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RELIABILITY ASSESSMENT OF OVERHEAD TRANSMISSION LINE TOWERS IN THE REPUBLIC OF CROATIA

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Original scientific paper

It is a fact that in some areas of Croatia overhead transmission lines had suffered extensive damage. Transmission line towers in Croatia are still designed by deterministic regulations, and modern European semi-probabilistic standards, though accepted, cannot be used because the Croatian normative aspect has not been adopted yet. An originally made map of damages of the overhead transmission lines in the Republic of Croatia for the period from 1979 till 2010 was used as a basis for the analysis of the current Regulation and modern European standards for calculation of the transmission line towers. The map was made by a systematic study of the Dalekovod Project Ltd.'s archives and includes damages which were caused by wind load, ice load, or a combination of ice and wind loads. The research presented in this paper includes analysis of six lattice steel towers, of which three were damaged, according to the current Regulation, EN 50341-1, and the same with the application of the German normative aspect EN 50341-3-4. Based on the results of the research guidelines for the development of the Croatian normative aspect are suggested.

Keywords: *assessment of reliability, Croatian normative aspect, European standards, map of damages, Regulation, transmission line tower*

Procjena pouzdanosti dalekovodnih stupova u Republici Hrvatskoj

Izvorni znanstveni članak

Činjenica je da su dalekovodi na nekim područjima Republike Hrvatske doživjeli havarije. Dalekovodni stupovi se u Republici Hrvatskoj još uvijek projektiraju po determinističkim propisima, a suvremene europske semi-probabilističke norme, iako prihvaćene, su nefunkcionalne jer još uvijek nije donesen prateći Hrvatski normativni dodatak. Osnova za analizu važećeg Pravilnika i suvremenih europskih norma za proračun dalekovodnih stupova bila je izrada karte havarija dalekovoda u Republici Hrvatskoj za razdoblje od 1979. do 2010. godine. Karta je izrađena sustavnim istraživanjem arhive tvrtke Dalekovod Projekt d.o.o. i obuhvaća havarije u kojima su uzroci bili djelovanje vjetra, djelovanje leda ili kombinacijom vjetra i leda. Istraživanje koje je prikazano u ovom radu obuhvaća analize šest nosivih čeličnih rešetkastih stupova, tri oštećena u havariji, prema važećem Pravilniku, EN 50341-1, te istoj uz primjenu njemačkog normativnog dodatka EN 50341-3-4. Na temelju rezultata istraživanja predložene su smjernice za izradu Hrvatskog normativnog dodatka.

Ključne riječi: *dalekovodni stup, europske norme, Hrvatski normativni dodatak, karta havarija, Pravilnik, procjena pouzdanosti*

1 Introduction

The development of the regulations for the overhead transmission lines in the Republic of Croatia started in 1949. Until today, regulations and standards for overhead transmission lines have undergone several changes. The last major change of the "Regulation on technical standards for construction of overhead transmission lines voltage 1 kV to 400 kV" [1] was in 1988 and it is still in application.

In the process of joining the European Union, Croatia has committed itself to adopting European standards, among which is the standard for the design of overhead transmission lines "EN 50341-1 Overhead electrical lines exceeding AC 45 kV" [2]. The same standard was adopted in Croatia in the year 2008 under the name HRN EN 50341-1, [3]. Croatian normative aspect is necessary for its application and it should be created by taking into account special features of design of the overhead transmission lines in the Republic of Croatia.

As all structures, overhead transmission line towers are exposed to various weather conditions that can be one of the potential causes of damage. It is a fact that the overhead transmission line is a line structure that often exceeds hundreds of kilometres, so the probability of extreme weather conditions affecting it is far greater than on the rest, spot-located, structures. Over the years, the damages on overhead transmission lines have been reported in some areas of Croatia. However, systematic analysis of possible critical areas has not been done yet.

It is the fact that the map of the damages of the overhead transmission lines provides an overview of the behaviour of the towers in real load conditions. This article presents the originally created map of the damages covering all detected rehabilitation projects of overhead transmission lines of 35 kV to 400 kV voltages in which the damage on overhead transmission line towers was noted. The map covers the period from 1979 till 2010 and it is the result of systematic research of the Dalekovod Project Ltd.'s archive. The background on which the map of the damages is made is a map of the Croatian electric power system for 110, 220 and 400 kV overhead transmission lines. That background map was produced by HEP OPS Ltd., who allowed using it for the research described in [4]. Damages were classified according to the causes of damage; damage caused by the wind load, ice load and the combined load of wind and ice loads. Damages from other causes (landslides, tree falls, war, etc.) are not shown on this map.

Considering the adoption of the Croatian national normative aspect in the near future, as a necessity for the application of the EN 50341-1, [3] it is interesting to compare the design of transmission line towers built in different areas of Croatia when calculated according to the current Regulation [1], according to the basic European standard EN 50341-1 [2] and by [2] using the German normative aspect EN 50341-3-4 [5] (hereinafter only the EN 50341-3-4, [5]).

Therefore, this paper presents the analysis results of six supporting transmission line towers used in various areas of Croatia. Three towers were selected from lines that have experienced damage, and each of them collapsed owing to a different load, or a combination of loads. It is assumed that the most reliable design is the one in which the simulated behaviour of the overhead transmission line towers coincides with the recorded mode of the tower's failure. On the basis of the conducted analysis, guidelines for the development of Croatian normative aspect are given at the end of the paper.

2 The map of damages

Damage is considered as the 'malfunction' of the overhead transmission line of considerable complexity that requires higher costs to be repaired, and besides that, the overhead transmission line is out of use for a long period of time and it requires the intervention of professional teams to be functional again, [6].

On the map of the damages, Fig. 1, the exact positions of the collapsed towers that failed in the damages of overhead transmission lines are marked. The research includes 67 rehabilitation projects of the damages. To get higher visibility, the damaged towers were listed in a specific area regardless of voltage level, and these values are entered near the position of the damaged towers. For better perception of the damage, in addition to the causal actions, the level of tower damage is also specified. For each causal action (combination) as for the level of damage it caused a specific symbol was given. Damages are classified into (Fig. 1):

- Knocked down or heavily damaged tower - the tower that almost entirely needs to be replaced to put the transmission line back in service.
- Medium damaged tower - the tower where the majority of the existing tower body can be used to repair it. On these towers whole tower heads and possibly a couple of diagonals under their heads were damaged.
- Slightly damaged tower - the tower on which the damage occurred mainly on the cross arms and/or the top.

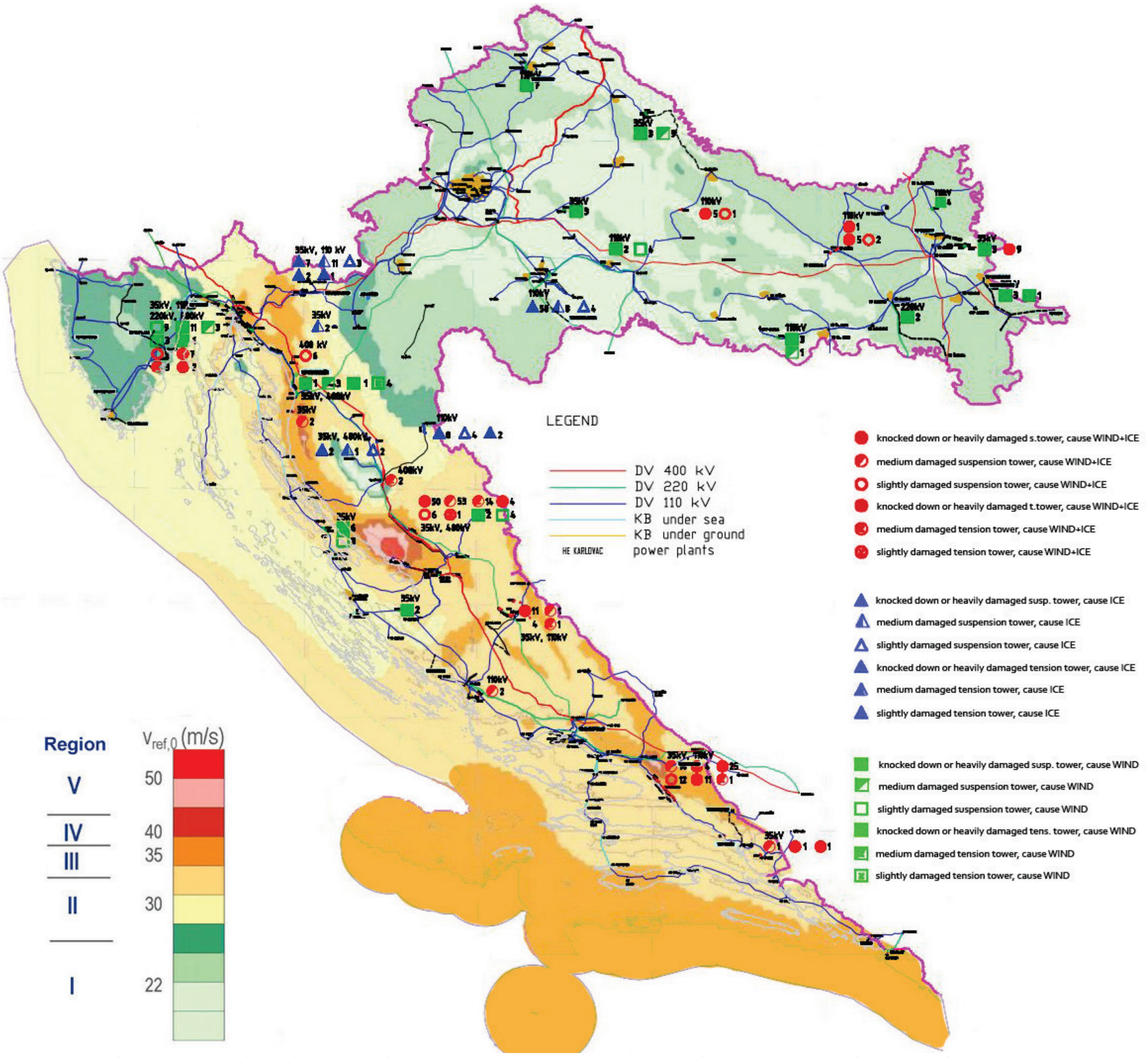


Figure 1 The map of the damages charted on map of the Croatian electric power system, folded with map of the wind from the HRN ENV 1991-2-4 [7]

Tab. 1 shows the basic statistic data of the analysed line damages. The causes of the damages are given in the first row. Depending on the damage cause, the percentages of the rehabilitation projects and weight of all damaged towers are given in the second and third row, respectively.

The percentages of the damaged supporting towers (the rest are tension towers) are given in Tab. 2.

EN 50341-1 [2] states that the supporting tower should be the least reliable component of the overhead transmission line, and should be the first to fail when the line is exposed to loads that exceed the design values. Next to fail should be the foundation and the equipment of the supporting tower, respectively. The parts of line for which the probability of survival should be at least 90 % are the tension towers and wires.

Table 1 Basic statistical data of the overhead

Damage cause	Wind load / %	Ice load / %	Combined wind and ice load / %
The percentage of rehabilitation projects	39	12	49
Percentage of weight of the damaged towers	10	9	81

Table 2 The percentages of the damaged supporting / tension towers

Cause of the damage	Wind load / %	Ice load / %	Combined wind and ice load / %
Percentage of the damaged supporting towers	94	98	87
Percentage of the damaged tension towers	6	2	13

It is clear from Tab. 2 that the probability of tension towers survival for combined wind and ice loads is 100 – 13 = 87 %. Therefore, required condition is not satisfied for the combination of wind and ice loadings. However, according to [2], the probability of survival should consider all load combinations, and so if we look at the statistical data in [4], it follows that the probability of survival for all tension towers in Croatia is 92 % and consequently the required condition is satisfied.

3 Loads on overhead transmission line towers

Neither the Regulation [1], standards EN 50341-1 [2] and EN 50341-3-4 [5] have the combinations of the loads defined in the same way nor are the input parameters for design the same. In the next few lines only the main differences between the Regulation, [1], and European standards [2, 5] are listed. The comparative review of the load combinations is given at the end of this section (Tab. 3).

Regulation, [1], is based on a deterministic approach, while the modern European standards [2, 5] are based on a probabilistic approach. Design of the compression members is similar, while design of the bolts and the tension members varies between Regulation [1], and European standards [2, 5]. Regulation [1], uses a global safety factor, while EN 50341-1 [2] and EN 50341-3-4 [5] use partial factors.

Table 3 The basic differences in determination of wind load according to the Regulation [1] and European standards [2, 5]

	The increase of the wind speed with height of the tower	The reduction of the wind span	The drag factor for the tower	The drag factor for the wire
Regulation	no	no	2,6	1,0
EN 50341-1	ln	yes	By calculation	1,0
EN 50341-3-4	linearly	yes	2,8	Dependant on the wire diameter

When designing according to Regulation [1] the ice load q_{ice} should be taken as the highest additional weight (ice) that occurs on average every five years, and can be expressed as:

$$q_{\text{ice}} = k_{\text{dt}} \cdot 0{,}18 \cdot 9{,}81 \cdot \sqrt{d}\ , \quad \text{N/m} \tag{1}$$

where d is the diameter of the wire (mm) and k_{dt} is additional load (weight) factor. The minimum additional load factor is 1,0. Common additional loads factors are 1,0; 1,6; 2,5 and 4,0, although in certain areas of the Gorski Kotar overhead transmission lines were designed with the additional load factor of up to 6,0. Data for the ice load are usually defined in collaboration with the National Meteorological and Hydrological Institute and they are based on the values applied to existing power lines along the projected route.

European standard EN 50341-1 [2] requires the reference value of ice depending on the required level of transmission line reliability (usually a reliability level 1 which corresponds to the return period of T = 50 years). In the absence of such data a standard allows designers to use data of the ice load based on the long-term experience and for the purposes of calculating with this standard the value for the ice load from the basic design of transmission line tower was adopted.

EN 50341-3-4 [5] defines ice loads according to three zones:

Ice load zone 1 $$q_{\text{ice},T} = 5 + 0{,}1 \cdot d, \ \text{N/m}, \tag{2}$$

Ice load zone 2 $$q_{\text{ice},T} = 10 + 0{,}2 \cdot d, \ \text{N/m}, \tag{3}$$

Ice load zone 3 $$q_{\text{ice},T} = 20 + 0{,}4 \cdot d, \ \text{N/m}. \tag{4}$$

Zone 1 applies for the areas where, due to the climatic conditions and confirmed by the long-term experience, only low ice loads occur which did not result in damage of overhead transmission lines. Zone 2 applies for the areas where, due to the climatic conditions and confirmed by the long-term experience, high ice loads have to be expected which among other things resulted in damage of overhead transmission lines. Zone 3 applies for the areas where, due to the climatic conditions (extremely unfavourable geographical situation) and confirmed by the long-term experience, very high ice loads have to be expected which resulted in considerable damage of overhead transmission lines.

According to the Regulation, [1], wind pressure should be calculated on the basis of the maximum wind speed that occurs on average every five years, and is obtained from the Meteorological Service for the relevant region (Regulation [1], Paragraph 10). Wind load data are usually defined in cooperation with the National

Meteorological and Hydrological Institute and they are based on the values applied for the design of existing overhead transmission lines in the vicinity of the projected route.

According to EN 50341-1 [2] and EN 50341-3-4 [5], wind pressure p is calculated with mean wind speed v_{mean}. Mean wind speed v_{mean} is defined as the mean wind speed in m/s over a period of 10 min at a height of 10 m above the ground in relatively open terrain (category II), [2]. Usually, it is calculated with the wind speed with return period of T = 50 years. Some of the basic differences between the Regulation [1] and the EN standards [2, 5] are given in Tab. 3.

Table 4 Overview of the load combination according to the Regulation, EN 50341-1 and EN 50341-3-4

Load case / Load combination	Regulation [1]	EN 50341-1 [2]	EN 50341-3-4 [5]
Maximum wind perpendicular to the line	68.1b	N1	A
Maximum wind at an angle to the line	-	N2	B
Maximum wind parallel to the line	68.1c	N3	C
Combined ice and wind load perpendicular to the line	-	N4, N7	D
Combined ice and wind load at an angle to the line	-	N5, N8	E
Combined ice and wind load parallel to the line	-	N6, N9	F
Symmetrically distributed / Uniform ice load	68.1a	2a	-
Asymmetrically distributed / Unbalanced ice load	-	2b, 2c, 2d	G_b
Dead weight at a minimum temperature	-	-	G_a
Broken conductor	69.1PG, 69.1PS, 69.1PD	J10_C gk, J10_C sk, J10_C dk	J_C gk, J_C sk, J_C dk
Broken earth wire	69.1PZU	J10_E	J_E
Cascade failure	-	K11	K

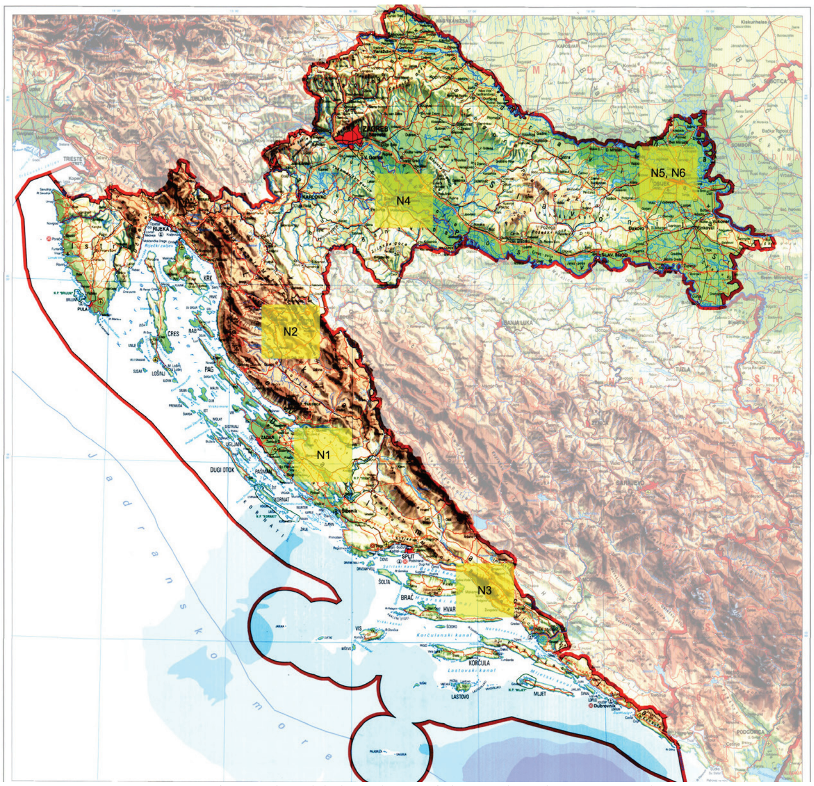


Figure 2 Map of Croatia with locations of the analysed representative towers

When determining loads according to the Regulation [1], all load combinations are calculated with a maximum working stress of the wire. The maximum working stress is usually calculated at –5 °C with ice load or at –20 °C without ice load, depending on which combination gives the governed value.

EN 50341-1 [2], as well as EN 50341-3-4 [5], does not recognize a single working stress with which all load combinations are calculated, so the working stress for each load combination depends on the defined load conditions.

The following table gives an overview of the basic load combinations. It should be noted that the basic standard [2] does not define the exact load combinations, but makes recommendations to define them. Therefore, the names for the combinations that are listed in Tab. 4 are adopted for the purpose of [4]. These load combinations follow the recommendations from the basic European standard [2].

Since the project specifications do not require the verification of serviceability limit state, the steel lattice towers are only checked for the ultimate limit states, for more details see Section 7.3.4 in [2].

4 Analysis of the representative transmission line towers built in different regions of Croatia

4.1 Selection of the representative towers

Certain regions of Croatia in which the damages of the overhead transmission lines have happened can be seen in Fig. 1. The following towers were chosen for the analysis: tower N1 was damaged by wind load, tower N2 was damaged by ice load, tower N3 was damaged by the combined ice and wind load and towers N4, N5, N6 that are still undamaged. Towers N1, N2, N3 and N4 are 110 kV standard voltage towers and towers N5 and N6 are 400 kV standard voltage towers. Locations of these towers are shown in Fig. 2.

Calculation of the internal forces and the design of towers was carried out in PLS Tower [8]. The internal forces are calculated by the second order theory and with compliance to [1, 2, 5] only buckling line *c* was used for determining the buckling resistance. Graphical presentations of the results for the governed load combinations are given below. The legend of elements utilization level is shown in Fig. 3. If the element in the graphical presentation of the results is shown in red that means its resistance is exceeded (pressure, tension and /or connection resistance). For other colours the same analogy should be followed.

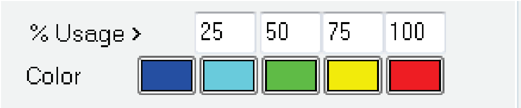


Figure 3 Legend of the elements utilization levels for the graphical presentation of the results

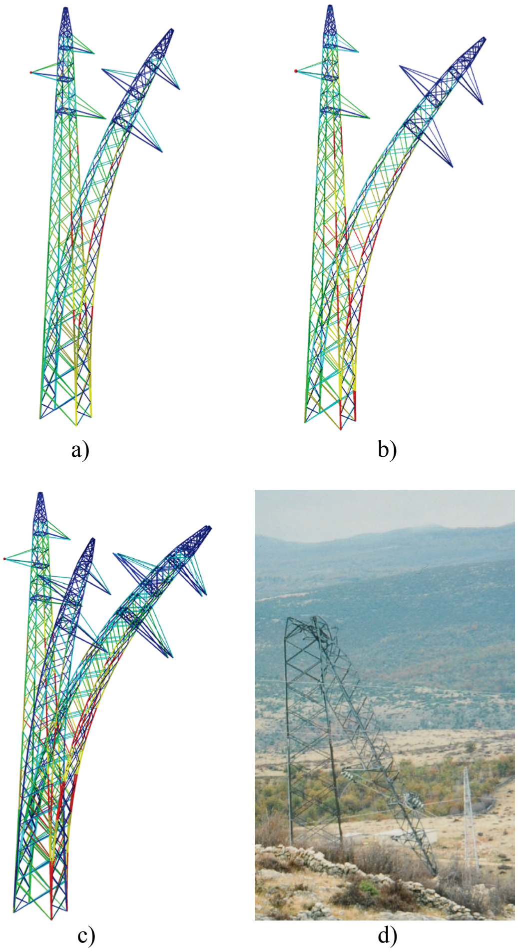
In order to illustrate the dominant direction of the load, deformations of the towers for the governed load combinations are also shown, as they also show the likely direction of the eventual collapse of the tower.

4.2 Analysis of the tower N1

The towers N1 were damaged on OHTL (overhead transmission line) 110 kV Obrovac - Zadar in February 1997. Wind load was identified as the cause of the damage. The basic wind pressure according to the Regulation is $p = 900$ N/m^2, and according to EN 50341-1 and EN 50341-3-4 mean wind speed is $v_{\text{mean}} = 30$ m/s. The ice load is $1{,}0 \cdot q_{\text{ice}}$ (according to EN 50341-3-4 [5] – zone 1 → $5 + 0{,}1 \cdot d$). The structure is made of hot rolled L or U profiles and plates with the quality of structural steel S235J0 (Č0361). Structural members are connected with grade 5.6 bolts.

Fig. 4 shows graphical results of the analysis of the tower N1. According to the Regulation [1], the results on deformed structure for the governed load combination 68.1b are shown in Fig. 4a). Fig. 4b) shows the utilization level of the members designed according to the EN 50341-1 [2] and deformation is given for the governed load combination N1. Fig. 4c) presents the results according to the EN 50341-3-4 [5] and the deformations are shown for the governed load combinations A and B.

All deformations are 50 times magnified in relation to the geometry of the structure. Typical damage of the 35 kV tower due to wind load is shown in Fig. 4d).



a) b) c) d)

Figure 4 Graphical representation of the maximum element utilization level of the tower N1: a) Regulation [1], b) EN 50341-1 [2], c) EN 50341-3-4 [5], and d). Photo of 35 kV tower damaged due to wind load.

Table 5 Results of analysis for tower N1's main legs

		REGULATION		EN 50341-1			EN 50341-3-4		
GROUP LABEL	ANGLE	MAX UTILIZATION / %	GOVERNED LOAD CASE	MAX UTILIZATION / %	GOVERNED LOAD CASE	DIFFERENCE BETWEEN EN50341-1 AND REGULATION / %	MAX UTILIZATION / %	GOVERNED LOAD CASE	DIFFERENCE BETWEEN EN50341-3-4 AND REGULATION / %
P1	90 × 90 × 9	98,03	68.1b	107,66	N1	9,63	115,50	B	17,47
P2	90 × 90 × 9	89,70	68.1b	98,27	N1	8,57	104,59	B	14,89
P3	80 × 80 × 8	105,44	68.1b	116,39	N1	10,95	121,53	A	16,09
P4	70 × 70 × 7	112,93	68.1b	123,97	N4	11,04	127,02	D	14,09
P5	60 × 60 × 6	99,54	68.1b	118,01	N4	18,47	117,99	D	18,45

Maximum utilizations of the tower's N1 main legs expressed as a percentage for the governed load combinations and the difference between the maximum utilization of European standards [2, 5] and the Regulation [1] are given in Tab. 5. In Tab. 4 we can see that the load combinations 68.1b, N1, A and B are combinations of the maximum wind on the transmission line what is consistent with the presumed cause of the failure (damage) of tower N1 on OHTL 110 kV Obrovac – Zadar. Considering that the standard tower N1 is designed by 'Provisional Regulations for the design and construction of transmission lines with voltages below 110 kV' (Appendix of the magazine 'Electricity' No. 7/1949) it is clear that the tower must be strengthened according to the Regulation [1].

The highest strengthening of the tower is required by EN 50341-3-4 [5] followed by EN 50341-1 [2] and at the end by the Regulation, [1]. According to the Regulation [1] and standards [2, 5], governed load combination is the maximum wind perpendicular (68.1b, N1, A) or at angle (B) to the line. However, according to the European standards [2, 5], for the head and the top of the tower governed combination is combined ice and wind load acting perpendicular to the line (N4, D). The results of tower strengthening, expressed in percentages, given in relation to the primary tower mass m = 2583 kg are listed below.

Required strengthening of the tower N2:

Regulation	EN 50341-1	EN 50341-3-4
188 kg (7,3 %)	202 kg (7,8 %)	440 kg (17,0 %)

Required strengthening in relation to the tower strengthened according to the Regulation:

Regulation	EN 50341-1	EN 50341-3-4
0 %	0,5 %	9,1 %

If we use the steel quality S355 for members (all except for L 35 × 5 × 4) first, required strengthening in relation to Regulation is:

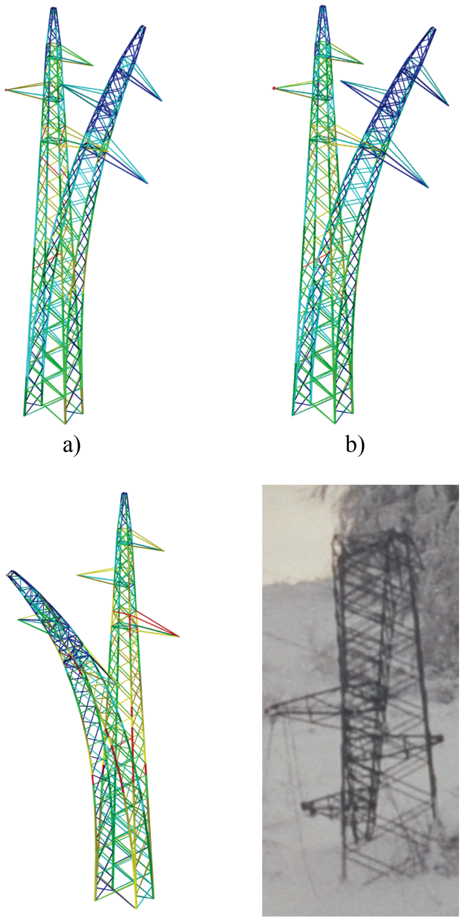
Regulation	EN 50341-1	EN 50341-3-4
0 %	2,3 %	4,5 %

4.3 Analysis of the tower N2

Tower-type N2 was damaged on OHTL 110 kV Lički Osik - Plitvice in December 1998. Ice load was identified as the cause of the damage. The basic wind pressure according to the Regulation is p = 900 N/m^2, and according to EN 50341-1 and EN 50341-3-4 mean wind speed is v_{mean} = 30 m/s. Ice load is $1{,}6 \cdot q_{\text{ice}}$ (according to EN 50341-3-4, [5] – zone 2 → $10 + 0{,}2 \cdot d$). The structure is made of hot rolled L or U profiles and plates with the quality of structural steel S235J0 (Č0361). Structural members are connected with grade 5.6 bolts.

Figure 5 shows graphical results for the tower N2. According to the Regulation [1], the results on deformed structure for the governed load combination 68.1b are shown in Fig. 5a). Fig 5b) shows the utilization level of elements designed according to EN 50341-1 [2] and deformation is given for the governed load combination N7. Fig. 5c) presents the results according to EN 50341-3-4 [5] and deformation is shown for the governed load combination G_b. All deformations are 50 times magnified in relation to the geometry of the structure. The collapsed (damaged) tower N2 on OHTL 110 kV Lički Osik – Plitvice is shown in Fig. 5d).

Maximum utilizations of the tower's N2 main legs expressed as a percentage for the governed load combinations and the difference between the maximum utilization of the European standards [2, 5] and the Regulation [1] are given in Tab. 6. From Tab. 4 we can see that the load combination 68.1b is a combination of the maximum wind perpendicular to the line. The load combination N7 is a combination of average wind load during the winter temperature (ϑ = –5 °C) which acts perpendicular to the direction of the line in moderate ice load on the conductor/earth wire. According to [5] the load combination G_b is unbalanced ice load that causes tower bending in the direction of the transmission line route. The combination G_b simulates the situation in the way that 50 % of ice load should be loaded on conductors and earth wire in the first adjacent span of the tower and in the second adjacent span there should be no ice load.



a) b)

c) d)

Figure 5 Graphical representation of the maximum element utilization level of the tower N2: a) Regulation [1], b) EN 50341-1 [2], c) EN 50341-3-4 [5] and d) Photo of damaged tower N2 from OHTL Lički Osik - Plitvice in 1998.

According to EN 50341-3-4 [5], tower N2 should be strengthened in the exactly same part where failure occurred on OHTL 110 kV Lički Osik - Plitvice, Fig. 5d). The tower must be strengthened because of the ice load, which was already identified as the cause of the damage of the OHTL 110 kV Lički Osik - Plitvice. This strengthening does not contribute to the large increase of the tower's mass. The load combinations with ice from the basic standard EN 50341-1 [2] are not governed for the design of the members of the tower N2. Moreover, tower N2 must be strengthened according to the Regulation [1], see Fig. 5. This difference occurred because the standard tower N2 was designed according to the Regulation, [9], in 1973 which was in force at the time of the design and construction of OHTL 110 kV Lički Osik - Plitvice. That Regulation [9] used the omega factor procedure which gives higher buckling resistance of the member in relation with Regulation, [1], which uses the reduction factor for buckling. The results of tower strengthening, expressed in percentages, given in relation to the primary tower mass m = 2119 kg are listed below.

Required strengthening of the tower N2:

Regulation	EN 50341-1	EN 50341-3-4
22 kg (1%)	4 kg (0 %)	162 kg (7,6 %)

If we would use the steel quality S 355 for members (all except for L 35×35×4) first, required strengthening is:

Regulation	EN 50341-1	EN 50341-3-4
1%	0 %	0,5 %

Table 6 Results of analysis for the tower N2's main legs

		REGULATION		EN 50341-1			EN 50341-3-4		
GROUP LABEL	ANGLE	MAX UTILIZATION / %	GOVERNED LOAD CASE	MAX UTILIZATION / %	GOVERNED LOAD CASE	DIFFERENCE BETWEEN EN50341-1 AND REGULATION / %	MAX UTILIZATION / %	GOVERNED LOAD CASE	DIFFERENCE BETWEEN EN50341-3-4 AND REGULATION / %
P1	90 × 90 × 9	78,37	68.1b	79,05	N7	0,68	97,49	G_b	19,12
P2	75 × 75 × 8	87,31	68.1b	89,73	N7	2,42	122,79	G_b	35,48
P3	60 × 60 × 6	78,07	68.1b	81,80	N7	3,73	111,66	G_b	33,59
P4	50 × 50 × 5	40,27	69.1 PZU	40,02	J10_E	0,25	70,11	J_E	29,84

Table 7 Results of analysis for the tower N3's main legs

		REGULATION		EN 50341-1			EN 50341-3-4		
GROUP LABEL	ANGLE	MAX UTILIZATION / %	GOVERNED LOAD CASE	MAX UTILIZATION / %	GOVERNED LOAD CASE	DIFFERENCE BETWEEN EN50341-1 AND REGULATION / %	MAX U UTILIZATION / %	GOVERNED LOAD CASE	DIFFERENCE BETWEEN EN50341-3-4 AND REGULATION / %
P1	90 × 90 × 9	92,24	68.1b	177,78	N7	85,54	192,70	D	100,46
P2	80 × 80 × 8	90,24	68.1b	178,94	N7	88,70	199,10	D	108,86
P3	60 × 60 × 6	82,23	68.1b	156,46	N7	74,23	189,95	D	107,72
P4	50 × 50 × 5	32,21	69.1 PZU	47,62	N7	15,41	62,45	D	30,24

4.4 Analysis of the tower N3

Tower-type N3 was damaged on OHTL 110 kV Kraljevac – Makarska in March 1993 and 1995. Combined wind and ice load was identified as the cause of the damage. The basic wind pressure according to the Regulation is p = 1300 N/m^2, and according to the EN 50341-1 and the EN 50341-3-4 mean wind speed is v_{mean} = 50 m/s. Ice load of $1{,}6 \cdot q_{\mathrm{ice}}$ (according to EN 50341-3-4 [5] – zone 2 → $10 + 0{,}2 \cdot d$). The structure is made of hot rolled L or U profiles and plates with the quality of structural steel S235J0 (Č0361). Structural members are connected with grade 5.6 bolts.

Fig. 6 shows graphical results of the tower N3. According to the Regulation [1], the results on deformed structure for the governed load combination 68.1b are shown in Fig. 6a). Fig. 6b) shows the utilization level of elements designed according to EN 50341-1 [2], a deformation is given for the load combination N7. Fig. 6c) presents the result of design according to the EN 50341-3-4 [5] and deformation is shown for the governed load combination D. All deformations are 50 times magnified in relation to the geometry of the structure. Fig. 6d) shows one of the collapsed towers type N3 that was damaged on OHTL 110 kV Kraljevac – Makarska.

Maximum utilizations of the tower's N3 main legs expressed as a percentage for the governed load combinations and the difference between the maximum utilization of the European standards [2, 5] and the Regulation [1] are given in Tab. 7. According to [1], from Tab. 4 we can see that the load combination 68.1b is a combination of the maximum wind perpendicular to the line. Load combinations N7 and D, according to the European standards [2, 5], are a combination of average wind load during the winter temperature (ϑ = –5 °C) which acts perpendicular to the direction of the line in moderate ice load on the conductor/earth wire which is the cause of the damage of the towers N3 on OHTL 110 kV Kraljevac – Makarska. Considering the fact that, according to the European standards, almost the entire tower must be strengthened, the mass increase is not reported.

4.5 Analysis of the tower N4

Tower type N4 is designed for loading conditions for the transmission lines that are aimed for the area of the city Sisak. In the area of Sisak, extensive damages of overhead transmission lines happened due to the ice load. The basic wind pressure according to the Regulation [1] is

$p = 900$ N/m^2, and according to the EN 50341-1 and the EN 50341-3-4 mean wind speed is $v_{\mathrm{mean}} = 22$ m/s. Ice load is $1{,}6 \cdot q_{\mathrm{ice}}$ (according to EN 50341-3-4 [5] – zone 2 $\rightarrow 10 + 0{,}2 \cdot d$). The structure is made of hot rolled L or U profiles and plates with the quality of structural steel S355 (Č0561) and S235J0 (Č0361) for L 35×35×4. Structural members are connected with grade 5.6 bolts.

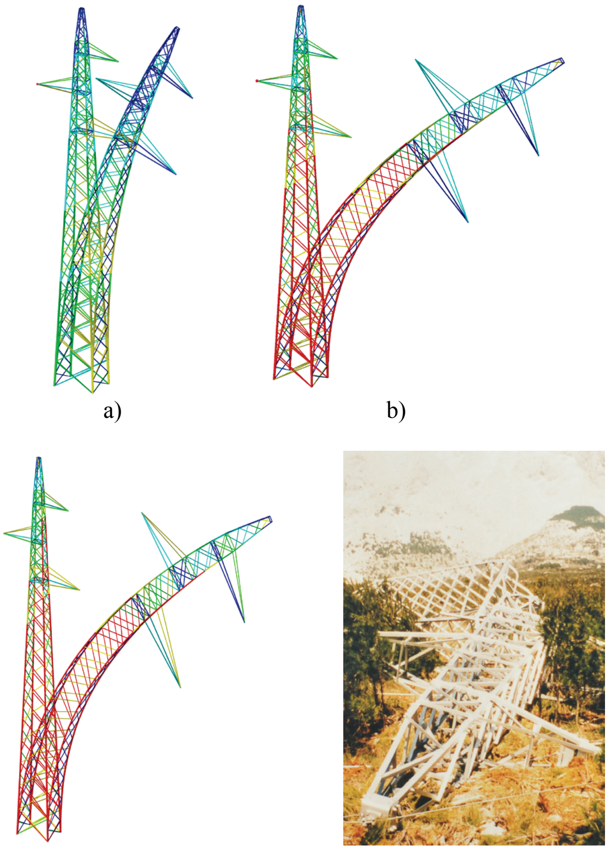

a) b) c) d)

Figure 6 Graphical representation of the maximum element utilization level of the tower N3: a) Regulation [1], b) EN 50341-1 [2], c) EN 50341-3-4 [5] and d) Photo of the collapsed tower N3 damaged on OHTL 110 kV Kraljevac - Makarska in 1993.

Fig. 7 shows graphical results of the analysis of the tower N4. According to the Regulation [1], the results on deformed structure for the governed load combination 68.1b are shown in Fig. 7a). Fig. 7b) shows the elements utilization level designed according to EN 50341-1 [2] and deformation is given for the governed load combination 2c. Fig. 7c) presents the results of design according to EN 50341-3-4 [5] and deformation is shown for the governed load combination G_b. All deformations are 50 times magnified compared to the geometry of the structure.

Maximum utilizations of the tower's N4 main legs expressed as a percentage for the governed load combinations and the difference between the maximum utilization of the European standards [2, 5] and the Regulation [1] are given in Tab. 8.

According to [1], from Table 4 we can see that the load combination 68.1b is a combination of the maximum wind perpendicular to the line. The load combinations 2c, according to [2], and G_b, according to [5], are the combinations of unbalanced ice load, which was detected as the cause of the damage of overhead transmission lines in the Sisak area.

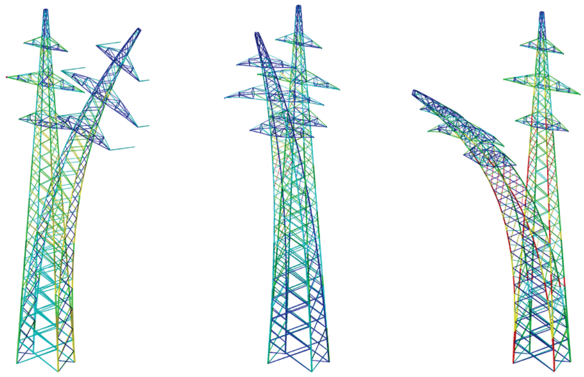

a) b) c)

Figure 7 Graphical representation of the maximum element utilization level of the tower N4: a) Regulation [1], b) EN 50341-1 [2], c) EN 50341-3-4, [5]

The results of tower strengthening, expressed in percentages, given in relation to the primary tower mass $m = 5070$ kg) are listed below.

EN 50341-3-4 390 kg (7,6 %).

Table 8 Results of analysis for the tower N4's main legs

		REGULATION		EN 50341-1			EN 50341-3-4		
GROUP LABEL	ANGLE	MAX UTILIZATION / %	GOVERNED LOAD CASE	MAX UTILIZATION / %	GOVERNED LOAD CASE	DIFFERENCE BETWEEN EN50341-1 AND REGULATION / %	MAX UTILIZATION / %	GOVERNED LOAD CASE	DIFFERENCE BETWEEN EN50341-3-4 AND REGULATION / %
P1	110 × 110 × 10	89,88	68.1b	59,84	2c	−30,04	107,38	G_b	17,50
P2	110 × 110 × 10	85,83	68.1b	58,48	2c	−27,35	104,95	G_b	19,12
P3	110 × 110 × 10	83,56	68.1b	72,05	2c	−11,51	129,48	G_b	45,92
P4	90 × 90 × 9	94,61	68.1b	67,71	2c	−26,90	121,80	G_b	27,19
P5	80 × 80 × 8	97,40	68.1b	71,72	2c	−25,68	128,84	G_b	31,44
P6	75 × 75 × 8	80,30	68.1b	65,19	K11	−15,11	102,75	G_b	22,45
P7	65 × 65 × 6	81,40	68.1b	71,86	K11	−9,54	97,91	G_b	16,51
P8	55 × 55 × 5	66,96	69.1 PZU	67,92	J10_E	0,96	84,24	J_E	17,28

According to the EN 50341-1 [2] it would be possible to optimize the tower. If we compare the seemingly different results of the analysis of the towers N2 and N4, which are calculated for the same conditions, we see that the results are analogous for both towers. Maximum strengthening is required by [5], then [1], while we get the minimum strengthening (in this particular case optimization) when design is conducted according to [2].

4.6 Analyses of the towers N5 and N6

Towers N5 and N6 are installed in the area where the damage is not frequent (the area from Zagreb to the east Croatian border, but excluding the wetland area around Sisak). Moreover, there were no large-scale damages. This is an area with low wind intensity and low values of ice load. For these loading conditions European standards [2, 5] give lower load conditions. Thus, the European standards [2, 5] result in lower internal forces in the structural members and consequently lighter towers are obtained.

Table 9 Results of analysis of tower N5's main legs

		REGULATION		EN 50341-1			EN 50341-3-4		
GROUP LABEL	ANGLE	MAX UTILIZATION / %	GOVERNED LOAD CASE	MAX UTILIZATION / %	GOVERNED LOAD CASE	DIFFERENCE BETWEEN EN50341-1 AND REGULATION / %	MAX UTILIZATION / %	GOVERNED LOAD CASE	DIFFERENCE BETWEEN EN50341-3-4 AND REGULATION / %
P1	120 × 120 × 12	65,05	68.1b	55,42	N1	−9,63	64,36	A	−0,69
P2	120 × 120 × 12	61,79	68.1b	52,41	N1	−9,38	61,59	A	−0,20
P3	120 × 120 × 10	68,06	68.1b	57,42	N1	−10,64	69,31	A	1,25
P4	110 × 110 × 10	66,06	68.1b	55,03	N1	−11,03	60,85	A	−5,21
P5	100 × 100 × 10	62,44	68.1b	51,91	K11	−10,53	57,78	G_b	−4,66
P6	100 × 100 × 10	68,12	68.1b	57,53	K11	−10,59	62,99	G_b	−5,13
P7	90 × 90 × 8	74,54	68.1b	63,94	K11	−10,60	68,48	G_b	−6,06
P8	75 × 75 × 8	72,84	68.1b	66,54	K11	−6,30	66,26	G_b	−6,58
P9	60 × 60 × 6	33,86	69.1 PZU	33,93	J10_E	0,07	43,44	J_E	9,58

Maximum utilizations of the tower's N5 main legs expressed as a percentage for the governed load combinations and the difference between the maximum utilization of the European standards [2, 5] and the Regulation, [1], are given in Tab. 9.

5 Conclusion

Croatia is currently in the final stage of the European integration process, and needs to adopt the European Union's rules. In this sense, continuous and efficient supply of electricity becomes an essential requirement. On the trail of these initial criteria, since non-delivery of electricity will generate costs, in the period that follows we will need to further reflect on the demands for the reliability of transmission and distribution networks.

The application of the European standards imposes itself as an essential factor to increase the reliability in this respect, and we shall need to implement and apply in practice modern Croatian standard HRN EN 50341-1 [3].

Application of the Regulation [1], which in contrast to the European standards [2, 5], does not provide a realistic assessment of the loading conditions, nor the load combinations that were recorded as the causes of the damages of the overhead transmission line towers in Croatia. Only the basic standard EN50341-1 [2], using the German normative Aspect EN50341-3-4 [5], for all the analysed towers requires strengthening of the recorded critical elements of the towers, and this strengthening does not significantly increase the mass of the towers. In the areas where the damages did not occur the European standards [2, 5] give lower load values on the towers so the towers can be optimized.

After the analysis and comparison of the theoretical results with the real behaviour of the towers the implication is that it is necessary to start applying the modern Croatian (European) standard [3] as soon as possible. For its application it is necessary to create Croatian normative aspect. When creating the Croatian normative aspect it would be well to consider the German normative aspect with taking into account the specificity of loads that act on Croatian territory. In this challenging work it is necessary to conduct probabilistic analysis because it is the only correct way to maintain the level of reliability required by modern standards.

6 References

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