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Influence of Fatigue on Cable Arrangement in Cable-stayed Bridges

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Abstract

Cable arrangement in cable-stayed bridges is one of the key issues in optimizing the design of this typology of bridges. Oscillating axial forces in the cables due to vehicular loading is usually the parameter on which attention of the designer is focused. The cables are particularly vulnerable to fatigue phenomena but the variation of axial forces in hangers depending on load configuration and cable arrangement was not deeply studied despite the fact that it is an important parameter in relation to the fatigue behaviour of the overall bridge. In this context, this paper mainly deals with the influence of fatigue on cable arrangement in cable-stayed bridges. The analysis is carried out by performing moving load analysis along the deck, and a parametric analysis of cable arrangement. Moreover, a lifetime assessment considering different corrosion propagation in cables is shown.

Keywords: structural optimization, fatigue, cable-stayed, long-span bridge, lifetime assessment

1. Introduction

A large number of cable-stayed bridges has been built all over the world in the last half a century. This kind of bridges is on a rapid growth mainly for the development of computer technology, high strength steel cables, orthotropic steel decks and construction technology. Because of its aesthetic appeal, and the rapid and easy erection, the cable-stayed bridge is considered as suitable for medium to long span bridges. Because of their huge size and nonlinear structural behaviour, the analysis of cable-stayed bridges is much more complicated than that of conventional bridges, such as truss and girder bridges. The sources of nonlinearity in cable-stayed bridges mainly include behaviour of the cables, and large deflection effects other than material constitutive laws. Nevertheless few studies have deepened the analysis of cable-stayed bridges with the aim of arranging and optimizing the geometric configuration of the cables taking fatigue into account. In fact cables are particularly vulnerable to premature failure or damage due to varying fatigue actions during the structure lifetime, as they are subjected to repeated loading with large force variations and millions of load cycles. A study on the effect of fatigue on the arrangement of hangers in tied arch bridges developed by some of the authors can be found in (Pellegrino *et al*., 2010).

Moreover, cable-stayed structures suffer from the continuous aggression of environmental agents (urban, industrial, marine, etc.): these effects appear through corrosion, whose direct consequences are the strong modifications of the geometrical and mechanical characteristics of the components. This can induce a significant reduction of the bearing capacity of the cable with time, sometimes resulting in its partial rupture due to cyclic actions. A large number of broken wires found in the suspension cables of some bridges (Elachachi *et al*., 2006; Tanaka and Haraguchi, 1985; Xercavins and Mondorf, 1980; Elliott and Heymsfield, 2003) has shown the absence of methods for assessing safety levels provided by old suspensions.

Fan and semi harp arrangements are the most commonly adopted schemes for hangers: in this work comparisons between these arrangements (Fig. 1), as structural alternatives for cable-stayed-bridge designers, are shown. Parametric analyses related to various geometric configurations of cables were developed and design solutions for arranging them in cable-stayed bridges are shown. Moreover the influence of fatigue on cable arrangement under vehicular live loads are deepen (EN 1991-2, 2005), and finally corrosion effects are also taken into account for lifetime predictions. The structural analyses

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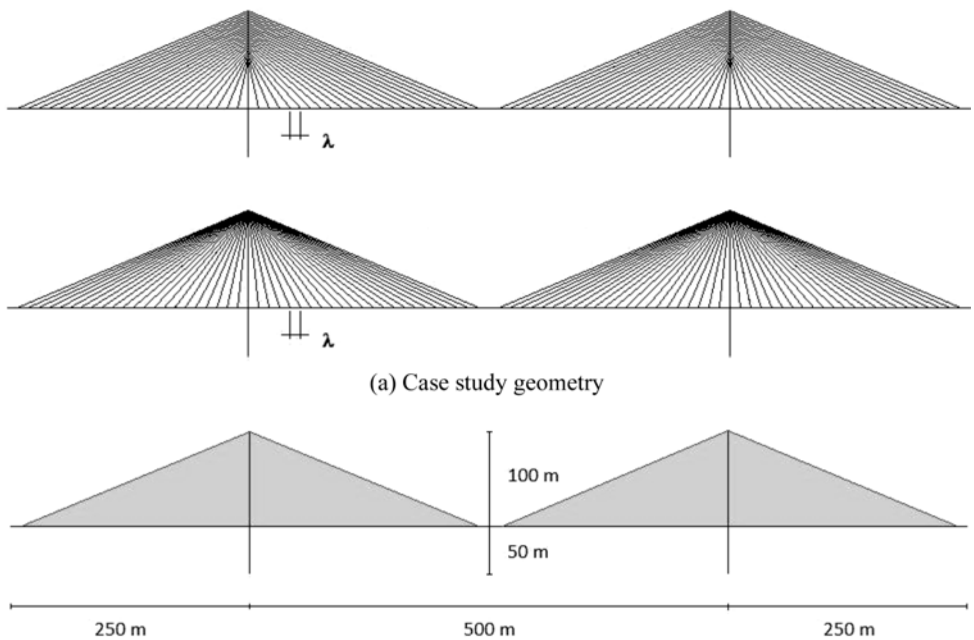
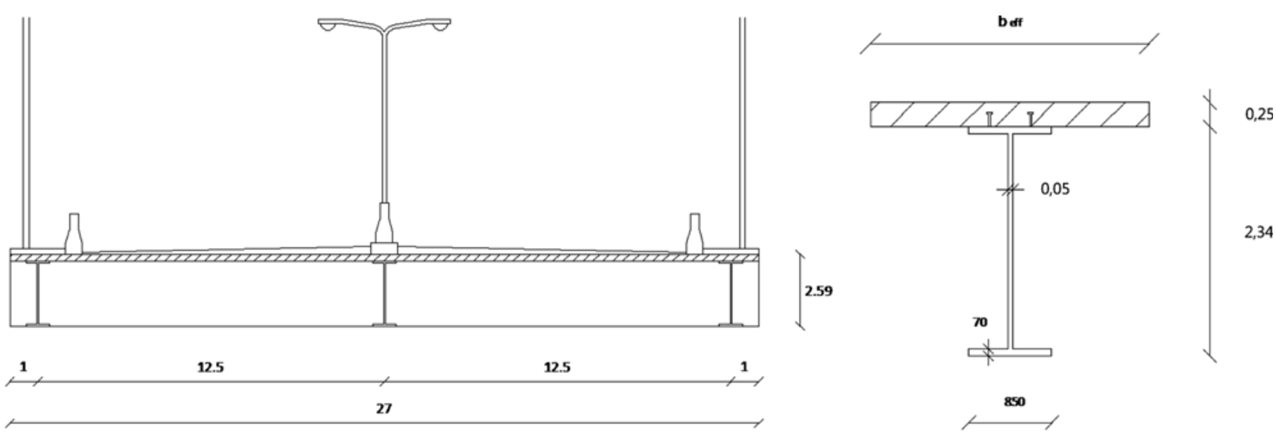


(a) Case study geometry

(b) Dimension in metre

Figure 1. Strand system configuration: on the top a semi-harp, and on the bottom a fan-type.



(a) Case study cross-section

(b) Dimension in metre

Figure 2. Case study detail of the deck.

are performed with the FEM software MIDASoft (2000). The search of the configuration of the support system, which minimizes the variation of normal stress is made in relation to a case study consisting in two cable arrangements contained in two vertical planes; in this framework two alternatives are considered: a fan pattern and a semi-harp pattern. Moreover, one of the aims of this work is to verify the field of applicability of the linear analysis for fatigue verification of cable-stayed bridges. For the particular case of the cable-stayed bridges, neglecting the geometric non-linearity and considering compressive forces in the cables can affect the final results of each structural analysis. Hence the same fatigue load models (EN-1991-2, 2005) are assumed for the non-linear model (which includes geometric non-linearity and tension-only regime for the cables) as a first step to obtain some information on the approximation implicitly assumed in the common linear approach for the fatigue analysis for cable-stayed bridges.

2. Case Study

The case study is for a typical cable-stayed bridge, symmetrical in the longitudinal and transverse direction, with composite steel-concrete girder and suspension system consisting in cables belonging to two planes. The deck span is 1000m long and 27m wide (Fig. 1), with three traffic lanes plus the emergency one for each

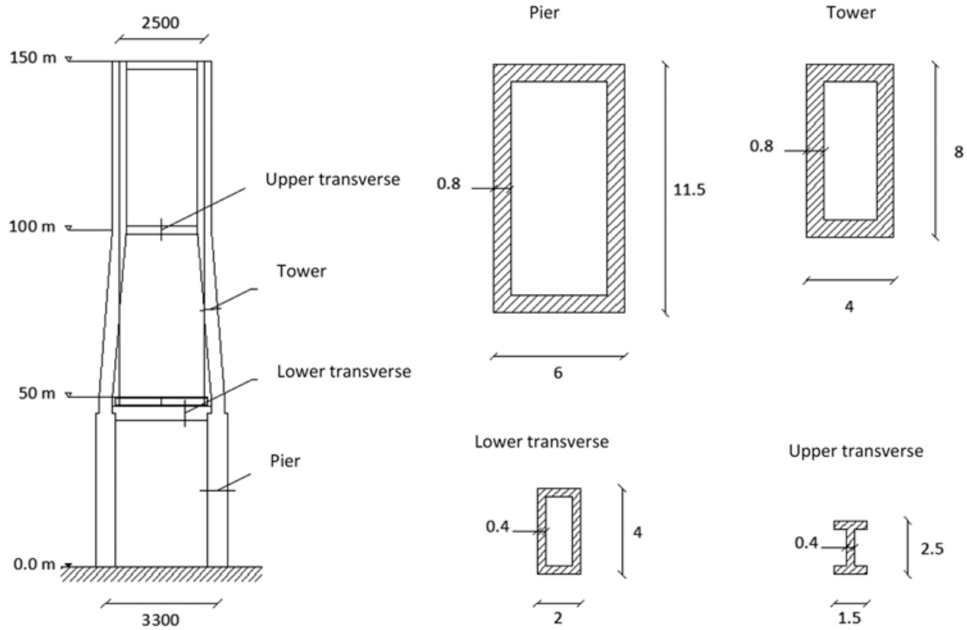


Figure 3. Case study detail of the pylons. Dimension in metre.

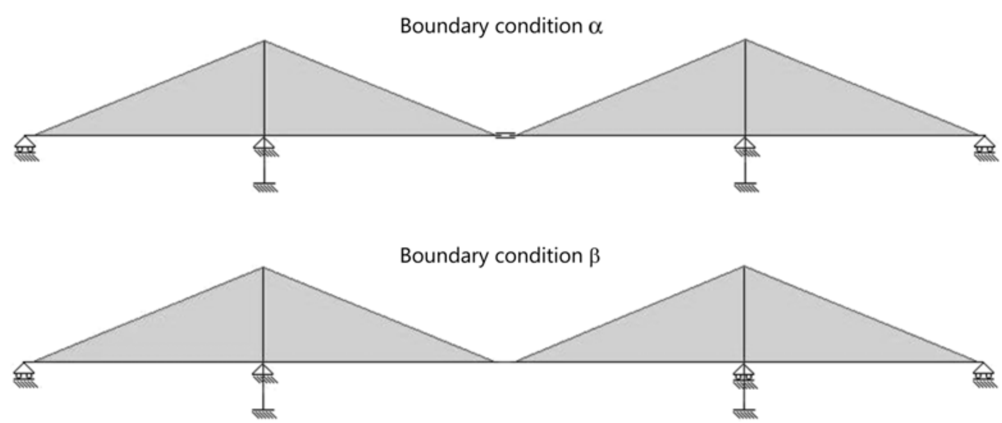


Figure 4. Case study detail of the alternative boundary conditions.

direction. The girder is composed by a steel-concrete composite section (Fig. 2). Girders consists of three double-T elements 12.5m spaced, whereas stringers are designed for the transverse direction with the same height and a variable spacing. Composite sections have been designed according to EN 1994-1-1 (2005). The bridge is composed by two pylons, made by double tower, and three transverse beams at 50-100-150 m height (Fig. 3). Concerning boundaries, two classes of models have been considered in relation to the restraint condition of the deck in the central span: the condition α consists in two continuous decks connected by an hinge whereas the condition β is represented by a continuous deck (Fig. 4). The analysis has been developed with MIDASoft (2000), by using beam elements for the deck and the pylons and truss elements for strands, according to Wilson *et al*., (1991). In Fig. 5 a scheme of the FEM model is shown. Adopted structural materials are the following: wire strands with diameter Φ=20 cm (ultimate stress f_u =1570 MPa, stress at 0.2% strain $f_{y0.2\%}$=1180 MPa), steel deck S355 J0 (ultimate stress f_u =510 MPa, yield stress f_y = 355 MPa) and concrete C30/37.

3. Initial Configuration

In cable-stayed structures, the outcome of any analysis, whether static or dynamic, depends primarily on the definition of the initial configuration, namely the structural response under dead loads. The initial shape of a cable-stayed bridge, once defined the weight of the various elements, depends only on the pretension force distribution in cables. Therefore the problem has a high degree of uncertainty, since a single structure can stand as different initial configurations. Many techniques for the detection of initial stress distribution of pretension exist: a finite element computation procedure for determining the initial

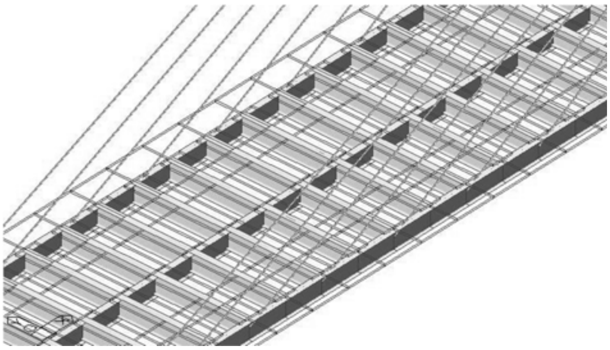


Figure 5. Case study detail of the fem model.

shape of cable-stayed bridges under the action of dead load of girders and pretension in inclined cables is presented for example in Wang *et al*. (1993).

Based on a reference configuration and an assumed cable pretension force, the equilibrium configuration under dead load is initially found. Further, by adjusting cable forces, a 'shape iteration' is carried out and a new equilibrium configuration, i.e., a more reasonable initial shape, is determined. The 'shape iteration' is then repeated until the desired tolerance is achieved. In this case, the "ULF-Unknown Load Factor" method has been chosen: this optimization technique is implemented in MIDASoft (2000) and allows to find the distribution of

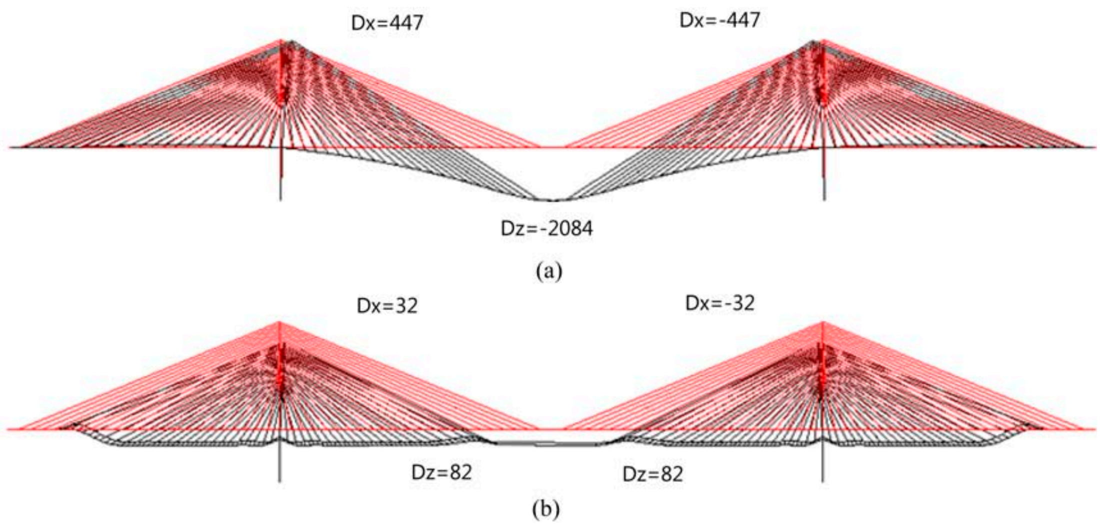


Figure 6. Initial configuration with permanent load in mm, without (a) or with (b) pretension forces.

Table 1. Design alternatives analyzed

Model A	Semi-harp		Fan	
	Without pretension	With pretension	Without pretension	With pretension
DR$_z$R midspan [mm]	-2084	-25	-2015	-25
DR$_x$R pylon [mm]	446	8	442	37
MR$_y$R midspan [kNm]	40151	2017	42650	4246
MR$_y$R support [kNm]	-25978	-11716	-32887	-11694
Model B	Semi-harp		Fan	
	Without pretension	With pretension	Without pretension	With pretension
DR$_z$R midspan [mm]	-1900	-25	-1831	-25
DR$_x$R pylon [mm]	410	6	404	5
MR$_y$R midspan [kNm]	36686	2900	39091	3140
MR$_y$R support [kNm]	-25142	-10893	-32221	-11374
Model C	semi-harp		Fan	
	Without pretension	With pretension	Without pretension	With pretension
DR$_z$R midspan [mm]	-1783	-25	-1714	-25
DR$_x$R pylon [mm]	386	5	379	4
MR$_y$R midspan [kNm]	34548	2266	36899	2471
MR$_y$R support [kNm]	-24833	-10871	-32174	-10818

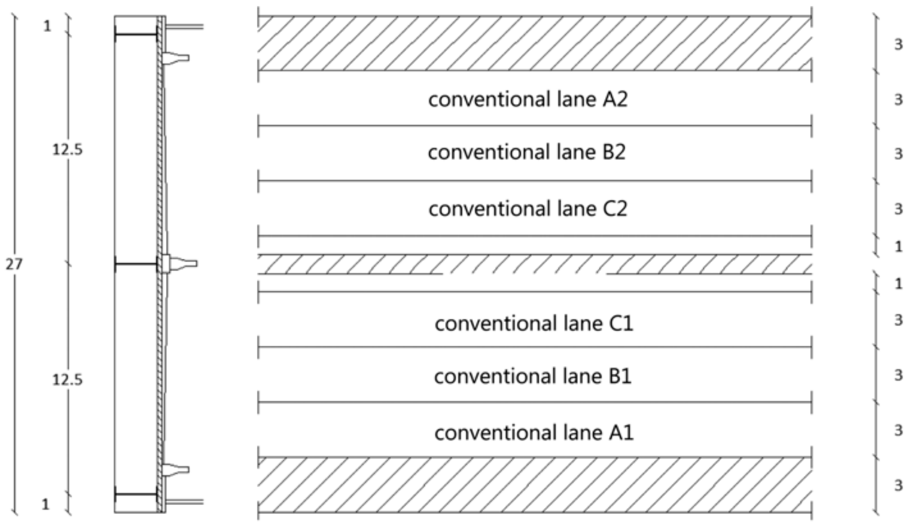


Figure 7. Conventional lanes division of the bridge deck according to EN 1991-2 (2003) code requirements. Dimension in metre.

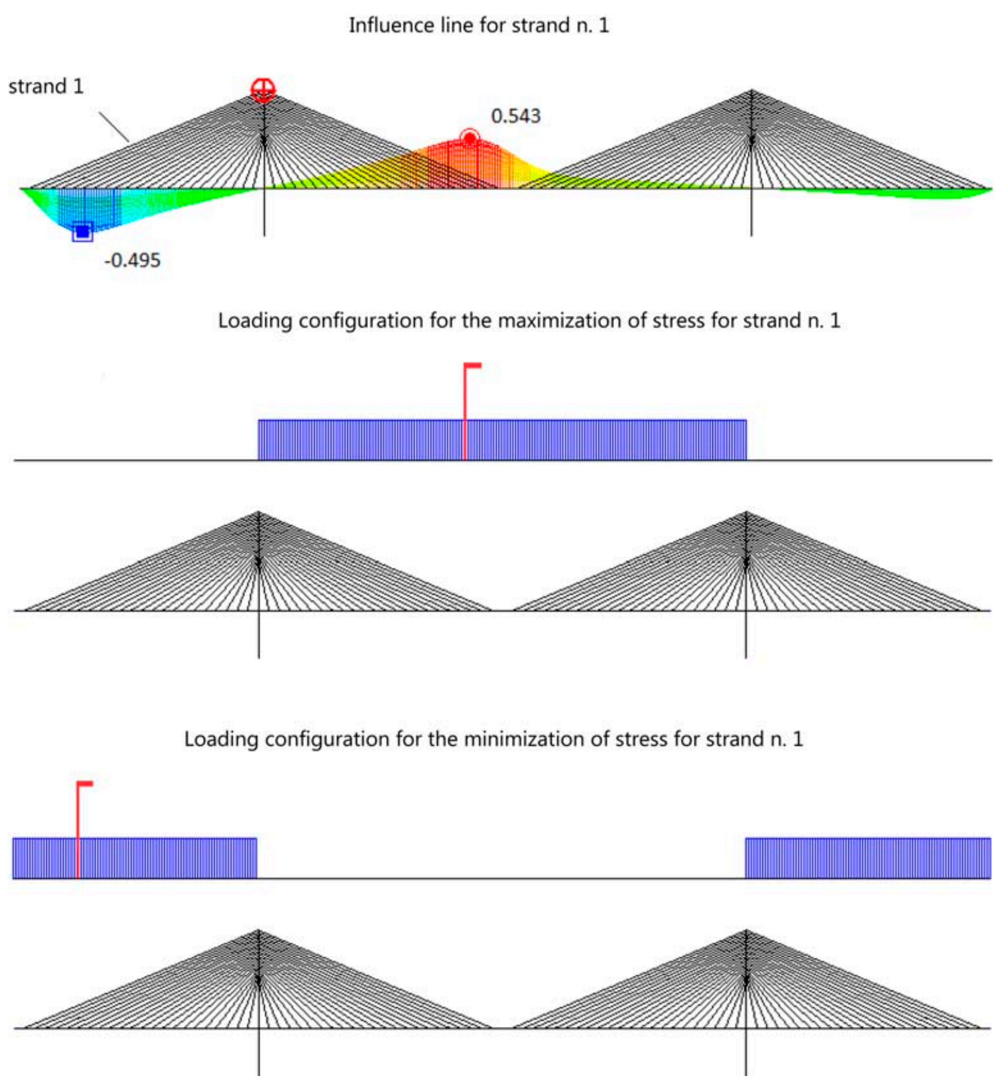


Figure 8. Loading conditions maximizing stress variations for the 1st strand, lateral view.

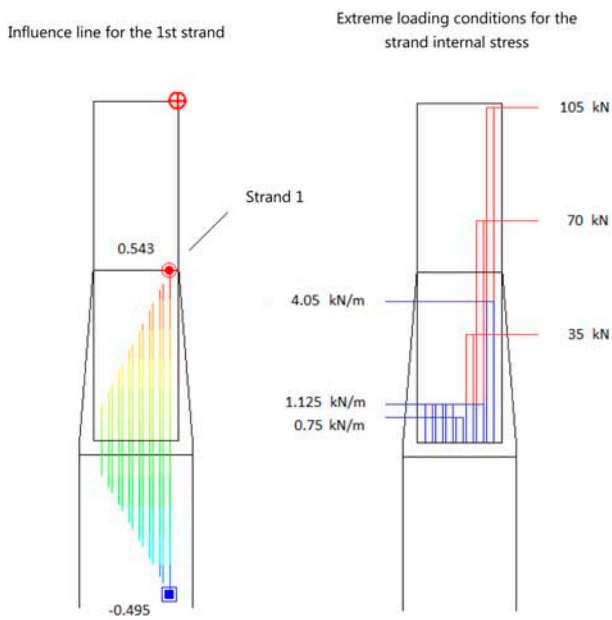


Figure 9. Loading conditions maximizing stress variations for the 1st strand, front view.

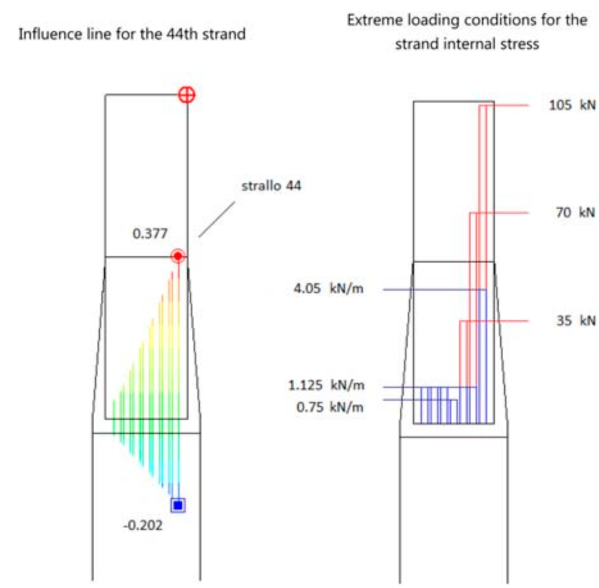


Figure 11. Loading conditions maximizing stress variations for the 44th strand, front view.

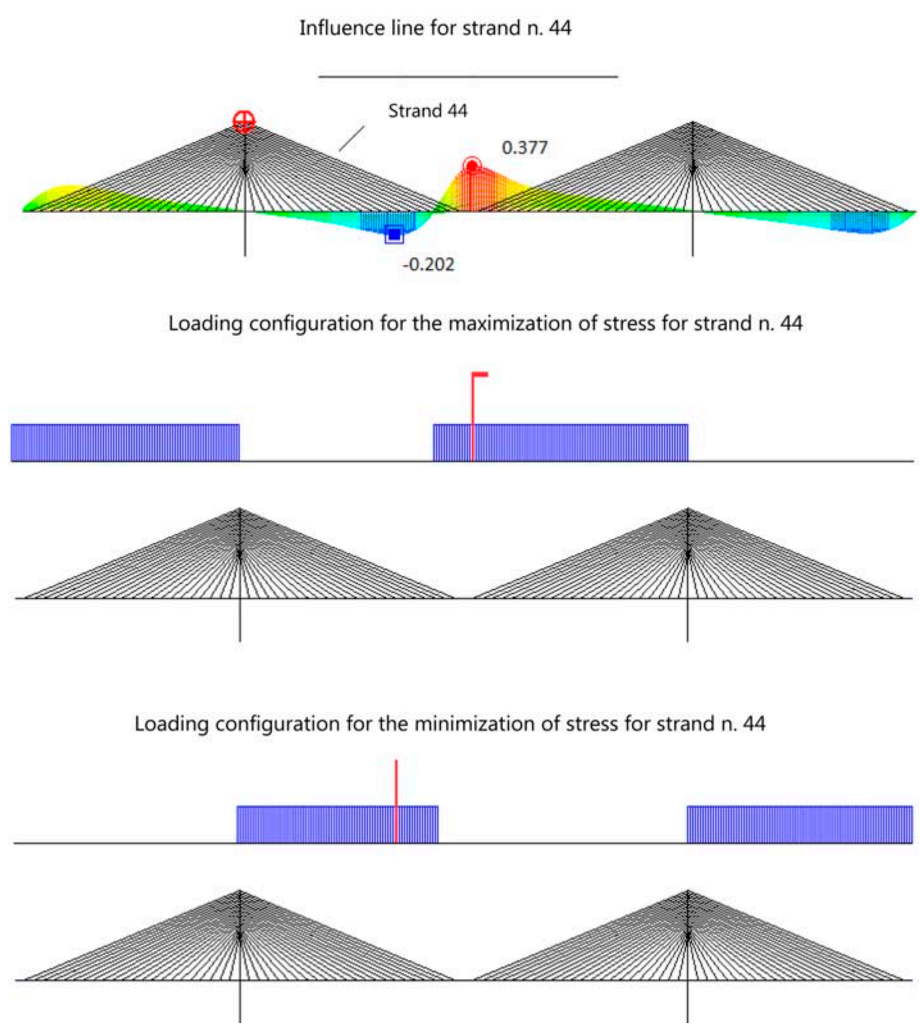


Figure 10. Loading conditions maximizing stress variations for the 44th strand, lateral view.

Table 2. Design alternatives analyzed

	Boundary condition α		Boundary condition β	
	Semi-harp	Fan	Semi-harp	Fan
Model A	λ=10.87 m	λ=10.87 m	λ=10.87 m	λ=10.87 m
Model B	λ=8.93 m	λ=8.93 m	λ=8.93 m	λ=8.93 m
Model C	λ=7.58 m	λ=7.58 m	λ=7.58 m	λ=7.58 m

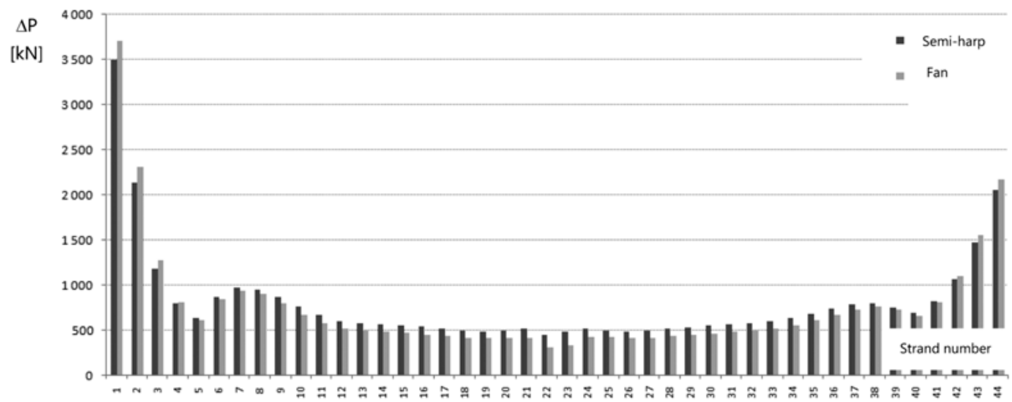


Figure 12. Model A, λ= 10.87 m, semi-harp and fan configurations, b.c.=α: variation of load in the strands related to a pylon.

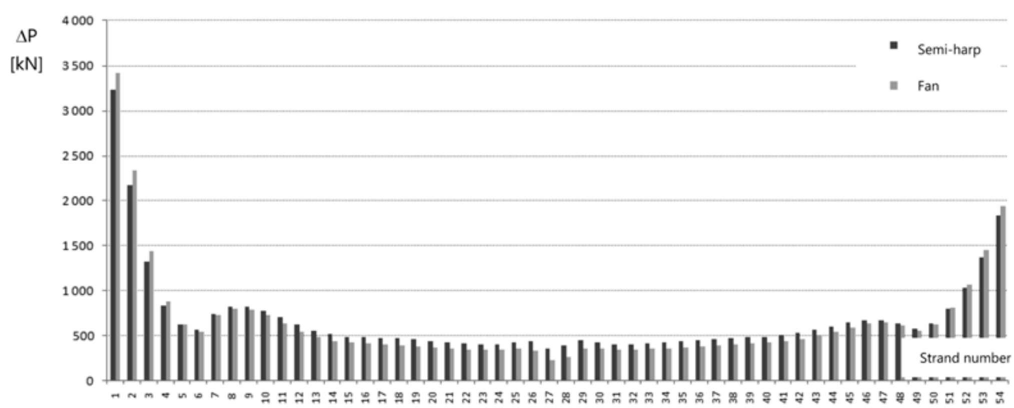


Figure 13. Model B, λ= 8.93 m, semi-harp and fan configurations, b.c.=α: variation of load in the strands related to a pylon.

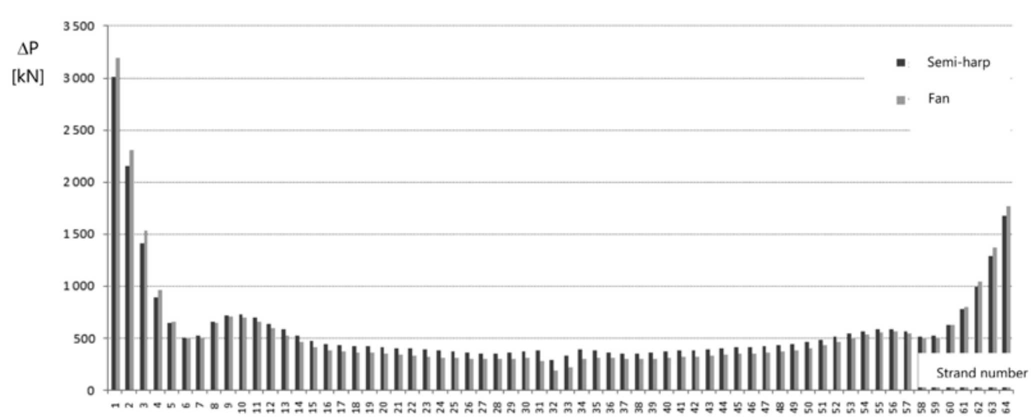


Figure 14. Model C, λ= 7.58 m, semi-harp and fan configurations, b.c.=α: variation of load in the strands related to a pylon.

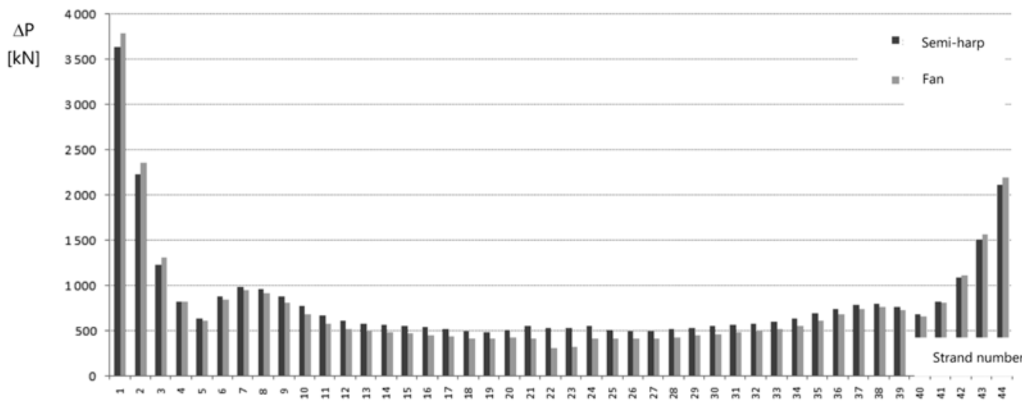


Figure 15. Model A, λ= 10.87 m, semi-harp and fan configurations, b.c.=β: variation of load in the strands related to a pylon.

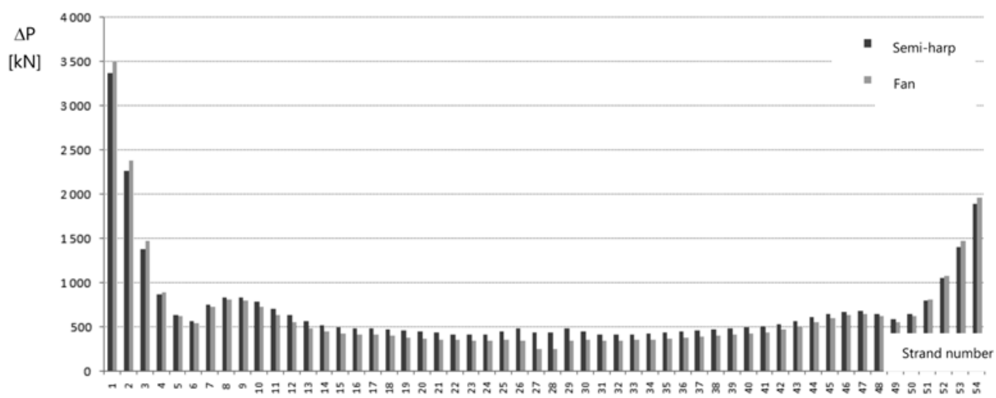


Figure 16. Model B, λ= 8.93 m, semi-harp and fan configurations, b.c.=β: variation of load in the strands related to a pylon.

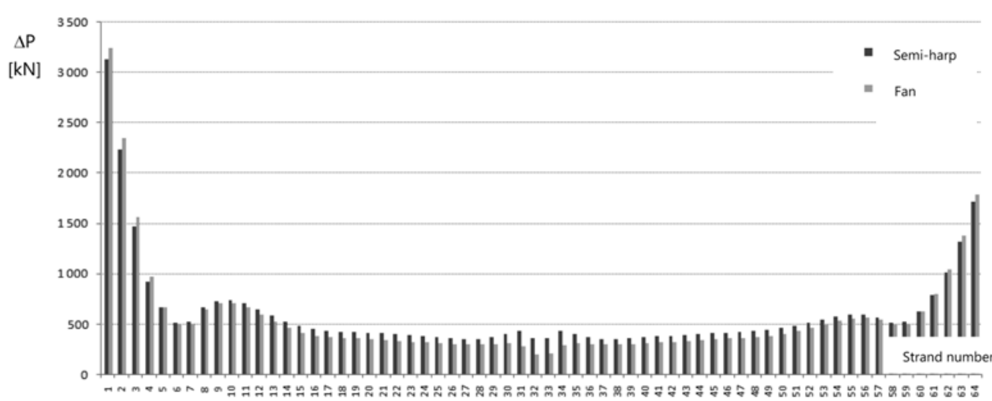


Figure 17. Model C, λ= 7.58 m, semi-harp and fan configuration, b.c.=β: variation of load in the strands related to a pylon.

pre-tension forces to meet specific conditions on structural response in relation to the permanent load status. Moreover, ULF method provides initial tension forces in cables satisfying the design conditions specified by the designer. The problem has been solved by fixing the desired tolerance of the vertical displacements of the nodes of the central deck between –25 and +25 mm, assuming the structural model at the initial time, before the activation of the long term phenomena. In Fig. 6, initial configurations are presented under the permanent load of the bridge with a suspension system in a semi-harp and boundary according to the condition α. In the first case (Fig. 6a) the deformation is related to permanent load only, whereas the second (Fig. 6b) introduces also the pretension forces. Some additional information on initial configurations parameters are given in Table 1.

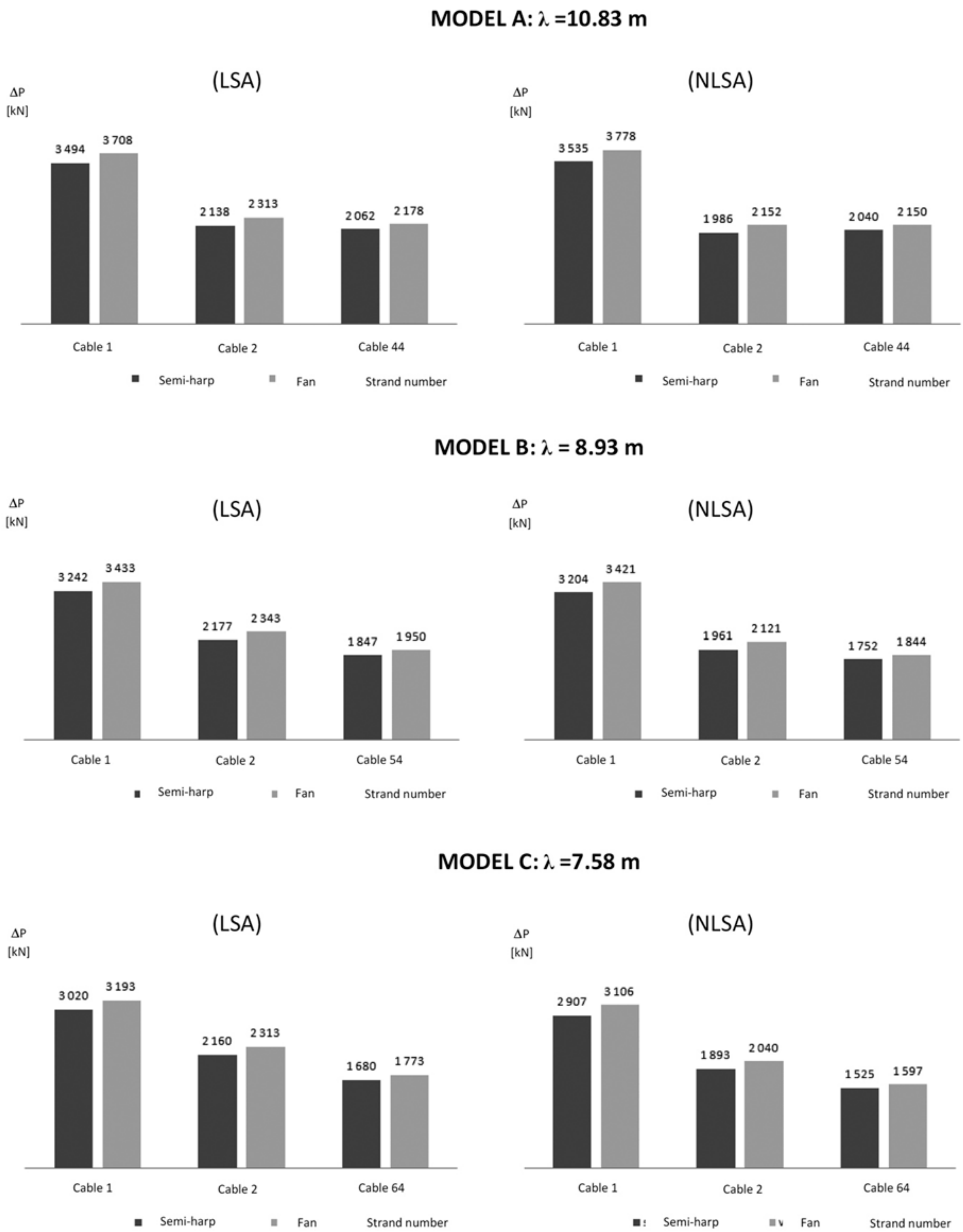


Figure 18. Comparison among solutions, boundary condition α.

4. Moving Load Analysis

Load models have been implemented according to EN 1991-2 (2005), in detail the load fatigue model 1 (LFM1). First permanent loads acting on the bridge and then those induced by traffic are included according to conventional lanes (Fig. 7). Finally the combinations of loads at the fatigue limit state are investigated, according to EN 1991-2 (2005). The "Moving Load Analysis - MLA", implemented in MidaSoft (2000), is used. According to this procedure, every traffic surface lane represents a zone in which traffic vehicles move and is defined according to the aforementioned Eurocode specifications. By performing the MLA analysis, the maximum/minimum design variables

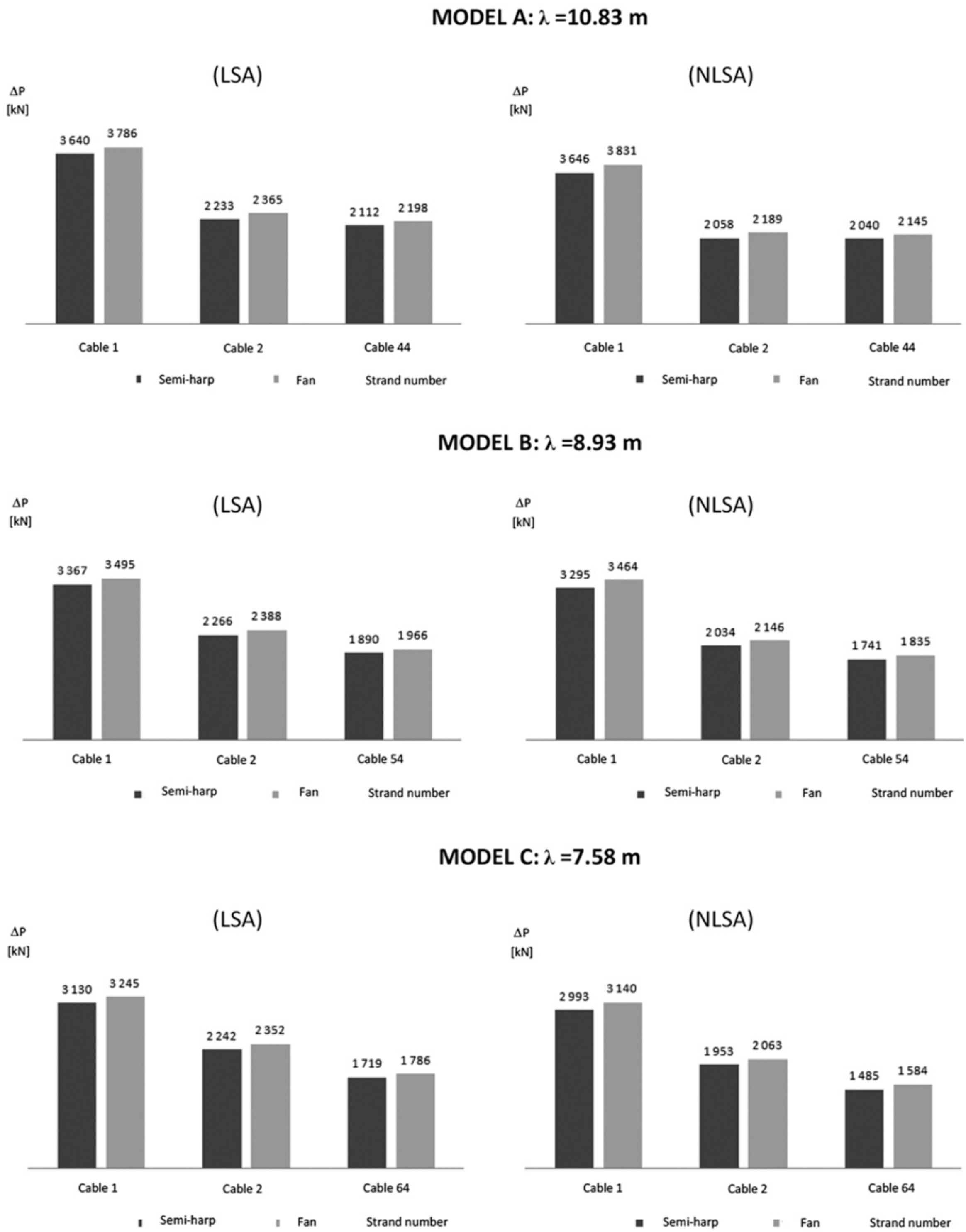


Figure 19. Comparison among solutions, boundary condition β.

are calculated. In the case of concentrated loads, the maximum/minimum design variables are calculated by multiplying the maximum/minimum influence line values pertaining to the required variable by the concentrated axle load values. As in the case of a uniform traffic lane load, the maximum/minimum design variables are found by the following procedure: first the positive and negative zones of the influence surface within the traffic lane pertaining to the required variable is identified, then influence surface values are integrated in the two separated zones, and is finally multiplied by the uniform traffic load. An additional step, concerns the identification of elements connected to the supports: this information is used to obtain the maximum negative moments due to

Table 3. LSA vs. NLS solutions, boundary condition α

		Difference LSA-NLSA condition α semi harp configuration	Difference LSA-NLSA condition α FAN configuration	Difference LSA-NLSA condition β semi harp configuration	Difference LSA-NLSA condition β FAN configuration
Model A	CABLE 1	1.2%	1.9%	0.2%	1.2%
	CABLE 2	9.4%	6.9%	7.9%	7.4%
	CABLE 44	1.1%	1.3%	3.4%	2.4%
Model B	CABLE 1	1.2%	0.3%	2.1%	0.9%
	CABLE 2	9.9%	9.5%	10.3%	10.1%
	CABLE 54	5.1%	5.4%	7.9%	6.7%
Model C	CABLE 1	3.7%	2.7%	4.4%	3.2%
	CABLE 2	12.3%	11.8%	12.9%	12.3%
	CABLE 64	9.2%	9.9%	13.6%	11.3%

Table 4. Stress variation in cables, boundary condition α (NLSA)

		Semi-harp [MPa]	Fan [MPa]
Model A	CABLE 1	112.51	120.27
	CABLE 2	63.22	68.51
	CABLE 44	64.93	68.45
Model B	CABLE 1	101.98	108.89
	CABLE 2	62.43	67.52
	CABLE 54	55.77	58.70
Model C	CABLE 1	92.53	98.87
	CABLE 2	60.26	64.93
	CABLE 64	48.56	50.85

Table 5. Stress variation in cables, boundary condition β (NLSA)

		Semi-harp [MPa]	Fan [MPa]
Model A	CABLE 1	116.07	121.95
	CABLE 2	65.49	69.67
	CABLE 44	64.94	68.28
Model B	CABLE 1	104.89	110.27
	CABLE 2	64.73	68.30
	CABLE 54	55.41	58.40
Model C	CABLE 1	95.28	99.94
	CABLE 2	62.18	65.67
	CABLE 64	47.26	50.43

traffic lane loads in a continuous span to satisfy the requirements specified in various standards provisions. According to this procedure, in Fig. 8-11 the loading conditions maximizing the stress variations for the 1st strand (longitudinal view in Fig. 8 and transversal view in Fig. 9), and the loading conditions maximizing the stress variations for the 44th strand (longitudinal view in Fig. 10 and transversal view in Fig. 11) are shown. The 1st and the 44th strand (i.e. the first and the last related to a pylon) are considered since they are those subjected to the maximum stress variations.

5. Linear Static Analysis

Assuming λ as the spacing among strands, three models have been compared and illustrated in Table 2. In detail, the following figures show the variation of load in the various strands. Figure 12, deals with the model A, with λ=10.87 m, a semi-harp vs. fan configuration, and α boundary condition. Figure 13, deals with the model B, with λ=8.93 m, a semi-harp vs. fan configuration, and α boundary condition. Figure 14, deals with the model C, with λ=7.58 m, a semi-harp vs. fan configuration, and α boundary condition. Figure 15, deals with the model A, with λ=10.87 m, a semi-harp vs. fan configuration, and β boundary condition. Figure 16, deals with the model B, with λ=8.93 m, a semi-harp vs. fan configuration, and β boundary condition. Figure 17, deals with the model C, with λ=7.58 m, a semi-harp vs. fan configuration, and β boundary condition. The linear analysis of the structure allows to obtain the variation of normal stress in the cables, induced by the effect of the live loads due to traffic. By comparing these arrangements, the fan-shaped pattern is more detrimental in the external elements, whereas the situation is unfavourable for the semi-harp pattern corresponding to the internal cables. However, the outer strands have been confirmed to be more stressed by a normal stress oscillation. Concerning the boundary conditions, slight differences in terms of load variations in cables could be observed, assuming the same spacing (λ). While, significant decrement in load variations could be noticed, referring to the same model (A or B) with decreasing spacing (λ).

6. Non Linear Static Analysis

Cables have been modelled as “tension-only” elements. This constitutive model allow the cables to bear tensile

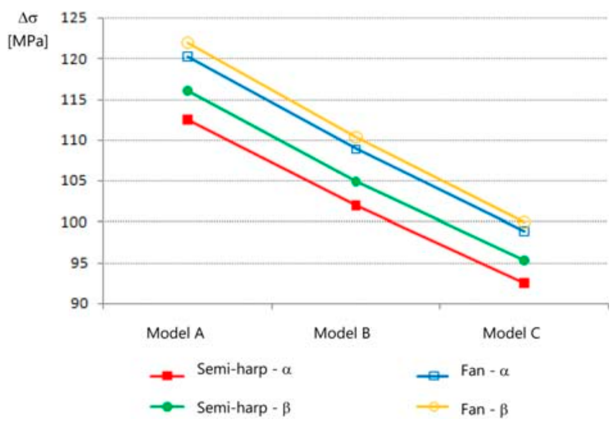


Figure 20. Comparison among different solutions, strand 1 (NLSA).

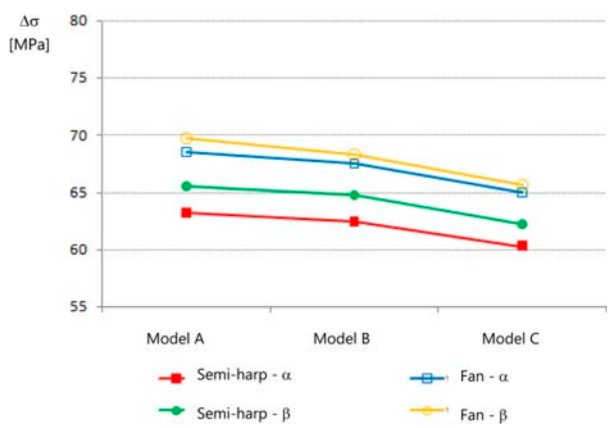


Figure 21. Comparison among different solutions, strand 2 (NLSA).

stresses only whereas compressive stresses are assumed as null. Moreover geometrical non linearity are also taken into account. According to these hypotheses, normal stresses in some significant cables are shown in Fig. 18 for the α boundary condition, and in Fig. 19 for the β boundary condition. The fan configuration seems to be again the worst with respect to stress variations. According to the results shown in Table 3, the maximum between LSA and NLSA remain below 13.6%. Axial stress variations are shown for NLS (Non-Linear Static) analysis for critical cables in the different boundary situations in Tables 4 and 5, whereas in Fig. 20, 21 and 22 they are presented for critical cables. These results highlight that the α boundary condition leads to lower stress variations in cables than condition β; moreover, increasing the number of cables it is possible to decrease the excursion of the normal stress in critical strands. Finally, the stress variation in cables achieved by a semi-harp configuration with respect to a fan configuration remains unchanged when boundary conditions of the girder and the distance between cables changes.

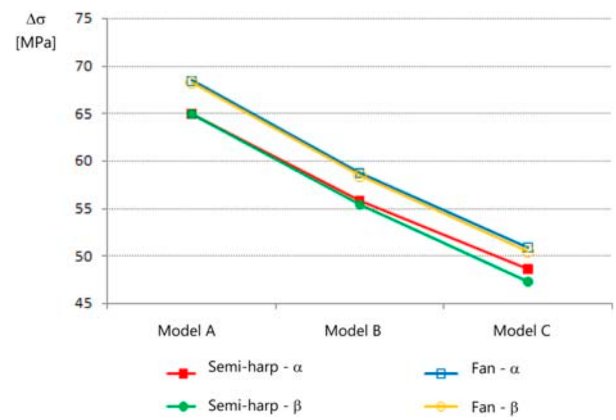


Figure 22. Comparison among different solutions, last strand 44-54-64 (NLSA).

7. Fatigue Verification

The fatigue endurance of tension components shall be determined using the fatigue actions previously described and the appropriate category of structural detail. The effective category should preferably be determined from tests representing the actual configuration used. However, in the absence of the tests described above, fatigue strength curves according to EN 1993-1-11 (2007) may be used. In this work three different cables have been considered with the aim of obtaining some elements about fatigue design for this particular case. So, fatigue verification have been performed according to EN 1993-1-9 (2005) procedures, according to the following detail category: C=160 for parallel wire strands with epoxy socketing, C=150 for spiral strands with metal or resin socketing and C=105 for prestressing bars. These categories are intended to be applied in compliance with the general requirements, including the preliminary check for stress limit of EN 1993-1-11 (2007). Results are reported in Tables 6-7, respectively for the boundary conditions α and β: only the semi harp configuration, with parallel wire strands (C=160), in both boundary conditions α and β resulted to be verified; in particular, all other sets of combination category detail/boundary conditions/model type, resulted to be affected by insufficient fatigue strength in correspondence with the cable n.1, the most subjected to live-load stress range.

8. Lifetime Assessment

The suspension system must be protected against corrosion by metallic and/or organic coatings if used in any aggressive environment: moreover, according to recent studies (Nürnberger, 2007; Lan and Li, 2009; Lan *et al*., 2009) the formation of a fatigue crack is influenced by physical-chemical interactions between the environment

Table 6. Fatigue verification according to EN1993-1-9, boundary condition α

Model type	Cable	Semi harp [MPa]	Fan [MPa]	Detail category Prestressing bars [MPa]	Damage equivalent fatigue verification Semi harp config.	Damage equivalent fatigue verification Fan
Model A	1	112,51	120,27	105	NO	NO
	2	63,22	68,51	105	OK	OK
	44	64,63	68,45	105	OK	OK
Model B	1	101,98	108,89	105	NO	NO
	2	62,43	67,52	105	OK	OK
	54	55,77	58,7	105	OK	OK
Model C	1	92,53	98,87	105	NO	NO
	2	60,26	64,93	105	OK	OK
	64	48,56	50,85	105	OK	OK
Model type	Cable	Semi harp [MPa]	Fan [MPa]	Detail category Spiral strands with metal or resin socketing [MPa]	Damage equivalent fatigue verification Semi harp config.	Damage equivalent fatigue verification Fan
Model A	1	112,51	120,27	150	NO	NO
	2	63,22	68,51	150	OK	OK
	44	64,63	68,45	150	OK	OK
Model B	1	101,98	108,89	150	OK	OK
	2	62,43	67,52	150	OK	OK
	54	55,77	58,7	150	OK	OK
Model C	1	92,53	98,87	150	OK	OK
	2	60,26	64,93	150	OK	OK
	64	48,56	50,85	150	OK	OK
Model type	Cable	Semi harp [MPa]	Fan [MPa]	Detail category Parallel wire strands with epoxy socketing [MPa]	Damage equivalent fatigue verification Semi harp config.	Damage equivalent fatigue verification Fan
Model A	1	112,51	120,27	160	OK	NO
	2	63,22	68,51	160	OK	OK
	44	64,63	68,45	160	OK	OK
Model B	1	101,98	108,89	160	OK	OK
	2	62,43	67,52	160	OK	OK
	54	55,77	58,7	160	OK	OK
Model C	1	92,53	98,87	160	OK	OK
	2	60,26	64,93	160	OK	OK
	64	48,56	50,85	160	OK	OK

and the steel surface, activated by fatigue. Not only liquids, but also gases and vapours may accelerate the deterioration process. Dry air is already a surface-active medium and reduces the fatigue strength in comparison to the vacuum. Coatings impermeable to oxygen and steam (e.g. sufficiently thick reactive resins) improve the fatigue behaviour not only in corrosive environment, but also in the air. An improvement could be reached for example by galvanizing the wire. Other concurring fatigue detrimental facts could influence the lifetime of the suspension system, as out of round sheaves, tight grooves, misaligned sheaves, undersized sheaves, worn bearings, vibration, slapping, whipping, reverse bends. Whereas adequate protection against corrosion is no more provided, the fatigue strength of cables could be compromised (Funahashi, 1995; Sih *et al*., 2008; Virmani, 1993). In order to give some insights on the effect of corrosion and concurring detrimental factors on the fatigue strength of cables, different corrosion propagation rates have been simulated. The corrosion rates have been considered according to Elachachi *et al*. (2006), Dieng *et al*. (2009), Cremona (2003), Weischedel and Hoehle (1995) and Camo (2003), checking their influence on the fatigue strength of the single cable. In Fig. 23, different

Table 7. Fatigue verification according to EN1993-1-9, boundary condition β

Model type	Cable	Semi harp [MPa]	Fan [MPa]	Detail category Prestressing bars [MPa]	Damage equivalent fatigue verification Semi harp config.	Damage equivalent fatigue verification Fan
Model A	1	116,07	121,95	105	NO	NO
	2	65,49	69,67	105	OK	OK
	44	67,94	68,28	105	OK	OK
Model B	1	104,89	110,27	105	NO	NO
	2	64,73	68,30	105	OK	OK
	54	55,41	58,40	105	OK	OK
Model C	1	95,28	99,94	105	NO	NO
	2	60,26	65,67	105	OK	OK
	64	47,26	50,43	105	OK	OK
Model type	Cable	Semi harp [MPa]	Fan [MPa]	Detail category Spiral strands with metal or resin socketing [MPa]	Damage equivalent fatigue verification Semi harp config.	Damage equivalent fatigue verification Fan
Model A	1	116,07	121,95	150	NO	NO
	2	65,49	69,67	150	OK	OK
	44	67,94	68,28	150	OK	OK
Model B	1	104,89	110,27	150	OK	OK
	2	64,73	68,30	150	OK	OK
	54	55,41	58,40	150	OK	OK
Model C	1	95,28	99,94	150	OK	OK
	2	60,26	65,67	150	OK	OK
	64	47,26	50,43	150	OK	OK
Model type	Cable	Semi harp [MPa]	Fan [MPa]	Detail category Parallel wire strands with epoxy socketing [MPa]	Damage equivalent fatigue verification Semi harp config.	Damage equivalent fatigue verification Fan
Model A	1	116,07	121,95	160	OK	NO
	2	65,49	69,67	160	OK	OK
	44	67,94	68,28	160	OK	OK
Model B	1	104,89	110,27	160	OK	OK
	2	64,73	68,30	160	OK	OK
	54	55,41	58,40	160	OK	OK
Model C	1	95,28	99,94	160	OK	OK
	2	60,26	65,67	160	OK	OK
	64	47,26	50,43	160	OK	OK

propagation rates (P.R.) have been assumed: P.R.1 stands for a linear effective area reduction of 10% in 60 years; P.R.2 for 25% in 60 years; P.R.3 for 50% in 50 years; P.R.4 stand for 60% in 20 years. The main results of this investigation have been reported respectively in Tables 8-11. In Tables 8 and 9 the corrosion limit is defined according to the maximum resisting area to satisfy the fatigue verification for the acting loads. For instance, an area loss of 3.4% (Tables 8, boundary condition α, model A, cable n.1) or of 0.4% (Tables 9, boundary condition β, model A, cable n.1) imply an insufficient fatigue strength. Common effective area reductions have been observed for example by Mayrbaurl (2000) and Parag *et al*. (1999). Moreover, the consequent lifetime of cables under the aforementioned propagation rate (P.R.) is reported in Tables 10 and 11 in time-years. In this table, the results in terms of lifetime for the three models and the four propagation rates are shown assuming the boundary conditions α and β: the A model, with the largest spacing λ between the cables, is generally that with the small lifetime; the propagation rate 4 implies the most detrimental condition for all the considered models; while the C model implies the longer lifetime. For e.g. considering a detail category 160, the boundary condition

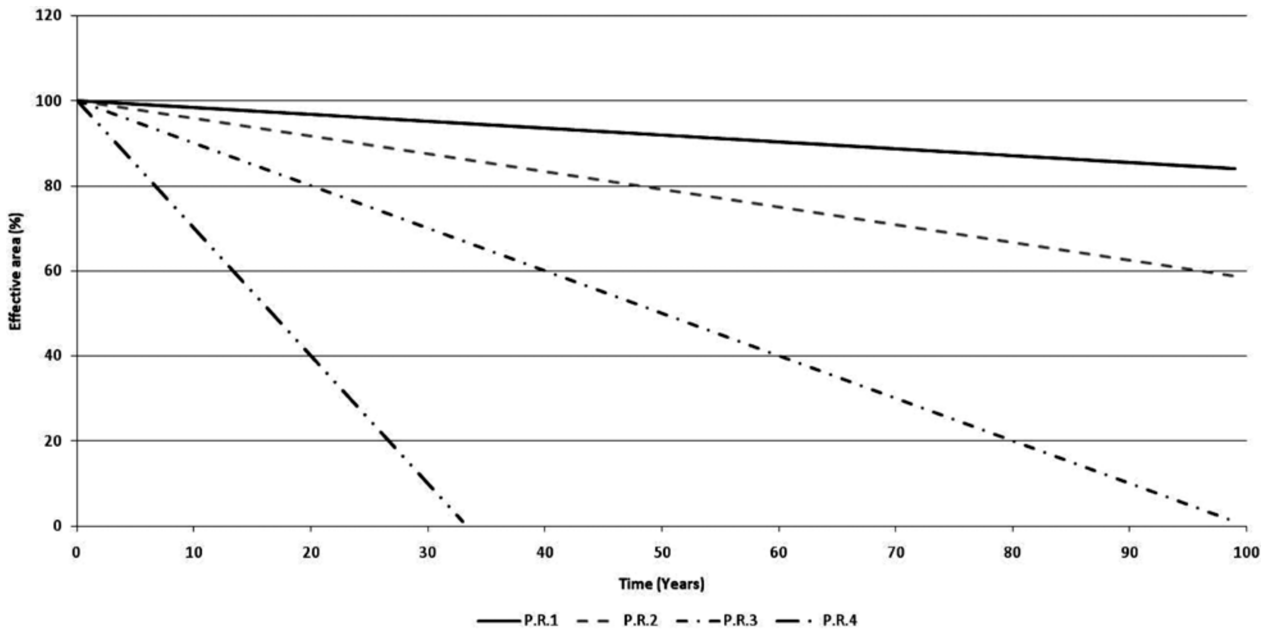


Figure 23. Corrosion propagation, different increase rate (P.R.i).

Table 8. Corrosion limit, boundary condition α

Model type	Cable	Semi harp [MPa]	Fan [MPa]	Detail category Parallel wire strands with epoxy socketing [MPa]	Corrosion limit Semi harp configuration [%]	Corrosion limit Fan configuration [%]
Model A	1	112,51	120,27	160	96,6	-
	2	63,22	68,51	160	54,3	58,8
	44	64,63	68,45	160	55,5	58,8
Model B	1	101,98	108,89	160	87,6	93,5
	2	62,43	67,52	160	53,6	57,9
	54	55,77	58,7	160	47,9	50,4
Model C	1	92,53	98,87	160	79,4	84,9
	2	60,26	64,93	160	51,7	55,7
	64	48,56	50,85	160	41,7	43,6

Table 9. Corrosion limit, boundary condition β

Model type	Cable	Semi harp [MPa]	Fan [MPa]	Detail category Parallel wire strands with epoxy socketing [MPa]	Corrosion limit Semi harp configuration [%]	Corrosion limit Fan configuration [%]
Model A	1	116,07	121,95	160	99,6	-
	2	65,49	69,67	160	56,2	59,8
	44	67,94	68,28	160	58,3	58,6
Model B	1	104,89	110,27	160	90,1	94,7
	2	64,73	68,30	160	55,6	58,6
	54	55,41	58,40	160	47,6	50,1
Model C	1	95,28	99,94	160	81,8	85,8
	2	60,26	65,67	160	51,7	56,4
	64	47,26	50,43	160	40,6	43,2

Table 10. Lifetime analysis, category detail C=160, boundary condition α

Model type	Cable	Lifetime P.R.1 Semi harp configuration [years]	Lifetime P.R.1 Fan configuration [years]	Lifetime P.R.2 Semi harp configuration [years]	Lifetime P.R.2 Fan configuration [years]	Lifetime P.R.3 Semi harp configuration [years]	Lifetime P.R.3 Fan configuration [years]	Lifetime P.R.4 Semi harp configuration [years]	Lifetime P.R.4 Fan configuration [years]
Model A	1	21	-	8	-	3	-	1	-
	2	>100	>100	>100	99	46	41	15	14
	44	>100	>100	>100	99	45	41	15	14
Model B	1	78	41	30	16	12	7	4	2
	2	>100	>100	>100	>100	46	42	15	14
	54	>100	>100	>100	>100	52	50	17	17
Model C	1	>100	95	49	36	21	15	7	5
	2	>100	>100	>100	>100	48	44	16	15
	64	>100	>100	>100	>100	58	56	19	19

Table 11. Lifetime analysis, category detail C=160, boundary condition β

Model type	Cable	Lifetime P.R.1 Semi harp configuration [years]	Lifetime P.R.1 Fan configuration [years]	Lifetime P.R.2 Semi harp configuration [years]	Lifetime P.R.2 Fan configuration [years]	Lifetime P.R.3 Semi harp configuration [years]	Lifetime P.R.3 Fan configuration [years]	Lifetime P.R.4 Semi harp configuration [years]	Lifetime P.R.4 Fan configuration [years]
Model A	1	2	-	1	-	0,35	-	0,12	-
	2	>100	>100	>100	97	44	40	15	13
	44	>100	>100	>100	99	42	41	14	14
Model B	1	62	33	24	13	10	5	3	2
	2	>100	>100	>100	99	44	41	15	14
	54	>100	>100	>100	>100	52	49	17	17
Model C	1	>100	89	43,75	34	18	14	6	5
	2	>100	>100	>100	>100	48	44	16	15
	64	>100	>100	>100	>100	59	56	20	19

α, model A, cable 1, the P.R. lifetime could be red for different configuration considered, the smi-harp and the fan. As a consequence, considering that the bridge design working life is typically considered 100 years, according to Eurocode (EN 1990, 2006), the optimal design configuration should be chosen also according these considerations.

9. Conclusions

Fatigue is one of the main problems affecting cable-stayed bridges. The fatigue life of a cable-stayed bridge can be improved by seeking the most efficient construction details, and optimizing the design of the suspension system in order to minimize live load stress ranges and lifetime detrimental effects. This study has been carried out in relation to alternative structural systems both in a fan and a perfect semi-harp cable arrangement; the possibility to extend the results obtained by varying the distance between the strands (λ) and the boundary conditions of the deck has been assessed. The static analysis has evidenced that the fan-shaped pattern is more detrimental in the external elements, whereas the situation is unfavourable for the semi-harp pattern corresponding to the internal cables, however, the outer strands have been confirmed to be more stressed by a normal stress excursion very close to its limit. The differences between linear static analysis and non linear static analysis in terms of load variations remain below 13,6%. Reducing the gap between strands (λ=10.83, λ=8.93, λ=7.58 m) or changing the boundary conditions (α or β), the improvement achieved by a semi-harp rather than by a fan configuration remains almost unchanged. Finally a fatigue and lifetime assessment has been carried out: fatigue strength resulted to be checked for the aforementioned case study (boundary condition α and β) only by adopting parallel wire strands with epoxy socketing (C=160); moreover, lifetime corrosion assessment has been studied in accordance to various propagation rates, and the critical resisting area loss of cables has been found for the various configurations and models.

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