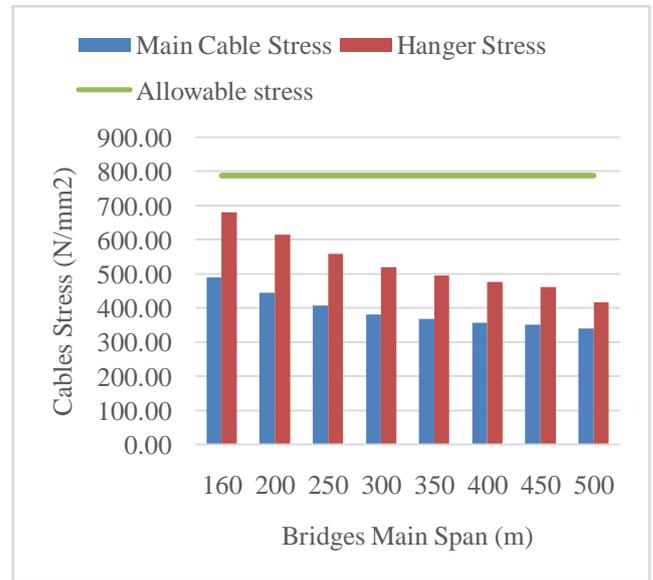
**Figure 9: Cable Forces with Girder Normal Force**

The normal force at cables increase significantly as the cables sustain nearly all of the permanent loads of the bridges in addition to participate with girder in bearing live loads according to stiffness for each of them.

The cables diameter (axial stiffness) to girder area (bending stiffness) ratio is considered to be responsible for how much loads is transferred for each of them so increasing the stiffness of any of them causes large forces to be resist.

The only thing that is not done according to what has been explained is the normal force at girder as reducing the girder stiffness causes large normal force at girder, this is as a result of the normal force at girder identified according to the cable normal force so reducing the girder stiffness increases the normal force at cables and the normal force at girder respectively.

**f) Stress**



**Figure 10: Cable Stress**

The stress at cables (main cable & hangers) reduced with increasing the span length.

The increase at cable diameter may not be necessary for handling the stress at cables as the graph shows that reducing the diameter won't cause any problems to the cables actual stress as both of the main cable and hangers cross section is efficient for stress allowable but the purpose of seeking large diameter is to maintain the load distribution ratio between cables and girder so the adopted cables area would be recommended.

The allowable stress of cables is calculated based on the cable material used and is specified according to Euro Code 1993-1-11 (Section 7).

**Cables Results**

The cables resistance is limited to the exposed tension force so the check of cables stress is the regarding concern at the process of cables analysis and design.

The fundamental basic in the selection of the cable section is to achieve the cable safety as well as to achieve the structure requirements for the rest of the components especially the girder cross section.

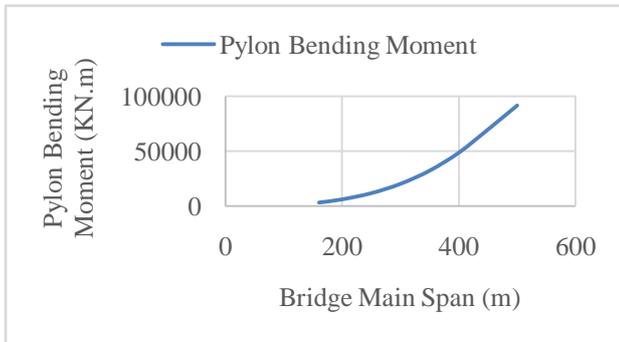
**Pylon Preview**

The pylon properties indicated at table (8)

**TABLE 8**  
**Pylon Properties**

Main Span (m)	Pylon Height (m)	Dimension (m)	Area (m <sup>2</sup> )	I <sub>x</sub> (m <sup>4</sup> )	I <sub>y</sub> (m <sup>4</sup> )
160	48.1	2.00*2.00	4.00	1.33	1.33
200	57.6	2.50*2.50	6.25	3.26	3.26
250	69.48	3.13*3.13	9.77	7.95	7.95
300	81.35	3.75*3.75	14.06	16.48	16.48
350	93.23	4.38*4.38	19.14	30.53	30.53
400	105.10	5.00*5.00	25.00	52.08	52.08
450	116.98	5.63*5.63	31.64	83.43	83.43
500	128.85	6.25*6.25	39.06	127.16	127.16

**g) Bending Moment**

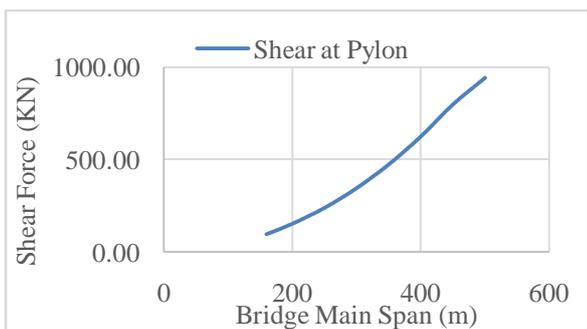


**Figure 11: Bending Moment at Pylon**

The bending moment at pylon increase significantly with increasing the bridge span as the differential cables horizontal force which acts on the pylon top increases and the pylon height increases as well which cause that large increase happen to the pylon bending moment.

The main cable horizontal forces for main and side spans should be equaled due to the cables identified angles and the cable saddle but the initial low differential horizontal force generated at pylon top of reference model is increasing by the span increase causes larger moment for each span increase.

**h) Shear**

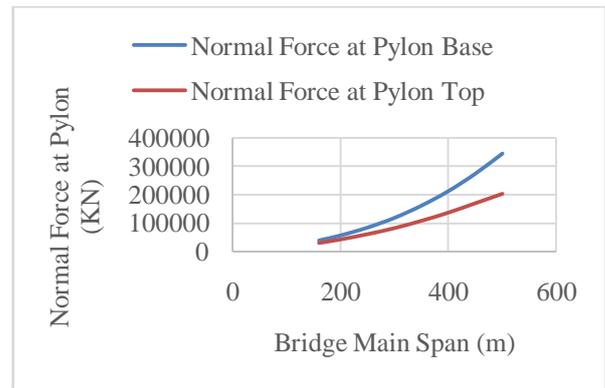


**Figure 12: Shear Force at Pylon**

The reference model procedures proved that the ratio of acting shear to the resistance of cross section consider low which means that all of other bridge models will have large resistance values compared to acting force.

The reason of these is that the increase at section resistance increase significantly due to the chosen pylon section and the increase of acting shear in incomparable to the increase in resistance shear.

**i) Normal Force**

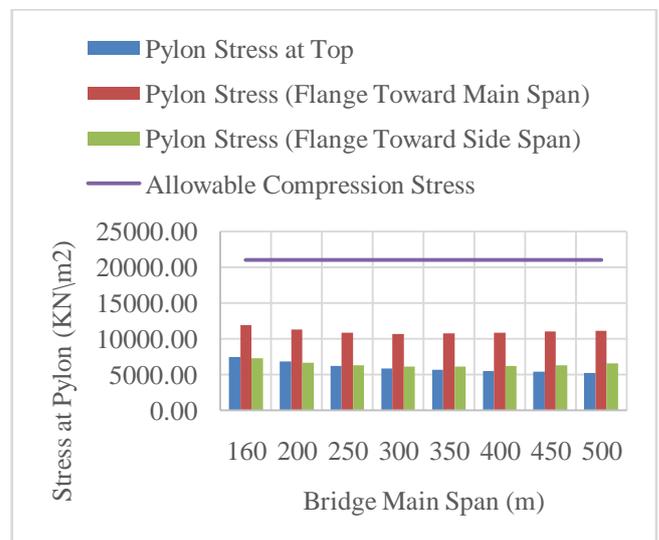


**Figure 13: Normal Force at Pylon**

The pylon normal force at top increases based on the increased happened to the cables forces.

The pylon normal force at base increases with great values depends on the increase happened to the pylon dimensions in addition to the force transferred from the girder to the pylon as the pylon participate with the cables in bearing the loads at girder.

**j) Stress**



**Figure 14: Stress at Pylon**

Two sections may be reviewed for stress at pylon, the first section is at top and the second is at base.

The top section of the pylon is exposed to normal force only which is the summation for main span and side span cables vertical components so as a result there is no possibility that the pylon top could resist tension force. The stress at pylon top is uniform at the whole section as there is no bending moment which would generate tension stress.

The pylon base exposed to larger normal force and also a bending moment, the stress values indicate that the normal force at the pylon cross section have a great effect on the pylon as all of the stress values are compression which shows that the bending moment considered has a little influence compared to normal force.

All of the stress values either at the pylon top or base locate at the permissible range for compression stress (no tension stress at pylon section).

#### k) Displacement

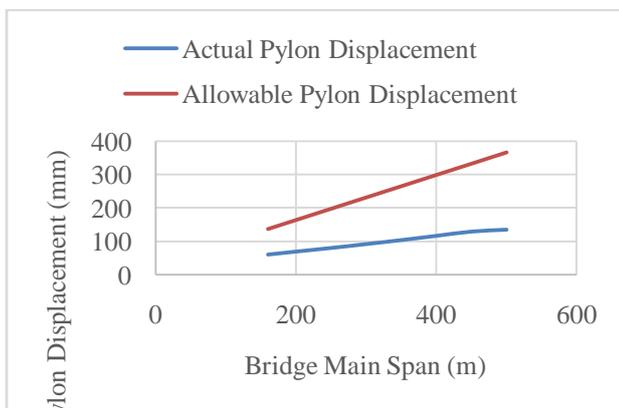


Figure 15: Pylon Displacement

The displacement occurred to the pylon is due to the differential force between horizontal main span cable and side span cable forces which act directly at the pylon top and cause a displacement to it. The increase at span affects the pylon height as the height of the pylon control the required sag ratio.

These two factors (Differential force & pylon height) cause large displacement to the pylon so increasing the pylon stiffness would be necessary to eliminate the large effect of these factors.

The limited increase at pylon displacement showed at figure (15) indicates that the adopted pylon dimensions succeeded to neutralize the effect the mentioned factors. The allowable pylon displacement is indicated according to  $(\Delta)=L/350$  so as increasing the pylon height causes larger

displacement it's also increase the permissible pylon displacement.

#### Pylon Results

The pylon properties don't govern the bridge behavior as the behavior of the girder and cable doesn't witness much effect due to the change happening to the pylon properties.

The pylon main role is to transfer the loads from the cables to the foundation so choosing any pylon material or dimensions which satisfy the bridge requirement with maintaining the requirement for the pylon itself should be sufficient.

### V. CONCLUSION

The following conclusions have been reached through the study

1. With increasing the span the actions of the bridge components (moment – shear – stress - deformation) increase linearly.
2. Bridge components for the chosen spans have been validated for ultimate and serviceability limit states and proved to meet the criteria.
3. The main factor for resultant actions is the cable material and diameter as it determines bending moment at girder and also normal forces in addition to the cable actions itself, so bridge cable consider to control the whole bridge behavior.
4. The bridge behavior during final geometry doesn't govern the maximum span possible to self-anchored bridge type.
5. Choosing prestressed concrete girder succeeded to meet the criteria but increasing cables area is a must to resist large self-weight so adopting lighter system would be more economic.

#### ACKNOWLEDGEMENT

First, thanks to God for giving me the opportunity to do this research in the scope of my master's degree. Thanks for my supervisors Prof. Dr. Amin Saleh Aly and Dr. Ayman Sayed Abo Beh who had an important role in my continuous encouragement and providing me with all necessary information to complete this research. Finally my love for my family for always supporting me at good and bad moments.

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#### Citation of this article:

Amin Saleh Aly, Ayman Sayed Abo Beh, Samy Farouk Ali El Din El Kady, "Span Increment Possibility of Self-Anchored Suspension Bridge", Published in *International Research Journal of Innovations in Engineering and Technology (IRJIET)*, Volume 3, Issue 2, pp 34-43, February 2019.

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