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Existing Eurocodes applied to a membrane structure

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Abstract

This article tries gaining insight in the effect of the partial factor starting by the analysis of a steel cable net structure according to Eurocode 3. Eurocode specifies a value of 1.35 for the partial factor for prestress. A cable net structure built in 1958, was used as a case study. In spite of the lack of design guidelines and calculation tools 58 years ago, the analysis according to the current design standard Eurocode 3 for steel shows that the results match quite well with the original calculation. Generally speaking, a reduction in the cross-section areas is observed using Eurocode 3. For the considered steel cable net structure a weight saving of 17% for a partial factor for prestress 1.35 is obtained. If a partial factor for the prestress 1.0 could be considered, the weight reduction would be 4% more. Furthermore, the article investigates the effect of the partial factor for prestress (1.0 or 1.35), there prestress contributes to the stiffness in the non-lineair structural behaviour of membrane structures. The value of the partial factor for prestress to be considered is a source of disagreement between experts in different countries. With a similar geometry as the steel cable net structure, a membrane structure is designed and analysed. For the primary steel structure the partial factor for prestress 1.35 has to be applied. A 2% weight saving for the pretension factor 1.0 versus 1.35 is obtained if the tensile surface including the membrane and the edge cables is considered separate from the primary structure. A sound conclusion though requires a thorough in-depth study for different shapes and for different membrane types.

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1. Introduction

Nomenclature

γ_P	partial factor for prestressing actions
γ_{Gi}	partial factor for permanent actions
γ_Q	partial factor for variable actions
χ	reduction factor for the relevant buckling mode according to the Eurocodes
σ_{ult}	ultimate stress
L_{cr}	buckling length
VC	vertical cable
LC	lateral cable
CC	catenary cable
TC	tension cable

1.1. Problem statement

Since the 1950s architects and engineers developed an increasing interest in building lightweight structures (e.g. cable net structures, tensile surface structures). The low weight of these structures enables the designer to cover large spans. Even though tensile surface structures were introduced more than 60 years ago, there is still no harmonized European standard specific for membrane structures whereas the Eurocodes are well-established for conventional buildings. Moreover for existing buildings and temporary structures, like tensile surface structures, research still has to be done towards standardization. The geometrically non-linear behaviour of membrane structures gives rise to an action effect which is not proportional to the increase of the action. As the superposition principle is no longer valid, this paper focusses on the influence of the partial factor for permanent loading (in Ultimate Limit State (ULS)).

Tensile structures gain stiffness and stability due to their double curvature and prestress. The effect of a partial factor for prestress of 1.0 or 1.35 for the considered structure is analysed. More specific it examines whether the partial factor will generate the 'worst case' loading, knowing that the prestress contributes to the stiffness. In ULS the maximum stress in the surface (steel cable net or membrane) is checked and the minimum is verified to avoid that tension becomes negative. In Serviceability Limit State (SLS) the deflection is verified to avoid ponding as well as inversion of curvature. A case study is performed for a steel cable net structure which was initially built as a temporary canopy. This structure was a Band Stand on the World Exposition of 1958 at the Heysel in Brussels (analysis by André Paduart) [1]. The study consists of two parts: (1) steel cable net analysis according to the Eurocode and (2) a similar analysis for the membrane structure.

1.2. Methodology

Firstly, the cable net structure is calculated based on the principles of the limit state design according to Eurocode 0 and 1. The elements are calculated according to the design standard Eurocode 3 for steel. The effect of the relevant partial factors γ_{Gi} =1.0 and 1.35, applied according to EN 1993-1-11 [2] for the prestress P (thus $\gamma_{Gi} = \gamma_P$) is studied. The prestress is considered as a single permanent action "G+P" for steel structures with tension components (i.e. the cable net of Paduart). Paduart's original calculations, including the assumptions, are compared with today's practice.

Secondly, as a specific Eurocode for prestressed membrane structures is not yet established, a membrane structure with similar geometry and prestress as the cable net is designed and analysed in the same way, using the same load combinations. It is evaluated if the approach adopted for the cable net is appropriate for the structural membrane cover.

2. Effect of the partial factor for prestress on safety and serviceability

The persistent design situation, referring to the condition of normal use is selected. In order to encompass all conditions that can occur during or after construction (e.g. creep), particular attention needs to be paid to the partial factor for prestress γ_P. Setting the prestress level during or adjusting after construction is not always very precise. That is why in practice the applied prestress level could be higher (or lower) than the design value. The most unfavorable combination of actions for the design stress levels in ULS can, according to EN 1990 A.2.2.1(12) [3] and to the Prospect for European Guidance for the Structural Design of Tensile Membrane Structures [4], be obtained assuming prestress as an additional action besides the considered external actions. Prestress being a permanent action, the partial factor for prestress $\gamma_P = 1.0$ and $\gamma_P = 1.35$ are used. As wind loading on doubly curved structures remains insufficiently defined in Eurocode 1, approximations have to be made.

In Serviceability Limit State (SLS), the deflection is verified to avoid ponding as well as inversion of curvature. Decreasing the prestress reduces the stiffness and thus will lead to unfavorable larger deflections. A partial factor for prestress $\gamma_P \leq 1.0$ could reflect this. In the present study, the partial factor for prestress $\gamma_P = 1.0$ is considered in SLS.

3. Case study description

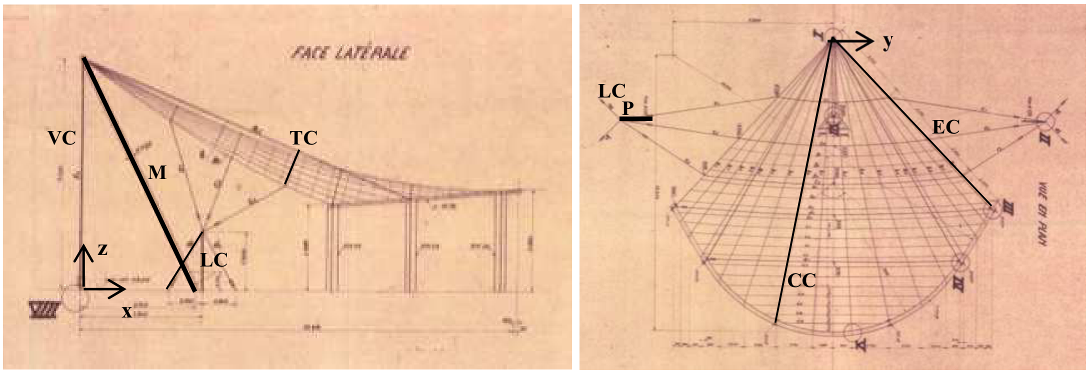

Fig. 1: Designation of the different elements and axes: VC vertical cable, LC lateral cable, CC catenary cable, TC tension cable, EC edge cable, M Mast and P Pole (left: elevation, right: plan view) [5, file 2326]

Before the structural Eurocodes were established, engineer A. Paduart (1914-1985) analysed the structure designed by architect O. Schlomblood named "the Band Stand". It was an anticlastic cable net structure that sheltered the musicians against weather conditions. The length (denoted as *x*-direction, Fig. 1, left drawing) equals 13.91 m, the width (denoted as *y*-direction, Fig. 1, right drawing) equals 20.4 m. The cable net goes from the top of the high mast at a height of 7.5 m to a lower curved concrete wall with a height varying between 2.82 m and 3.22 m (denoted as *z*-direction, Fig. 1, left drawing). The cable net consists out of sixteen catenary cables (CC) in the longitudinal or *x*-direction and five tension cables (TC) in the transverse direction or *y*-direction. The top of the high mast was connected to the ground by a vertical cable. The top of the lateral poles were connected to the ground by two lateral cables. The following abbreviations are used: vertical cable: VC, lateral cable: LC, catenary cable: CC, tension cable: TC and edge cable: EC.

Early tensile structures on Expo '58, the World Exhibition, were the subject of research of one of the co-authors' MSc-thesis. The geometry, loads and material information in this article are based upon this thesis [6] and later publication [7]. The canvas, of which the material properties are unknown, was merely placed between the tension and the catenary cables. Thereby it was not tensioned and so it did not contribute to the structural stability. However the Band Stand could have been executed as a prestressed membrane structure.

3.1. Materials and sections considered in the original calculation note

Paduart used a reduction coefficient 0.39 to take into account buckling phenomena for the high mast and the lateral poles. The buckling length for both was calculated assuming a hinge at the top and a clamped boundary condition at the bottom. Table 1 gives the data of the components calculated by Paduart.

Table 1: Properties of the components calculated by Paduart

	Mast	Pole
Buckling length [m]	6.08	1.9
Outer diameter [mm]	159	51
Wall thickness [mm]	6	3
Radius of gyration [mm]	54.1	17
Slenderness [-]	112	112

Assuming a steel grade S355 and buckling curve *c* for cold formed circular hollow sections, according to EN1993-1-1 [8] a reduction factor $\chi = 0.34$ would be obtained. This gives smaller values for the buckling stress. The steel grade is chosen as an upper limit for the stresses obtained by Paduart equal to 1660 kg/cm² (163 MPa) for the mast and 1102 kg/cm² (108 MPa) for the poles. The allowable stress method used by Paduart seems thus to be conservative. However, in the limit state design according to Eurocodes, partial safety factors are applied to the load. Knowing that this is not the case in Paduart's calculation, univocal conclusions on safety margins shall not be drawn based upon this buckling resistance check. Note that due to the use of the calculation note of Paduart, the units used are not always according to the SI-units, in which case a conversion is added between brackets.

No specifications were found in the archival documents about the dimensions of the used cables. However in the calculation note of Paduart the break load per group of cables is specified. This load in the cables is obtained by multiplying the maximum tension in the different groups of cables with a safety factor of 2.5. No ultimate strength values for the cables of the Band Stand were found. Historical documents of a contemporary building mentioned values for the ultimate strength σ_{ult} = 1570 MPa. The break load can be used to determine the sections of the different groups of cables. In Table 2 the break load per group of cables and the eventual corresponding diameters are given. The diameters are calculated according to the found ultimate strength. It must be noticed that the radius is obtained considering the cross-section of the cable as a full circular section.

Table 2: Break load per group of cables and the corresponding diameter

Group of cables	N_{break} [kg (kN)]	Diameter [mm]
Catenary cables (distributed load 33 kg/m²)	1730 (16.9)	3.71
Tension cables (distributed load 47 kg/m²)	10600 (104.0)	9.18

3.2. Load models considered in the original calculation and according to the Eurocode

In the calculation note of Paduart, the following load cases are considered:

- Self-weight of the construction: 6 kg/m^2
- Wind: 50 kg/m^2 (upward - in Paduart's calculations wind acts vertically) for the tension cables
- Accidental loading: 10 kg/m^2 (downward)

The self-weight has been combined with the distributed loads (25 kg/m^2) representing the prestress:

- Load on the catenary cables: 25 kg/m^2 + 3 kg/m^2 = 28 kg/m^2

- Load on the tension cables: 25 kg/m^2 - 3 kg/m^2 = 22 kg/m^2

The maximum loading per cable direction:

- Load on the catenary cables: 28 kg/m^2 + 5 kg/m^2 (accidental) = 33 kg/m^2
- Load on the tension cables: 22 kg/m^2 + 25 kg/m^2 (wind) = 47 kg/m^2

The latter four values can be understood as follows: the wind load will partly be taken by the tension cables (increasing the stress), partly by the catenary cables (reducing the stress). To remain tensioned under load, the prestress is set to a distributed load of 25 kg/m^2 (0.25 kN/m^2). From this, the prestress per cable segment can be calculated. The cable forces under the maximum loading of 33 kg/m^2 (0.33 kN/m^2, catenary cables) and 47 kg/m^2 (0.47 kN/m^2, tension cables) are obtained by applying a factor of 33/25 and 47/25 respectively.

In the analysis according to the Eurocode (performed with the software Easy [9]), the following load cases are considered:

- The prestress, being a design parameter, is chosen according to the prestress foreseen by Paduart
- For wind loading six cases are specified according to EN 1991-1-4 [10] Table 7.1, Table 7.3 and Table 7.7 and summarised in Fig. 2: cases 1, 3, 4 and 6 can be decisive
- As the canopy was designed to be dismantled after summer, behaviour under snow load was not checked

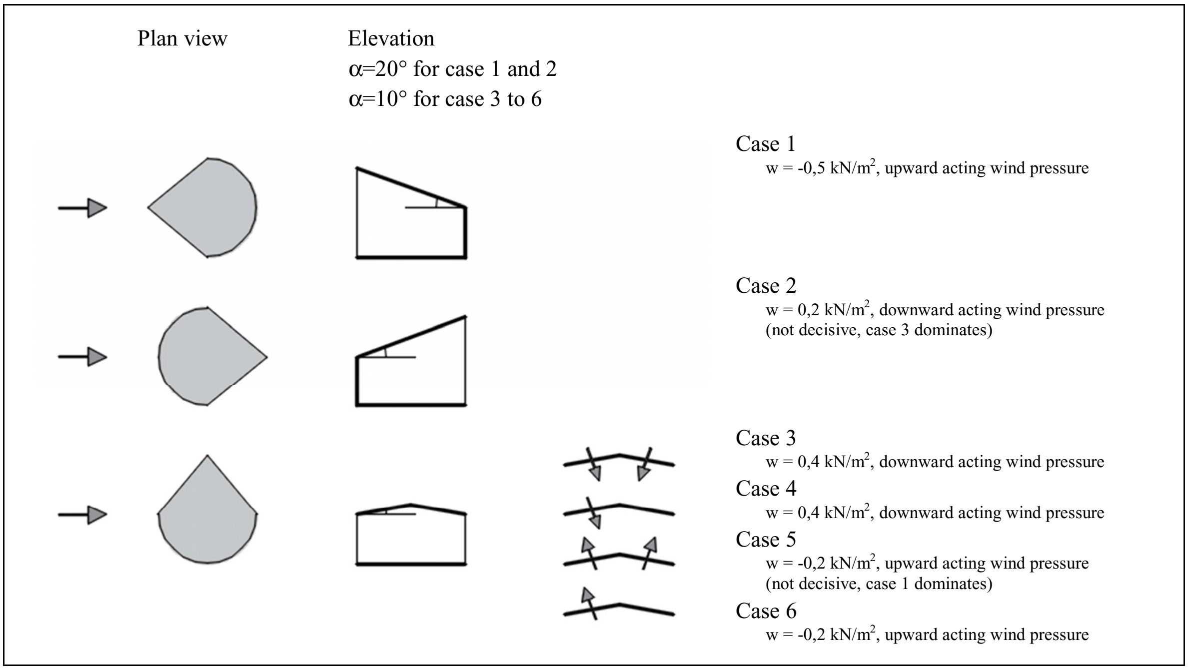

Fig. 2: Un-factored wind pressure, to be applied perpendicular to the surface

4. Cable net structure

The form finding of the steel cable net was done in EASY [9] with the force densities obtained from the forces specified by Paduart. He obtained the break load of the cables (1st line in Table 3) by multiplying the maximum tension force by a safety factor of 2.5. With corresponding sections and the Young's modulus of the cables 140 kN/mm^2 (not specified in the calculation note of Paduart) the axial stiffness of the elements (= E*A) is derived and a static analysis without external loading was performed. The last two lines in Table 3 show the pretension forces. As expected, increasing the partial factor for prestress from 1.0 to 1.35 increases the forces with 35%.

Table 3: The break load for the cables (according to Paduart), the stiffness in the elements and the forces under prestress (3D analysis)

		VC	LC 1	LC 2	CC	TC	EC	Mast	Pole
Calculation Paduart	Break load [kg]	34200	5300	3100	1730	10600	2400	-18700	-1945
	Break load [kN]	335	52	30	17	104	24	-183	-19
	Section [mm²]	245	39	18	11	68	15	2880	452
	E-modulus [kN/mm²]	140	140	140	140	140	140	210	210
	Stiffness [kN]	34326	5465	2538	1515	9451	2100	604800	94920
Calculation according to Eurocode	γ_P=1.0 Force [kN]	95	11	11	9	9	11	11	23
	γ_P=1.35 Force [kN]	129	14	14	12	12	15	15	30

Only the four dominant variable wind load cases (Cases 1, 3, 4 and 6, see Fig. 2) are retained in the combinations of actions in the ULS check with a partial factor for variable actions γ_Q = 1.5. To evaluate the influence of the partial factor for prestress γ_P on the structural design, this factor is set first to 1.0, next to 1.35. From the comparison of the results in Table 4 (the underlined values are the maxima per element for the four combinations of actions), it can be seen that increasing the prestress with 35%, the maximum forces in the elements under variable loading will also increase, but not as much as 35%. Part of the loading is transferred to the cables in the other direction causing there a reduction in the tension.

Table 4: Maximum forces in the elements in ULS for the partial factor for prestress 1.0 and 1.35

Max. normal forces [kN]	Wind cases	VC	LC 1	LC 2	CC	TC	EC	Mast	Pole
Factor wind: 1.5, prestress: 1.0	1	81	41	31	10	59	8	-118	-38
	3	121	0	1	14	6	9	-189	-1
	4	110	4	3	14	16	10	-170	-4
	6	96	27	22	13	40	9	-145	-24
Factor wind: 1.5, prestress: 1.35	1	115	44	33	14	64	11	-168	-40
	3	142	1	3	17	16	10	-219	-2
	4	139	8	6	18	24	11	-214	-10
	6	127	30	24	17	46	12	-192	-27

The cross-section area of cables and poles is updated based upon the resistance check of the elements as well as the buckling stability check of the mast and poles for the four ULS combinations of actions according to Eurocode 3, with the partial factor for the steel material for cables being 1.2 and for the mast and steel poles 1.0. For the cables a value for the Young's modulus of 160 kN/mm^2 was considered [11]. Table 5 summarizes the results. The original calculation note assumed an ultimate stress for the steel cables equal to 1570 MPa and a break load which is 2.5 times the maximum force occurring in each group of cables (underlined values in Table 3). Whereas EN 1993-1-11 [3] gives a nominal tensile strength for round steel wires of 1770 MPa and, with a partial factor of 1.2, a design value of 1475 MPa.

Table 5: Cross-section area and stiffness according to Eurocode 3 for the partial factor for prestress 1.0 and 1.35

		VC	LC 1	LC 2	CC	TC	EC	Mast	Pole
Factor wind: 1.5,	Section [mm²]	82	28	21	10	40	6	2289	410
prestress: 1.0	Stiffness [kN]	13082	4426	3384	1562	6400	1031	480703	86052

Factor wind: 1.5,	Section [mm²]	96	30	22	12	43	8	2421	419
prestress: 1.35	Stiffness [kN]	15349	4751	3525	1898	6932	1258	508397	88030

When comparing Paduart's calculation and the analysis according to the Eurocode, it has to be taken into account that the considered load cases are different. The calculation according to the Eurocode is more accurate, as in the initial analysis only one wind load was considered, being a uniformly distributed vertical uplift loading.

Nevertheless the results for the high mast and lateral poles match rather well. For instance, the cross-section area of the high mast in Paduart's calculation note is 28.8 cm², for a maximum load of 18700 kg (183.4 kN). The calculation according to the Eurocode gives for the high mast 24.2 cm² (Table 5) for a maximum design load of 219 kN (Table 4). The maximum force values for the catenary cables, tension cables and edge cables are of the same order of magnitude (Table 3 and Table 4), but the maximum force in the vertical cable is much higher in the calculation by Paduart.

Generally, the cross sections obtained from the calculation according to the Eurocode are smaller than the initial ones mentioned in the analysis by Paduart, only a few sections are slightly bigger. The calculation according to the Eurocode, being a 3D analysis, is more accurate. Besides the resistance check of the cables and the resistance and stability check of the poles, the verification of the results show that for the partial factor for prestress equal to 1.0 (as well as for 1.35 but this situation is less stringent) the force in some cables are zero. This means that the cable net is not bi-directionally tensioned for the considered load case. For reasons of compatibility with Paduart's initial setting, the prestress value was kept. Normally if zero values are obtained for a certain load case, the pretension of the cable net must be set higher until the cable net stays tensioned under all specified load cases.

The density of steel is 7850 kg/m³. The weight of the steel cable net and supporting structure obtained by Paduart was 1.61 kg/m². It is reduced to 1.27 kg/m² (21% reduction) and 1.33 kg/m² (17% reduction, Table 6) when the calculation is performed according to the Eurocode with the partial factor for prestress set to 1.0 and 1.35 respectively. It should be noted that the weight of cover, connections and foundations is not included.

Table 6: Weight of the steel cable net structure for the partial factor for prestress 1.0 and 1.35

		Primary structure					Cable net + edge cables		
		VC	LC 1	LC 2	Mast	Pole	CC	TC	EC
Factor wind: 1.5,	Section [mm²]	82	28	21	2289	410	10	40	6
prestress: 1.0	Length [m]	7.5	6.2	6.2	8.4	5.6	98.1	85.9	24.1
	Weight [kg]	0.93	0.28	0.19	150.94	18.01	2.16	4.55	0.43
	Total [kg/m²]					**1.22**			**0.05**
Factor wind: 1.5,	Section [mm²]	96	30	22	2421	419	12	43	8
prestress: 1.35	Length [m]	7.5	6.2	6.2	8.4	5.6	98.1	85.9	24.1
	Weight [kg]	1.09	0.29	0.20	159.64	18.43	2.35	4.64	0.48
	Total [kg/m²]					**1.28**			**0.05**

Deflections for the four combinations of actions in SLS (with the partial factor for wind and for prestress equal to 1.0) were calculated in EASY. Paduart did not report on the deflection in his calculation note. The deformation results in EASY prove that ponding and inversion of curvature do not occur. Maximum deflections are listed in comparison with the maximum deflections occurring in the prestressed membrane structure in Table 12.

5. Membrane structure

Under the same load combinations, the structure is re-designed as a tensile membrane structure [12]. The membrane prestress is set to 6.5 kN/m in the longitudinal direction (*x*-direction) and 6 kN/m in the transverse direction (y-direction). This value is set higher than the prestress in the cable net (~2 kN/m) to avoid inversion of curvature under loading. The properties of the membrane are summarized in Table 7. The chosen grid for the membrane is regular orthogonal.

Table 7: Properties of the membrane

PVC-coated polyester membrane	
Stiffness warp direction [kN/m]	753.0
Stiffness weft direction [kN/m]	612.0
Crimp [kN/m]	219.5
Shear [kN/m]	30.0
Weight per m² [kg/m²]	1.05

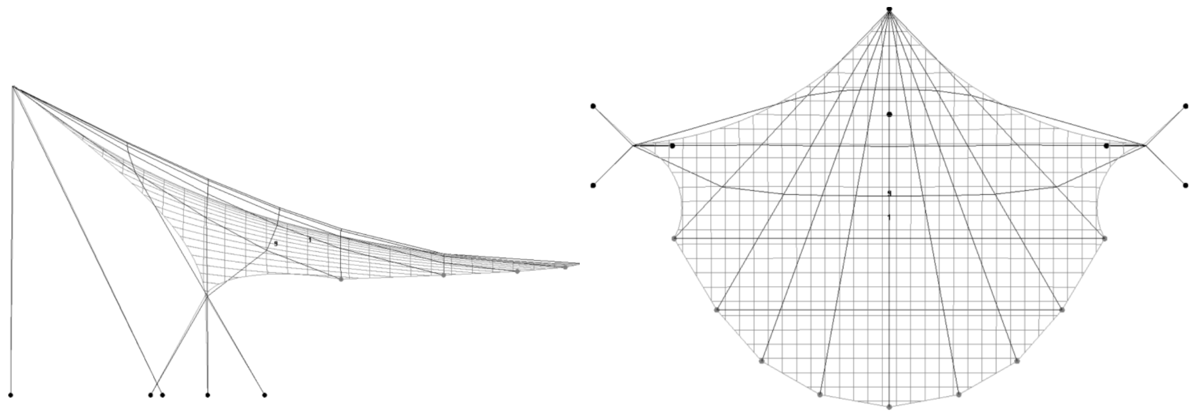

Fig. 3: Membrane structure (rectangular mesh) fitting the shape of the cable net structure as good as possible (left: elevation, right: plan view)

The process of finding the appropriate equilibrium shape for the membrane structure was one of trial and error. The basic principle was that the coordinates of the points connecting the membrane to the primary structure stay at the same position and that the shape fits well. In Fig. 3, it can be seen that the anti-clastic curvature of the membrane is not exactly the same as the curvature of the cable net, but that the overall geometry corresponds.

The influence of the partial factor for prestress 1.0 or 1.35 is investigated for the prestressed membrane structure. The same ULS and SLS load cases as considered for the cable net are analysed. Table 8 summarizes the maximum normal forces for the steel elements depending on the wind load case. The maximum forces per wind case are underlined. From this table it can be derived that wind case 1 and wind case 3 are the most critical. Table 9 summarises the sections for the steel members based upon the resistance check of the elements as well as the buckling stability check of the poles for the four ULS combinations of actions according to Eurocode 3.

The impact of a partial factor for prestress 1.0 or 1.35 on the weight of the structure is analysed. As the main focus of this paper concerns the membrane, the influence is considered for the whole structure as well as for the membrane including the edge cables. In all simulations the same PVC-coated polyester membrane is used.

It is observed (Table 10) that when using a partial factor for prestress 1.0 instead of 1.35 the weight per covered area of the total structure decreases with 6% (connections and foundation not included). If only the tensile surface, containing the membrane and the edge cables, is considered a decrease of only 2 % is noticed.

Table 8: Maximum normal forces in the steel elements for the partial factor for prestress 1.0 and 1.35

Max. normal forces [kN]	Wind cases	VC	LC 1	LC 2	EC 1	EC 2	Mast	Pole
Factor wind: 1.5, prestress: 1.0	1	152.0	94.1	82.3	108.7	30.4	-261.3	-89.1
	3	184.8	55.9	66.1	112.5	11.5	-338.8	-66.7
	4	174.0	61.5	68.2	106.6	13.3	316.6	-69.1
	6	156.0	80.2	75.2	99.8	23.2	-275.1	-81.4
Factor wind: 1.5, prestress: 1.35	1	208.5	113.5	104.0	137.1	33.6	-360.2	-110.2
	3	237.3	79.2	89.8	144.5	16.9	-434.6	-91.8
	4	229.1	84.1	90.4	139.6	18.4	-416.5	-94.3
	6	213.0	101.0	98.2	130.4	27.3	-376.3	-104.7

Table 9: Section and stiffness for the supporting components and edge cables for the partial factor for prestress 1.0 and 1.35

		VC	LC1	LC2	EC1	EC2	Mast	Pole
Factor wind: 1.5, prestress: 1.0	Section [mm²]	125.3	63.8	55.8	76.3	20.6	3575.0	710.0
	Stiffness [kN]	20046.1	10207.5	8927.5	12203.4	3297.6	149100.0	750750.0
Factor wind: 1.5, prestress: 1.35	Section [mm²]	160.9	76.9	65.5	92.9	23.1	3900.0	770.0
	Stiffness [kN]	25741.0	12311.9	10478.6	14871.9	3699.0	819000.0	161700.0

with the partial factor for prestress 1.35 the weight of the primary structure has increased 68% for the membrane solution (2.15 kg/m²) compared to the cable net structure (1.28 kg/m²). The tensioned membrane requires a heavier supporting structure, mainly caused due to the higher prestress which is needed to avoid inversion under wind.

Table 10: Weight of the tensile surface structure for the partial factor for prestress 1.0 and 1.35

		Primary structure					Membrane + edge cables		
		VC	LC 1	LC 2	Mast	Pole	Membrane	EC 1	EC 2
Factor wind: 1.5, prestress: 1.0	Section [mm²]	125.3	63.8	55.8	3575.0	710	-	76.3	20.6
	Length (surface) [m(²)]	7.5	6.2	6.2	8.4	5.6	(146.2)	23.1	8.4
	Weight [kg]	7.38	3.1	2.72	235.74	31.21	153.51	13.83	1.35
	Total [kg/m²]					**1.96**			**1.18**
Factor wind: 1.5, prestress: 1.35	Section [mm²]	160.9	76.9	65.5	3900	770	-	92.95	23.12
	Length (surface) [m(²)]	7.5	6.2	6.2	8.4	5.6	(146.2)	23.1	8.4
	Weight [kg]	9.47	3.87	3.29	257.17	33.85	153.51	16.85	1.52
	Total [kg/m²]					**2.15**			**1.20**

It is observed from Table 11 that when using a partial factor for prestress 1.35 instead of 1.0 the ratio between the maximum ocurring stress and the tensile strength decreases with 4 %.

Table 11: Ratio of the maximum tensile stress in the membrane versus the strength, for the partial factor for prestress 1.35 and 1.0

Partial factor for prestress	1.35	1.0
Maximum tensile stress (kN/m)	15.68	15.04
Tensile strength (kN/m)	80	80
Ratio	**5.1**	**5.3**

In SLS it is verified whether the structure is suffering from the phenomena ponding or inversion. The partial factors for prestress and for wind load are both set to 1.0. Table 12 gives the maximum deflection for each load case for the steel cable net (column 2) and for the prestressed membrane (column 3). Wind case 1 (uniform uplift) is the most critical for the prestressed membrane while wind case 6 causes the highest deflection for the steel cable net.

Table 12: Maximum deflection in SLS for the four combinations of actions

Wind case	Deflection in the steel cable net [m]	Deflection in the tensioned membrane [m]	Inversion	Ponding
1	0.15	0.42	No	No
3	0.07	0.18	No	No
4	0.15	0.17	No	No
6	0.18	0.30	No	No

6. Conclusions

In this study a pretensioned steel cable net was analysed according to the Eurocode, using a partial factor for prestress of 1.35 in ULS. Compared with the original calculation of 1958, the analysis according to the Eurocode gave more accurate and economical results.

As a case study, a similar membrane structure was analysed under the same load cases. The approach adopted for the cable net is applicable for the structural membrane cover. The analysis of the studied case allowed comparing both the steel cable net and the membrane structure and confirmed the limited effect of the augmentation in the partial factor for pretension by 35% versus the increase in weight for the cable net structure by 5% and the increase in weight for the tensioned membrane cover by only 2%.

The partial factor for prestress 1.35 in ULS has to be used for the dimensioning of the steel supporting structure any way. A partial factor for the membrane prestress higher than one takes into account that: (1) in practice the initial pretension of the membrane could be higher than the design value and (2) a decrease in tension in time due to the creep phenomenon could be anticipated without an excessive increase in weight of the structure.

A broader in-depth study for membrane structures is needed (different shapes, typologies, material properties …) to be able to postulate general conclusions. Further research will focus on the structural reliability of membrane structures.

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