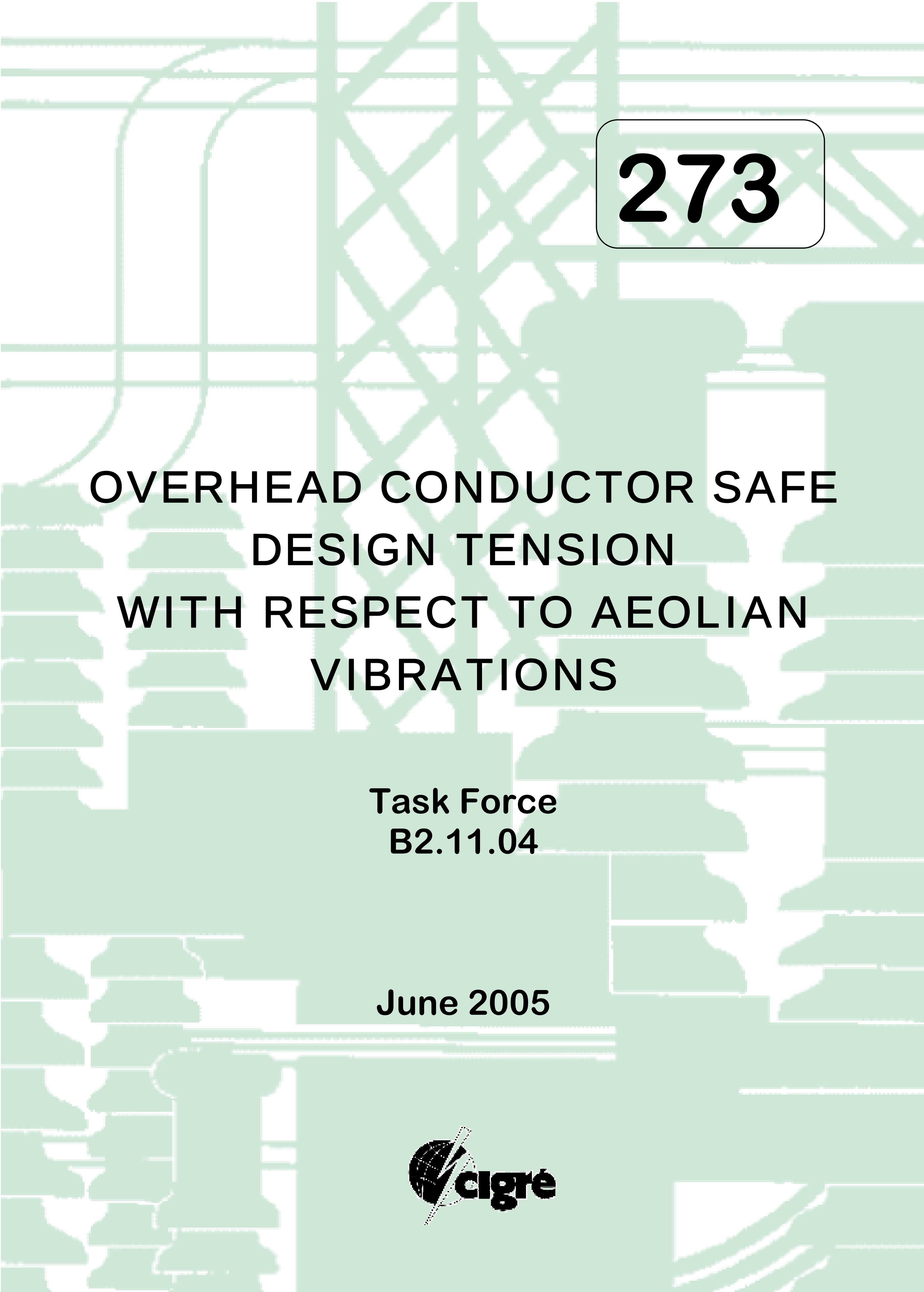

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OVERHEAD CONDUCTOR SAFE DESIGN TENSION WITH RESPECT TO AEOLIAN VIBRATIONS

Task Force
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TASK FORCE
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EXECUTIVE SUMMARY

There may be several motives for controlling overhead conductor tension at the design stage. One of the most obvious reasons is to ensure that maximum tension resulting from the assumed most severe climatic loading does not exceed the conductor allowable tension. At the opposite end, it may be required to limit minimum tension while the conductor is operating at maximum temperature so that line clearance is not violated. A third motive, which should not be disregarded, is to restrict conductor susceptibility to harmful conductor vibrations.

As a matter of fact, it is well known that stranded conductors get more vulnerable to Aeolian vibrations as tension is increased. This is true for all conductor systems whether they are used *in solo* or in bundles and whether they are fitted or not with damping and/or spacing devices. Therefore, there is a need to set an upper limit to conductor unloaded tension that may prevail for a significant period of time.

This brochure deals with this important issue. It starts in Section 2 with a critical examination of the EDS concept which was put forward in 1960 by CIGRÉ SC6 with the intent to provide guidance on such conductor safe design tensions with respect to Aeolian vibrations. It is noted, for example, that the 18% EDS value which was proposed as safe for ACSR conductors did lead, in spite of all, to fatigue failures in a significant number of cases, thus motivating the present work further. In this conjuncture, one of the first and most important tasks of the Task Force was to question the relevance of the EDS (% of the Ultimate Tensile Strength) as conductor tension parameter. On account of its improved ability to rate conductor self-damping capacity, on the one hand, and to generalise results as widely as possible, on the other hand, it was resolved to adopt parameter H/w, the ratio between the initial horizontal tensile load H and conductor weight w per unit length. As stated in the brochure, this tension refers to initial horizontal tension before any significant wind and ice loading and before creep, at the average temperature of the coldest month on the site of the line.

Another parameter of prime importance is wind turbulence since it affects to a great extent the Aeolian power imparted to vibrating conductors. This is scrutinised in Section 3 of the brochure insofar as it relates to roughness of the terrain crossed by the lines.

Single unarmored, unprotected single conductors of the most common types are considered in Section 4 of the brochure. Then comes the description of analytical models from four different organisations that were used to draw tentative recommendations about safe design tensions of unarmored, unprotected single conductors. These recommendations were finally ratified on account of a successful “reality check” against available field experience.

Section 5 of the brochure deals with single conductor lines protected by means of Stockbridge-type vibration dampers set up at span extremities. Addition of dampers obviously calls for the introduction of another parameter intended at rating the protective capacities of the damping system. As justified in this section, the rating parameter that was selected is LD/m, the ratio of the product of span length L and conductor diameter D to conductor mass m per unit length.

Similarly to what was done in the previous section, Section 5 goes on with a description of the two analytical models that were used to predict safe design tensions, which are then compared with all available test line and field experience, again as a “reality check”. This part of the brochure concludes on the Task Force recommendations which are provided both graphically and algebraically.

Finally, Section 6 of the brochure deals with bundled conductor lines, particularly, twin horizontal bundles, triple apex-down bundles and quad horizontal bundles made up of conventional stranded conductors fitted either with damping spacers or non-damping spacers or a combination of non-damping spacers and span-end Stockbridge-type dampers. It starts with a thorough review of literature about field tests carried out in the past, mainly on dedicated test lines, on bundled conductors set up in parallel and at the same tension as identical single conductors. It then covers a review of field experience gathered on 91 bundled conductor lines erected in North America. This is followed by a description of the methodologies that were used to arrive at safe design tension for each one of a number of bundled conductor systems. In this case, these methodologies are purely empirical, relying on field experience and full scale test line data.

The Task Force recommendations are summarised in a table at the end of Section 6 in the form of simple algebraic expressions, each one associated to a specific conductor system and to one out of four terrain categories. For sake of completeness, the table also incorporates the Task Force recommendations for single conductors fitted or not with Stockbridge-type dampers set up at the span extremities.

1. INTRODUCTION

There may be several motives for controlling overhead line conductor tension at the design stage. One of the most obvious reasons is to ensure that maximum tension corresponding to the assumed most severe climatic loading does not exceed a predefined, acceptable conductor tension. At the opposite end, it may be required to limit tension while the conductor is operating at maximum temperature so that line clearance is not violated. A third motive is to restrict conductor susceptibility to harmful Aeolian vibrations.

As a matter of fact, it is well known that stranded conductors get more vulnerable to Aeolian vibrations as tension is increased. This is true for all conductor systems whether they are used *in solo* or in bundles and whether they are fitted or not with damping and/or spacing devices. Hence, there is a need to set an upper limit to conductor unloaded tension that prevails for significant periods of time.

Guidance to such safe design tension with respect to Aeolian vibrations was provided before, more particularly in 1960 by the so-called EDS (Every Day Stress) Panel [1], working under appointment of CIGRE SC6 (since disbanded). However, as discussed in the following section of this brochure, it was felt timely to revise the Panel's recommendations.

It was a premise for the Task Force that it would be quite difficult to work out a revised guide on the basis of field experience only due to the rarity of well documented cases. Accordingly, the Task Force's terms of reference have been: *To produce a practical guide for the selection of safe design tensions in form of generic values for specific classes of single transmission line conductors to avoid damage due to Aeolian vibrations during a typical design lifetime. This guide should be based on existing experience and current knowledge on wind energy input, conductor self-damping and conductor fatigue endurance. A theoretical model should be used that translates energy balance into amplitude and number of cycles of vibration at the clamps to assess vibration severity*.

This brochure deals with this very important issue in the design and operation of overhead transmission lines. It starts with a review of the Every Day Stress (EDS) concept. That is followed in Section 3 by a review of the influence of terrain cover or roughness on wind turbulence, which is known to affect to a large extent wind power imparted to conductors. Single, unarmored, unprotected single conductors of the most common types are considered in Section 4. The following section deals with single conductor lines protected by means of Stockbridge-type vibration dampers set up at span extremities. Section 6 of the brochure deals in turn with bundled conductor lines, particularly twin horizontal bundles, triple apex-down bundles and quad horizontal bundles made up of conventional stranded conductors fitted either with damping spacers or non-damping spacers or a combination of non-damping spacers and span-end Stockbridge-type spacers.

2. REVIEW OF THE EVERY DAY STRESS (EDS) CONCEPT

Forty-five years have elapsed since the presentation, at the CIGRÉ 1960 session, of Report 223 [1] of CIGRÉ SC6, which showed the conclusions reached by the EDS Panel appointed in 1953 to investigate the fatigue damages caused to transmission line conductors by the Aeolian vibrations.

In that report the EDS, expressed as a percent of the conductor breaking strength (or UTS, Ultimate Tensile Strength), was defined as the maximum tensile load to which a conductor can be subjected, at the temperature which will occur for the longest period of time, without any risk of damage due to Aeolian vibrations. Different values of EDS were given for bare conductors and for conductors with armour rods only, dampers only and armour rods and dampers. The Panel's recommendations are shown in Table 2.1.

Table 2.1 EDS panel recommendations for safe design tensions in percent UTS.

	Unprotected lines	Lines equipped with		
		Armour rods	Dampers	Armour rods and dampers
Copper conductors	26			
ACSR	18	22	24	24
Aluminium conductors	17			
Aldrey conductors	18		26	
Steel conductors				
1. Rigid clamps	11			
2. Oscillating clamps	13			

Since Report 223 was issued, new conductors have been put in service and lines have been built for the first time in new areas. With the broader experience, the recommended EDS values have appeared to be insufficient to explain the fatigue damage found on these more recent lines. In fact, in retrospect, even the statistical conclusions drawn from EDS Panel do not seem quite correct.

For example, Table 2.2 shows the results of an analysis of the EDS Panel data for bare ACSR conductors. It indicates that for lines that have been in service for 10 to 20 years, 45% of the lines with an EDS<18% and 78% of the lines with an EDS>18% revealed damages. As can be seen, the 18% EDS value proposed as "safe" lead to fatigue failures although at a slower rate.

Table 2.2 Summary of damaged lines as per the EDS panel

Service life	% of lines damaged	
Years	EDS < 18%	EDS = > 18%
< = 5	5.26	25.00
> 5 < = 10	20.93	35.29
> 10 < = 20	45.00	78.00
> 20	58.93	91.67

Research and testing performed since 1960 have provided information that was not available to the EDS Panel. Self-damping tests on conductors showed that the increased tensile load reduces the power dissipated by a vibrating conductor. To represent such effect, it is now considered more convenient, in order to generalise the results, to use the ratio H/w between the horizontal tensile load and the conductor weight per unit length rather than the % of UTS. This may not have been evident to the EDS Panel because the vast majority of the lines up to 1962 were built with the classical 30/7, 26/7 and 54/7 stranding ACSR. With such cables, the increase of UTS due to an increase of the conductor diameter brought also an equal increase in the conductor weight.

The EDS Panel classified the lines on the basis of terrain, (flat, hilly, mountainous, etc.), but it is now well known that what influences the wind power is the surface roughness of the ground which creates turbulence.

Finally, it is well known that conductor fatigue is the result of an accumulation of dynamic bending strains in the presence of fretting [2-3]. It follows that a parameter often ignored is the occurrence of dangerous winds on the line. In some locales, the occurrence and direction of these winds is only related to general meteorological conditions but in other locations, close to large water bodies or in desert areas, the thermal differences in areas surrounding the line cause daily air flows in one direction and in the other. Under such conditions the rate of dynamic stress accumulation can be significantly greater than in other areas.

All this information can now better explain the dispersion of the time to failure of the lines investigated by the EDS Panel and, in general, of present similar lines in service.

It should be pointed out that the Panel offered its recommendations with clear reservations regarding their fundamental soundness. Much poor experience that resulted from trying to apply the recommendations was the result of ignoring those reservations.

In view of sometimes unsatisfactory experience with the Panel's recommendations, and of improved current understanding of Aeolian vibration, it is felt that new proposals are appropriate.

3. TURBULENCE AS A FUNCTION OF TERRAIN

Turbulence in the wind affects the amount of Aeolian vibration power that is imparted to a vibrating conductor. Maximum power is transferred when wind causes a Strouhal frequency of vortex shedding that is close to the frequency at which the conductor is vibrating [4]. Due to the travelling-wave nature of conductor vibration, the conductor's vibration frequency, or frequency spectrum, is the same all along the span. If the wind speed is not constant all along the span, there must be parts of the span where maximum power transfer does not occur, and total wind power input must be less than would occur in perfectly uniform wind. Fluctuations in wind speed with time - gustiness - also reduce wind power input, because the vibration of the span cannot change frequency fast enough to follow short-term wind speed variations. Both the span-wise variations and the gustiness are reflections of turbulence in the wind structure.

The turbulence that influences Aeolian vibration arises from the interaction of the mean wind with the ground. The magnitude of the turbulence is ordinarily taken as the root-mean-square variation of wind velocity about the mean speed, and *turbulence intensity* is expressed as the ratio of that RMS variation to the mean wind velocity.

Turbulence intensity at any particular field location is strongly influenced by the local terrain, and especially the nature of the ground cover. Obstacles to wind flow, such as trees and buildings, and even blades of grass, shed vortices somewhat as conductors do. These vortices comprise the turbulent component of the wind. Naturally, large obstacles shed large vortices and result in large turbulence intensity, while small obstacles, with their small and short-lived vortices, result in low intensity.

Very large obstacles such as hills, ridges and mountains do not cause turbulence as understood here. Rather, they shape the flow to conform to these gross orographic features. For example, valleys may funnel the wind, increasing its speed and actually reducing its turbulence intensity.

Field measurements have yielded tables of typical values of intensity found in various classes of ground cover. The values in Table 3.1 pertain to elevation above ground of 10 metres [9]. Tables with more finely-divided classifications are available. For example, Wieringa [10] provides twice as many.

Table 3.1 Typical values of turbulence intensity.

Terrain	Turbulence Intensity
Open sea; large stretches of open water	0.11
Rural areas; open country with few, low, obstacles	0.18
Low-density built-up areas; small town; suburbs; open woodland with small trees	0.25
Town and city centers with high density of buildings; broken country with tall trees	0.35

The intensities given in these tables are typical of values measured during strong winds and, in fact, such measurements show consistent results only during strong winds. Measurements during light to moderate winds, say up to 8 or 10 m/s (hourly average), show a great deal of dispersion. This dispersion results from effects of the buoyancy acquired by parcels of air that are in contact with the surface when they are heated or cooled by the ground. Heating causes these parcels to rise, churning the atmosphere as they do, resulting in increased turbulence. Cooling, on the other hand, causes the atmosphere to stratify, with the cool layer sticking to the ground and blocking the movement of surface-generated turbulence upward. Because of these effects, turbulence intensity during the light-to-moderate winds associated with Aeolian vibration can be much larger, or significantly smaller than the values reported in the table. For example, in rural areas, intensity can be as high as 0.50 or as low as 0.07, depending upon whether the ground surface is warmer or colder than the air.

4. SINGLE UNPROTECTED CONDUCTORS

This section aims at recommending safe design tensions for unarmored, unprotected single conductor lines.

Modelling

All models that were employed to estimate safe tensions basically rely on the Energy Balance Principle [11] to predict steady state vibration in terms of fy_{max} (the product of vibration frequency and maximum vibration amplitude at antinodes), that is the response of a span when excitation by the wind is balanced by the internal damping of the span. The flow chart (Fig. 4.1) shows parameters that, in a modelling approach, may serve to describe the properties of the structural system (the span) and the wind excitation, and Table 4.1 summarizes which of these parameters were considered in models of four different organizations, and how they were quantified.

Two approaches were followed to assess computed vibration levels (the span response) with regard to the tolerance of the conductor to vibration. In the Endurance Limit Approach, vibration levels are considered to result in an infinite lifetime of the conductor, if they do not exceed a definite limit value (the endurance limit in terms of fy_{max}). Conductor tensions that lead to vibration levels below the endurance limit are regarded as safe.

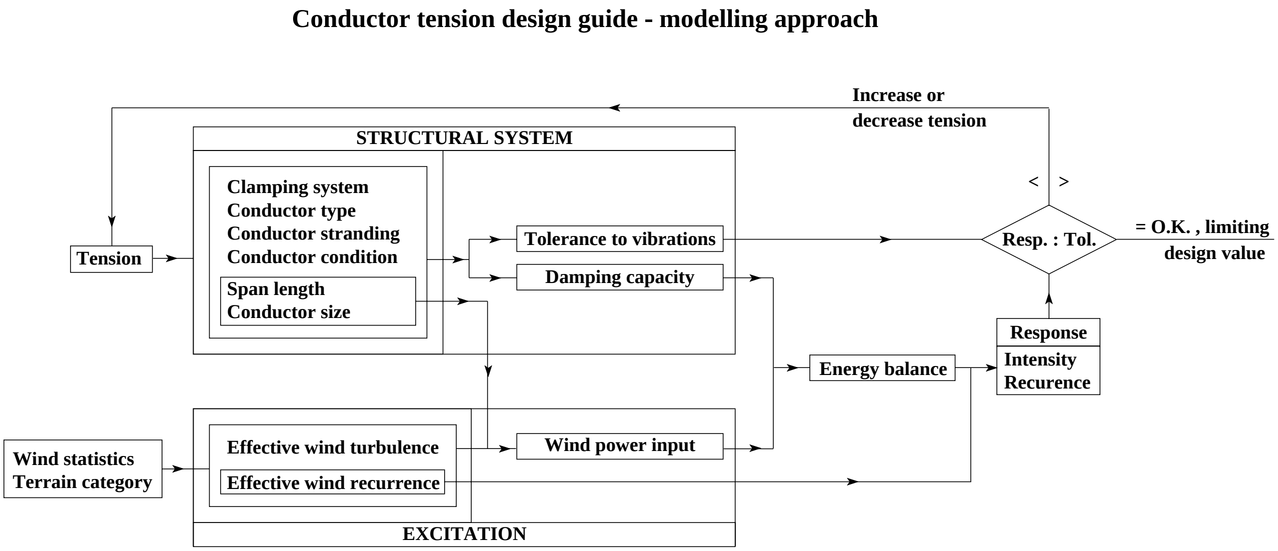

Figure 4.1 Parameters describing undamped structural system and wind excitation.

Table 4.1 Basic assumptions underlying model calculations.

Organisation	RIBE/Krispin [5]	IREQ/Hardy, Leblond [6]		Alcoa Fujikura/Rawlins [7]		Claren [8]
Approach	Endurance limit	Endurance limit	Cumulative damage	Endurance limit	Cumulative damage	Cumulative damage
Conductor damping capacity	Measured (decay method, span with pivoted ends)	Measured (ISWR method) and Calculated on the basis of similarity laws calibrated by means of measured data		Measured (ISWR method)		Calculated on the basis of equations that were derived from measured data
Wind power input	Laminar & reduced for turbulence	Laminar & reduced for normally-distributed turbulence		Laminar & reduced for turbulence		Laminar & reduced for turbulence
Wind recurrence	–	–	Rayleigh-distributed (4.5 km/h avrg)	–	Linearly increasing probability density from 0 to 7 mph, constant probability density (0.057) between 7 and 12 mph, linearly decreasing from 12 to 27 mph. Proper winds to occur half of the time.	Rayleigh-distributed (2.5 m/s avrg)
Vibration mode shape	Sinusoidal	Narrow band random vibration (peak amplitudes Rayleigh-distributed, maximum amplitude limited to 6 times rms-value at each frequency)		Sinusoidal	Random (Flat probability density from 0.4 to 1 times the EBP-amplitude)	Random (amplitudes normally distributed about a mean corresponding to 50% of the maximum laminar amplitude at respective frequency, maximum amplitude limited to 3.5 times that mean value)
Conductor tolerance to vibration	Fatigue endurance as per [13]	Fatigue endurance as per [13]	S/N-curves based on [13] data for several probabilities of survival	Fatigue endurance as per [13]	S/N-curves based on [13] data	CIGRÉ Safe Border Line
Clamping system	Fixed metal to metal clamps	Fixed metal to metal clamps		Fixed metal to metal clamps		Fixed clamps
Predicted fatigue life	Infinite	Infinite	50 years with a probability of survival of 95%	Infinite	100 years	30 years

In the Cumulative Damage Approach, one assigns a certain portion of fatigue damage to each vibration cycle. These small fractions of fatigue damage are assumed to accumulate at a certain rate during the service life of the conductor, until fatigue breakage occurs. The usual assumption is that of linear damage accumulation (Miner's Rule). This approach requires assumptions on the recurrence of fatigue inducing stress levels to determine the number of occurrences at different stress levels, and data on the probability of vibration exciting wind has to be introduced into the model. Probabilistic considerations may be expanded to the S-N-curves that define the fatigue inducing intensity of different vibration levels, and different S-N-curves may be surmised for different levels of probability of survival. Safe conductor tensions that are calculated on that ground necessarily pertain to a certain predicted fatigue life of the conductor.

Safe design tensions as predicted by the different organizations are depicted in Figs. 4.2 and 4.3 as a function of wind intensity of turbulence. Figures 4.2a & b were worked out on the basis of the Endurance Limit Approach while Figs. 4.3a & b were prepared on the basis of the Cumulative Damage Approach for multi-layer A1/Syz (ACSR) and A1 (AAC) conductor classes [12] as well as for multi-layer A3 (AAAC) and A1/A3 (ACAR) conductor classes respectively. Also shown in the figures are the tensions recommended by the EDS Panel, translated in terms of H/w, for different conductor types. As the Panel did not account for the effect of turbulence, their recommended tensions appear as flat horizontal lines in the figures.

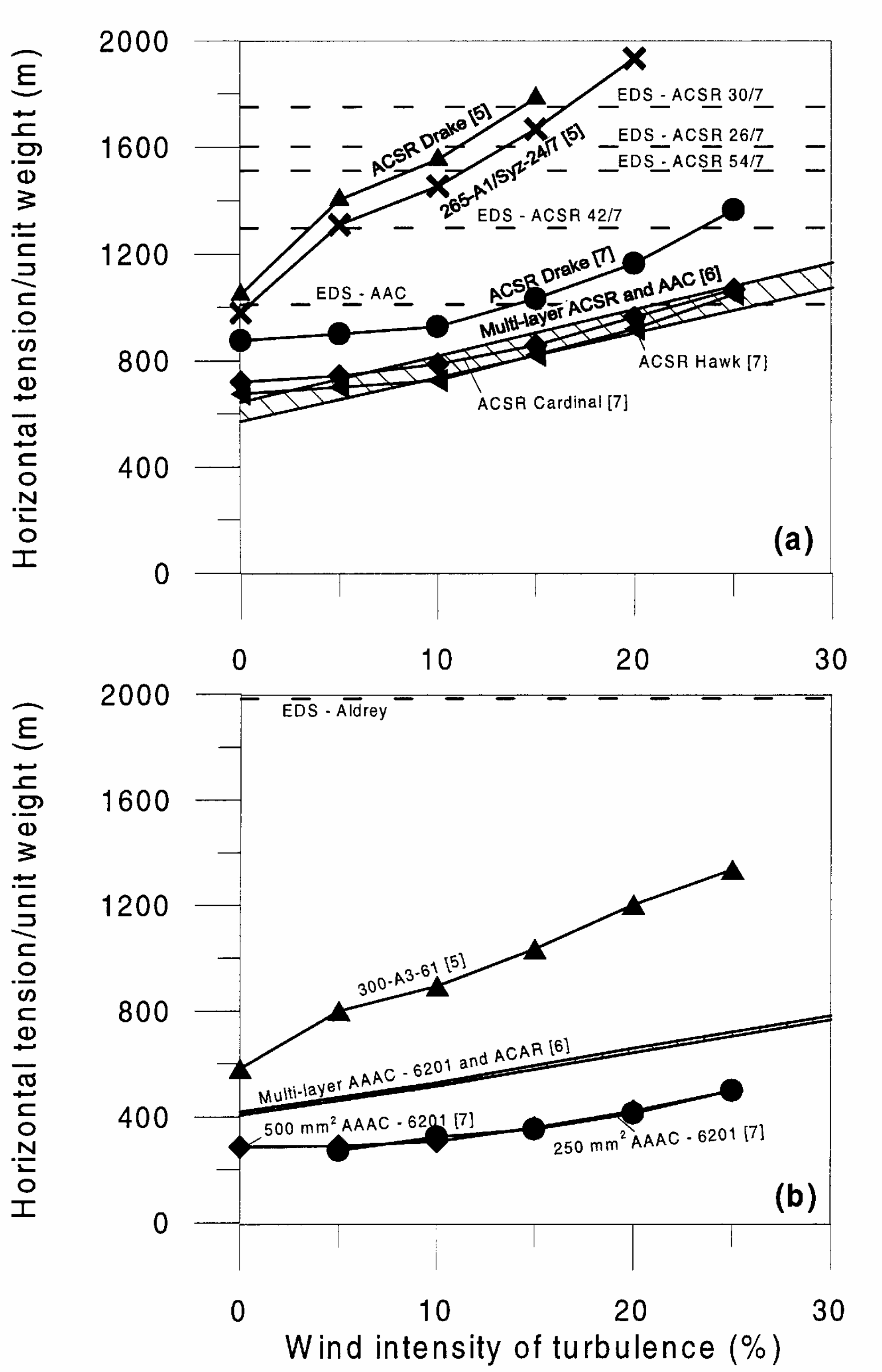

Figure 4.2 Predicted conductor safe design tension according to endurance limit approach. (a) Multi-layer A1 (AAC) and A1/Syz (ACSR) conductors; (b) Multi-layer A3 (AAAC-6201) and A1/A3 (ACAR) conductors.

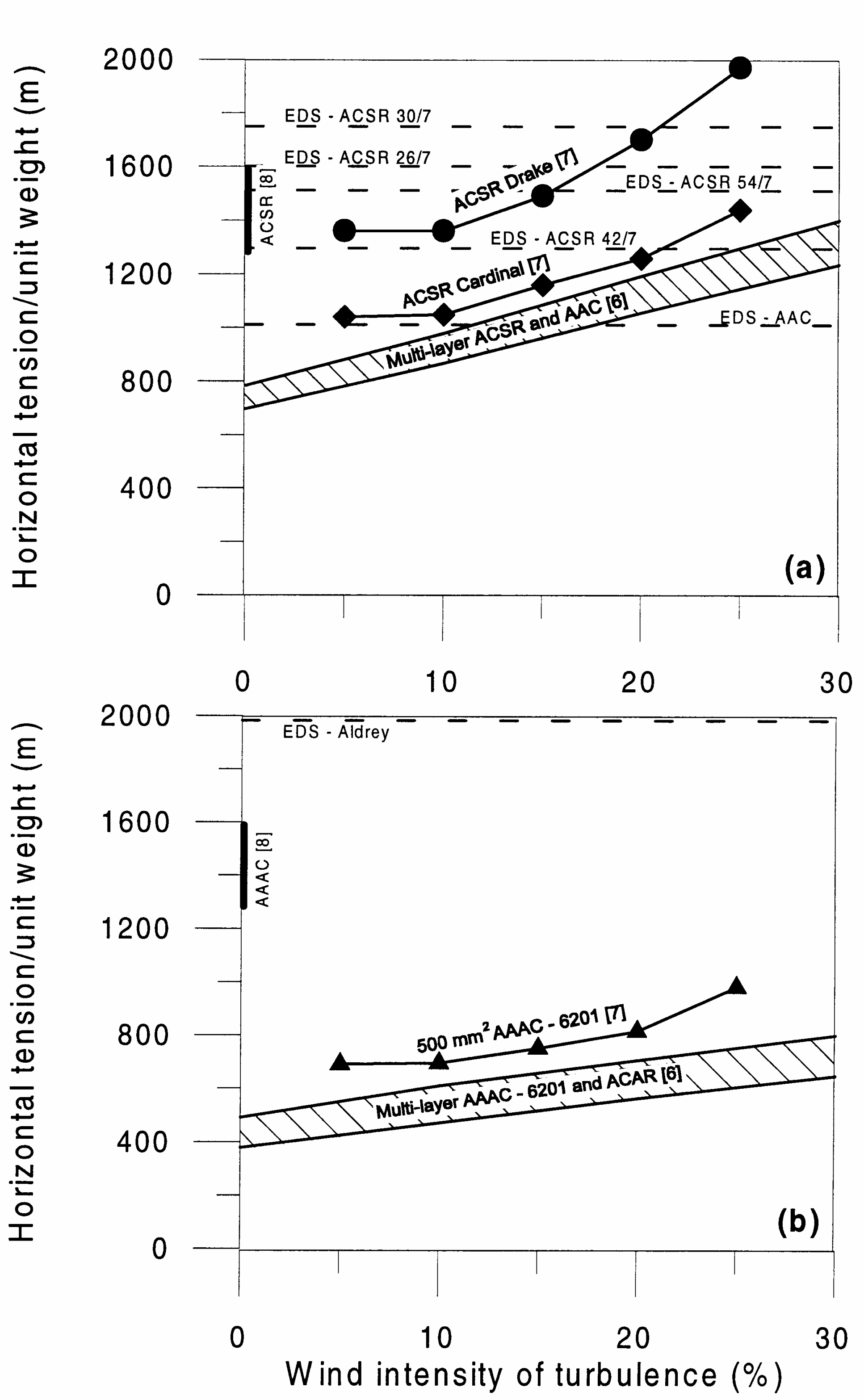

Figure 4.3 Predicted conductor safe design tension according to cumulative damage approach. (a) Multi-layer A1 (AAC) and A1/Syz (ACSR) conductors; (b) Multi-layer A3 (AAAC-6201) and A1/A3 (ACAR) conductors.

On the contrary, calculated safe design tensions are seen to increase with intensity of turbulence pointing out that conductors are less susceptible to Aeolian vibration excitation by turbulent winds.

It will be noticed that despite a considerable scatter in predicted safe tensions according to organizations, they generally stand well below the corresponding EDS values, particularly at the lowest intensities of turbulence. As for the scatter, it appears to result mainly from differences in predicted conductor self-damping.

Three organizations computed admissible *H*/*w* for A3 (AAAC-6201) all aluminum alloy conductors that are from 30 to 50% lower than those for A1 (AAC) all aluminum conductors or A1/Syz (ACSR) steel reinforced aluminum conductors. This is the result of their calculations being performed on the basis of lower fatigue endurance characteristics for the A3 conductors as per reference [13].

Lastly, it may be observed that recourse to the cumulative damage approach leads to more permissive *H*/*w* than the alternative approach. That stands to reason on account of the former approach allowing for a certain number of vibration cycles above the conductor endurance limit while the latter does not.

Comparison With Field Experience

Uncertainties in the data and assumptions that are required to determine maximum safe tensions on the basis of the Energy Balance Principle have made it necessary to consider known experience with existing lines when specifying protection for new lines. For that purpose, collections have been made of historical data on existing lines, relative to their design tensions and the occurrence or not of fatigued strands. Analyses of such collections have been published by Zetterholm [1], Rawlins *et al* [14], Dulhunty *et al* [15] and Doocey *et al* [16].

These analyses rely upon evidence that there exist parameters that can rank spans according to their risk of fatigue damage, and that well-chosen ranking parameters can properly rank collections of spans of different design, as long as each collection is confined to a certain limited class. For example, ACSR spans with dampers would belong to a different class from ACSR spans with armor rods, and copper conductor spans, with dampers or with armor rods, would belong to different classes from the ACSR spans. The power of such analyses hinges upon choosing the ranking parameters well, defining the various classes narrowly enough, and yet retaining enough cases in each class to define a pattern that distinguishes spans that are likely to experience fatigue from the general population.

As noted earlier, the method adopted by the Task Force, to estimate maximum safe tensions for Aeolian vibration, was Energy Balance Analysis. However, it also made use of the field experience approach, as a “reality check.” In doing that, it was the view of the Task Force that, since it was first concerned only with undamped, unarmored spans, the most significant design parameter influencing the probability of fatigue is conductor tension, because of the impact of tension upon conductor self-damping. However, tension can be expressed in various forms, such as force, stress, percent of rated strength and others. The Task Force was faced with the need to choose a form, for use as a *ranking* parameter that would be indifferent to such things as conductor diameter, in order gather as many field cases into each class as possible. The parameter that was selected was H/w.

Since tension H for any span is not constant, but varies with temperature, ice or wind loading history and creep, it was necessary to define the reference condition for determining H. The Task Force decided to use the average temperature for the coldest month as reference temperature, and to determine tension for initial conditions, *i.e.*, before wind and ice loading and creep.

The Task Force drew from several sources to form a collection of field experience cases for undamped spans, i.e., spans equipped with neither dampers nor armor of any type. This collection was used as a "reality check" on the predictions of maximum safe design tensions based on the Energy Balance Principle, developed by Task Force members. The collection contained enough cases to be useful only for conventional round strand ACSR. There were not enough cases to indicate safe tension limits for aluminum or aluminum alloy conductors, ground wires or OPGW. The ACSR collection is shown in Table 4.2.

In Table 4.2, the individual rows pertain to existing undamped ACSR lines for which data is available. They are arranged in order of increasing H/w, and for each line it is indicated whether conductor fatigue is known to have occurred.

The tension-ranking parameter H/w is expected to correlate with failure experience, and a limiting value of H/w below which failures do not occur is expected to exist. Spans having H/w values greater than this limit may survive without experiencing fatigue failure due to the protective effects of terrain features such as trees and buildings, or where the line runs parallel to a valley that channels the wind. However, no failures should occur where H/w is below the limit.

The table suggests that the limit may be about H/w = 1000 meters. However, there are not enough experience cases in the vicinity of that value to support more than a tentative conclusion. The lowest failure case, with H/w = 1030 meters, involved pin-type insulators with hand-formed ties, whereas almost all the other cases involved spans supported by suspension clamps. Thus, the departure of this case from the main pattern may indicate that pin insulator supports cannot be included in the same class as suspension clamp supports. In addition, the span was short, making the determination of tension particularly sensitive to the precision of "sagging in" and to the choice of reference temperature. If this case is ignored, the safe limit may be as much as H/w = 1400 meters. However, there are not enough experience cases in the interval between 1000 and 1400 m to determine where in this range the limit should fall. One can only conclude it is somewhere in this interval.

Table 4.2 Field Experience Cases for Undamped ACSR.

Conductor Diam (mm)	Al / St Strands	Average Span (m)	*H*/*w* (m)	Fatigue failure
21.9	36/12	200	707	
21.9	36/12	395	844	
24.2	54/7	137	934	
8.0	6/1	61	1029	Yes
21.8	26/7	183	1358	
26.6	26/19	362	1397	Yes
16.5		310	1405	Yes
18.8	30/7	396	1511	Yes
18.8	30/7	350	1554	
10.7	12/7	300	1607	Yes
21.8	26/7	274	1638	
25.9	30/7	396	1655	Yes
21.8	26/7	326	1723	
20.5	26/7	300	1731	Yes
25.4	54/7	346	1735	
19.9	26/7	170	1738	
22.4	30/7	333	1747	
21.0	30/7	390	1761	Yes
12.7	6/1	107	1772	
22.4	30/7	340	1865	Yes
21.7	48/7	295	1881	Yes
18.8	30/7	270	1908	
18.8	30/7	360	1959	
11.7	12/7	264	1996	Yes
19.6	30/7	350	2001	
19.6	30/7	350	2001	
26.4	32/19	655	2095	Yes
26.4	32/19	445	2108	Yes
26.4	32/19	520	2116	Yes
22.4	34/19	475	2154	
25.1	26/7	580	2162	
26.4	32/19	475	2176	
21.9	36/12	315	2243	
18.3	26/7	440	2279	Yes
31.7	114/37	425	2297	Yes
31.7	114/37	415	2300	Yes
31.7	114/37	374	2382	Yes
14.4	12/7	194	2458	Yes
22.3	30/7	350	2861	Yes

General Discussion

Attempts to determine maximum safe tensions for Aeolian vibration on the basis of field experience only have been difficult and sometimes unsuccessful. This is due to the fact that actual conductor condition, tension history and even, on occasions, design tensions are not known. One way round is to have recourse to modelling which is the method adopted by the Task Force. One substantial advantage of this approach is the possibility to consider all relevant parameters and variables in a systematic manner.

However, caution is compulsory despite the improved scientific appearance of the modelling approach. Vibration-induced fatigue degradation of conductors is a problem of a highly complex and highly random nature that is not easily amenable to mathematical analysis. From the very first, the wind, the sole cause to Aeolian vibrations, is itself strongly random, with the wind speed and direction fluctuating continuously both time-wise and space-wise, as noted above. The conductors respond to variations in weather conditions associated with the passage of major weather systems by displaying markedly different amplitudes and frequencies on different days, and even different hours of the same day. They respond to differences in wind structure by vibrating less when and where the wind is turbulent or gusty. Thus, the rate of accumulation of fatigue cycles is random over time and varies markedly with location.

What is more, conductor self-damping, which determines the vibration intensity, is a strong function of tension which itself is far from being a constant depending on non-deterministic variables such as conductor temperature and also creep which in turn depends on wind and ice loading history. For ACSR conductors, self-damping is even dependent on the share of tension between the aluminium strands and the steel strands and that is again a function of temperature and creep.

Conductor fatigue endurance, the conductor faculty to resist vibratory motion without strand failure, is another random variable that comes into play. It has been determined that lifetime before first strand failure of several samples of the same conductor, tested according to the same ideal laboratory protocol, may be scattered over a range as large as 1-50. Dispersion in the cycles to failure is indeed inherent to metal fatigue, and is increased by effects of variability in mill processing and, particularly, effects of fretting.

Moreover, there is already a large scatter in the available experimental data yet, pertaining to the same simplified vibratory schemes. Hence, there is a 2 to 1 factor between the highest and the lowest value of maximum wind power input into conductors according to investigators [17]. What is even more consequential, there may be one order of magnitude difference in conductor self-damping estimate at the same tension according to testing methods [17]. Likewise, as regard conductor fatigue, there is a 2 to 1 ratio in the endurance limit of multilayer ACSR's whether it is extracted from EPRI's Orange Book [13] or from the CIGRÉ Safe Border Line [18]. That entire scatter would probably intensify had the true nature of the beat-pattern-like vibrations been duly considered.

All that without saying anything about the great diversity in conductor types, sizes and makes as well as in suspension clamps or other supporting devices.

All those complexities and uncertainties just enhanced the necessity of resorting to sound analysis and judgement. Obviously, simplification is required to overcome complexities. Some conservatism is needed to counterbalance uncertainties. And comparison against field experience and test line results is a necessity to gain confidence in the recommended safe tensions. That has been the philosophy that has guided the Task Force throughout.

Hence, initial tension at the average temperature of the coldest month was chosen as a base to the recommendations knowing that any temperature increase, any wind and ice loading as well as the inevitable creep would soon reduce tension permanently, thus alleviating the vibration severity. Furthermore, the recommended safe tensions stand well in the lower range of the predicted values.

The recommended safe *H*/*w* may appear over-conservative. Nevertheless, it should be noticed that they generally stand above the 17-18% of UTS recommended by the EDS Panel for all aluminum A1 (AAC) conductors and low steel-content aluminum conductors A1/Syz (ACSR).

Recommendations

The maximum safe design tensions with respect to Aeolian vibrations of undamped and unarmored conductors, as recommended by the Task Force, are shown in Table 4.3 as a function of terrain category. The table uses *H*/*w*, the ratio of horizontal tension in the span to conductor weight per unit length, as the tension parameter. It is important to note that this horizontal tension refers to initial horizontal tension, before wind and ice loading and before creep, at the average temperature of the coldest month on the site of the line.

Recommended safe tensions apply to the following round strand conductors: all aluminium A1 (AAC) conductors; all aluminium alloy A2 or A3 (AAAC) conductors; aluminium/aluminium alloy A1/A2 or A1/A3 (ACAR) conductors and steel-reinforced aluminium A1/Syz (ACSR) conductors. It was resolved to give a uniform recommendation for all types of conventional conductors using aluminium and/or aluminium alloy. Although a lower fatigue endurance of A2 (AAAC) conductors may be surmised from reference [13], there seems to be no well documented field evidence to support a more pessimistic tension recommendation for these conductors.

Terrains have been divided into four categories according to general characteristics. Should there be any doubt about real terrain category, the lowest class should be selected.

Table 4.3 Recommended conductor safe design tension at the average temperature of the coldest month as a function of terrain category. Valid for homogeneous aluminium and aluminium alloy conductors Ax (AAC and AAAC), bi-metallic aluminium conductors Ax/Ay (ACAR) and steel reinforced aluminium conductors A1/Syz (ACSR).

Terrain category	Terrain characteristics	$\left(H/w\right)_{adm}$ (m)
1	Open, flat, no trees, no obstruction, with snow cover, or near/across large bodies of water; flat desert.	1000
2	Open, flat, no obstruction, no snow; *e.g.* farmland without any obstruction, summer time.	1125
3	Open, flat, or undulating with very few obstacles, *e.g.* open grass or farmland with few trees, hedgerows and other barriers; prairie, tundra.	1225
4	Built-up with some trees and buildings, *e.g.* residential suburbs; small towns; woodlands and shrubs. Small fields with bushes, trees and hedges.	1425

The maximum safe design tensions recommended herein should be suitable most of the time. However, special situations require specific attention. Such is the case for extra long spans, or spans exposed to pollutants that may decrease the self-damping or the fatigue endurance of the conductor, or spans often covered with ice, rime or hoarfrost, or spans operated at high temperature.

Generally speaking, damping spans is inexpensive and that is certainly preferable to hazarding conductor fatigue breaks. Moreover, use of damping may allow higher tensions resulting in significant cost savings in line construction.

Use of armour rods or special supporting devices such as cushioned clamps and helical elastomer-bushed suspensions may justify higher design tensions on otherwise unprotected conductors. Information on safe tension, when these devices are employed, should be obtained from their suppliers.

Existing lines using single unprotected conductors strung at a tension exceeding the recommended value for the terrain may require inspection and field measurement. Techniques to perform such vibration measurements have been described previously [19].

Incidentally, in some countries, the maximum safe design tension may be governed by the maximum climatic loading rather than by Aeolian vibrations.

5. DAMPED SINGLE CONDUCTORS

This section aims at recommending safe design tensions for single conductor lines protected by means of Stockbridge-type vibration dampers set up at the span extremities.

Modelling

The two models that were employed to estimate safe tensions basically rely on the Energy Balance Principle [11] to predict steady state vibration in terms of $f\,y_{max}$ (the product of vibration frequency and maximum vibration amplitudes at antinodes), that is the response of a span when excitation by the wind is balanced by the self-damping in the conductor and by damping devices.

The flow chart in Fig. 4.1 shows parameters that, in a modelling approach, may serve to describe the properties of the structural system (the span and span-end damping arrangements) and the wind excitation, and Table 5.1 summarizes which of these parameters were considered in models of different organisations, and how they were quantified.

Table 5.1 Basic assumptions underlying model calculations.

Organisation	IREQ / Leblond & Hardy [25]	Alcoa Fujikura / Rawlins [26]
Approach	Endurance Limit	Endurance Limit
Conductor damping capacity	Calculated on the basis of similarity laws calibrated by means of measured data (ISWR method).	Measured (ISWR method)
Span-end damping	Travelling wave approach using complex damper stiffness measured on shaker	Measured efficiency of span-end damping arrangement
Wind power input	Laminar or reduced for normally-distributed turbulence	Laminar or reduced for turbulence
Vibration mode shape	Narrow band random vibration (peak amplitudes Rayleigh-distributed, maximum amplitude limited to 3.5 times RMS-value at each frequency)	Sinusoidal
Conductor tolerance to vibration	Fatigue endurance as per [13]	Fatigue endurance as per [13]
Clamping system	Fixed metal to metal clamps	Fixed metal to metal clamps

As the Task Force focused on Stockbridge-type dampers applied at span ends, information on the span-end damping was needed to be employed in the Energy Balance analysis. Data was available that was obtained by indoor testing techniques described in IEEE Std 664-1993, "*IEEE Guide for Laboratory Measurement of the Power Dissipation of Aeolian vibration Damper for Single Conductors*" (see also ref. [20]). One technique uses a conductor span to determine the so-called efficiency of a span-end damping arrangement which can directly be used in the Energy Balance [21]. Another technique consists in measuring the dynamic characteristics of a Stockbridge-type vibration damper on a shaker. Travelling wave analysis was then used to predict the span-end dissipation characteristics from the measured complex characteristics of the damper [21].

The Endurance Limit Approach, as defined in Section 4, was generally followed to assess computed vibration levels (the span response) with regard to the tolerance of the conductor to vibration. In this approach, vibration levels are considered to result in an infinite lifetime of the conductor, if they do not exceed a definite limit value (the endurance limit in terms of $f\,y_{\max}$). Conductor tensions that lead to vibration levels below the endurance limit are regarded as safe.

Selection of Parameters

The Task Force has focused on Stockbridge-type dampers, since this is at present the type most widely used on conductors. It is noted that there are differences in design and application rules among Stockbridge dampers of different sources. The Task Force is not in a position to distinguish among these, and does not feel that it should. Thus, it has been forced to seek a single safe tension criterion for a population that is not homogeneous, even though limited to Stockbridge-type dampers.

The Task Force was aided, in dealing with this difficulty, by the observation that tests on laboratory spans as well as on an outdoor test span [22] have shown somewhat similar level of damping efficiency[1] using dampers of various sources. This observation was found to be true, even for widely different conductor sizes, when applied to well-designed and properly applied dampers of sizes appropriate to the conductors in question. In fact, certain utility specifications specify the same minimum level of performance in terms of damping efficiency for a significant range of conductor sizes [23].

The similarity in damping efficiency levels pointed toward a particular parameter to use in rating the protective capabilities of dampers. This rating parameter, $L\,D\big/\sqrt{H\,m}$, (where L is actual span length, D is conductor diameter, H is horizontal tension in the conductor and m is mass of the conductor per unit length) has been used in analyses of collections of field experience data on fatigue of overhead conductors [24] to rank spans according to the difficulty in damping them, based on the line design variables, span length, conductor size and tension. The parameter is proportional to the damping efficiency required to control vibration amplitude to a given level. Since the Task Force had adopted the parameter H/w (where w is weight of the conductor per

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[1] Damping efficiency is defined [21] as the ratio of power actually dissipated by the damper to the power that would be dissipated by a perfect damper - one that absorbed incident waves without reflection - at the same frequency and amplitude. In the laboratory, damping is measured through the inverse standing wave ratio [20].

unit length) to rate the effect of tension on conductor self damping, it was able to simplify the set of rating parameters $LD/\sqrt{Hm}$ and H/m to LD/m and H/w respectively.

Predicted Safe Design Tension

Safe design tension as predicted by Leblond and Hardy [25] for one conductor type over a full range of span lengths and by Rawlins [26] for three sets of conductor types and span lengths is depicted in Fig. 5.1 in terms of the span parameter LD/m and the tension parameter H/w. As a rule, the calculations were carried out using the endurance limit approach for the A1/Syz[2] (ACSR) aluminium-conductors-steel-reinforced indicated in the legend. The results shown here were determined on the basis of an assumed constant level of wind turbulence ranging from 5% to 30%. It will be noticed that despite a large scatter in the calculated safe design tension according to the source, there is a fair agreement in the minimum, more conservative, values.

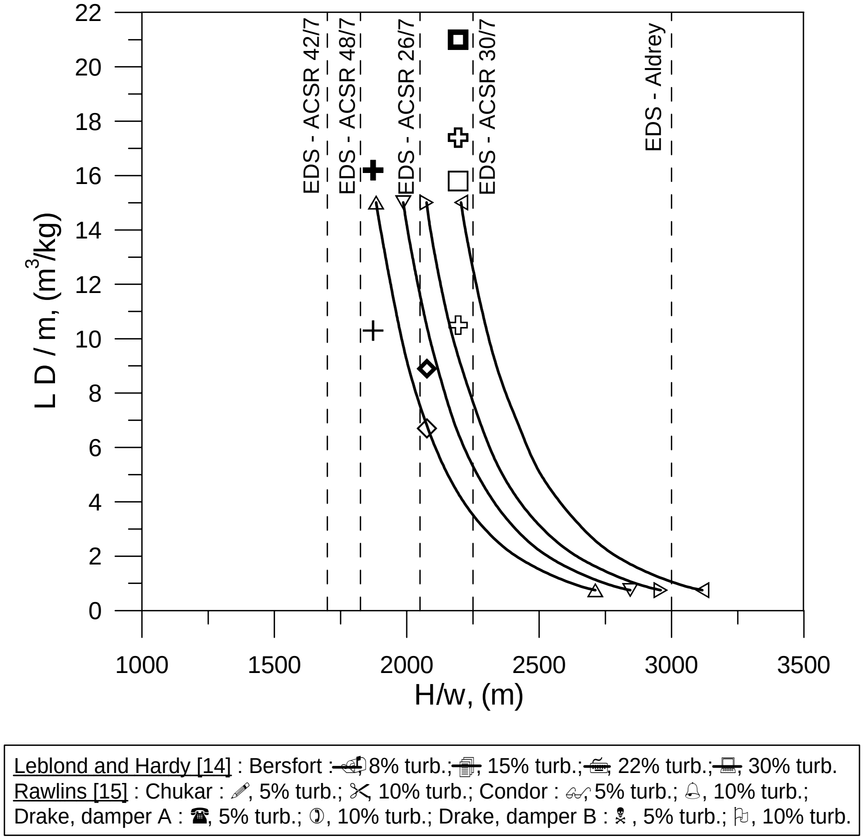

Figure 5.1 Predicted safe boundaries according to endurance limit approach.

Also shown in Fig. 5.1 are the safe tensions recommended by the EDS Panel, translated in terms of H/w, for different damped A1/Syz (ACSR) and Aldrey conductors. As the Panel did not

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[2] International Electrotechnical Commission (IEC) conductor designation [12] : see Table 5.3.

account for the span length, their recommended tensions appear as straight vertical lines in the graphics. For the common range of span parameters, $5 < LD/m < 15$ (m3/kg), it may be observed that the safe design tension as calculated by the endurance limit approach for 8% wind turbulence is respectively more permissive, about equally permissive or less permissive than the corresponding EDS values for low steel content, medium steel content or high steel content A1/Syz (ACSR) conductors. However, for Aldrey conductors, the calculated safe design tension is definitely much more conservative over all the span range than the value recommended by the EDS Panel, i.e. 26% of UTS or about 3000 m.

Comparison With Field Experience

In the previous section dealing with Unprotected Single Conductors, it was remarked, "Uncertainties in the data and assumptions that are required to determine maximum safe tensions on the basis of the Energy Balance Principle have made it necessary to consider known experience with existing lines when specifying protection for new lines." These uncertainties are even more significant in the present case where dampers are involved. The analytical basis for applying the Energy Balance Principle is still open to question and is, in fact, currently under scrutiny by CIGRÉ TF B2.11.01 "Vibration Principles". Thus, the need to test the present recommendations against past experience is even greater than before.

It is worthwhile to examine the range of the ranking parameters LD/m and H/w actually represented in overhead lines. Fig. 5.2 shows a collection of points representing a number of actual lines, all of which are protected by Stockbridge-type dampers. It is not certain that all of these lines were free of fatigue damage, but most probably were. The collection was drawn from files of Task Force members.

Figure 5.2 includes the estimated safe boundaries depicted in Fig. 5.1. It is evident that many existing lines fall on the safe side of the estimated safe boundaries, but a significant number fall on the "unsafe" side. It is likely that a few of these "unsafe" lines did experience damage, and that others were protected from severe vibration by very rough terrain, beyond Category 4. However, the Task Force interprets the presence of so many cases on the unsafe side as indicating a conservative bias in the estimated safe boundaries.

The TF found only meagre information on field experience cases where conductor fatigue occurred in lines protected by Stockbridge type dampers. Table 5.2 summarises cases from questionnaires collected by CSC6 [2] and SC22 WG04 for all damper types. Only three cases, Items 1, 5 and 6, clearly pertain to Stockbridge dampers. Items 7 and 8 may or may not pertain to Stockbridge dampers, but it is considered likely that the fatigue occurred before any dampers were installed. For Items 1 and 6, the damage may have occurred in spans that were not fitted with dampers. For Item 1, the figure for H/w applies to the design value of H. Actual tension was higher due to contractor error, but an actual value was not reported. Thus, Item 5 represents the only case that is clearly valid for testing the estimated safe boundaries against field experience. The case led the utility to increase the number of dampers in designing its lines, implying that the damaged line had originally been fitted with less damping than might have been required.

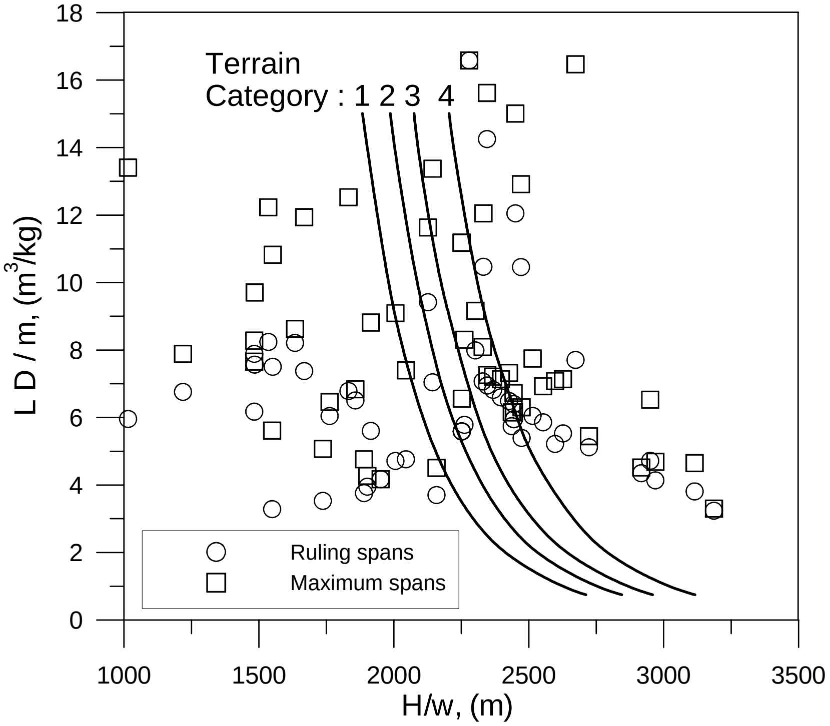

Figure 5.2 Ranking parameters of damped ACSR lines in North America (no water crossings) in relation to estimated safe boundaries.

Table 5.2 Field experience conductor fatigue cases – ACSR.

Item	Diam. mm	Stranding	Span metres	*H/w* metres	*LD/m* m^3/kg	Damper type	Note
1	16.28	26/7	167	1542	4.983	Stockbridge	1
2	31.59	54/7	360	2017	5.755	Torsional	
3	27.00	30/7	290	1851	5.861	Dumbell	
4	27.00	30/7	305	1851	6.164	Dumbell	
5	26.60	26/19	380	1994	6.971	Stockbridge	
6	31.77	54/7	320	2031	5.086	Stockbridge	2
7	27.72	54/7	305	1677	5.691	“yes”	3
8	24.20	54/7	268	1406	5.592	“yes”	3
9	26.40	32/19	510	2227	8.496	Bretelles	
10	27.72	54/7	330	1734	6.140	Elgra	

1. Dampers may have been installed in dead-end spans and at angle towers only. *H/w* based on design tension. Actual tension was higher due to contractor error.
2. Not all spans were damped. Damage may have only occurred in spans that were protected by armour rods only.
3. Lines were built in 1930 and 1927, respectively, before dampers were commercially available. Evidently, dampers were added later. Damage likely occurred before they were installed.

Figure 5.3 shows all of the cases from Table 5.2, for comparison with the estimated safe boundaries. All but Item 9 fall on the “safe” side of all four boundaries. The one valid case for Stockbridge dampers, Item 5, falls slightly on the safe side of the Terrain Category 1 boundary. Item 6, which may or may not be valid, falls similarly. Both cases came from Category 1 terrain. Their position in the plot suggests that the proposed safe boundaries are not excessively conservative.

Figure 5.3 also includes data from a number of operating lines where there is information that fatigue damage to conductors has not occurred. The cases drawn from the test line are particularly well documented because of the close control of conductor tensions, careful vibration measurements and close inspection for damage. All these cases are in harmony with the proposed safe boundaries.

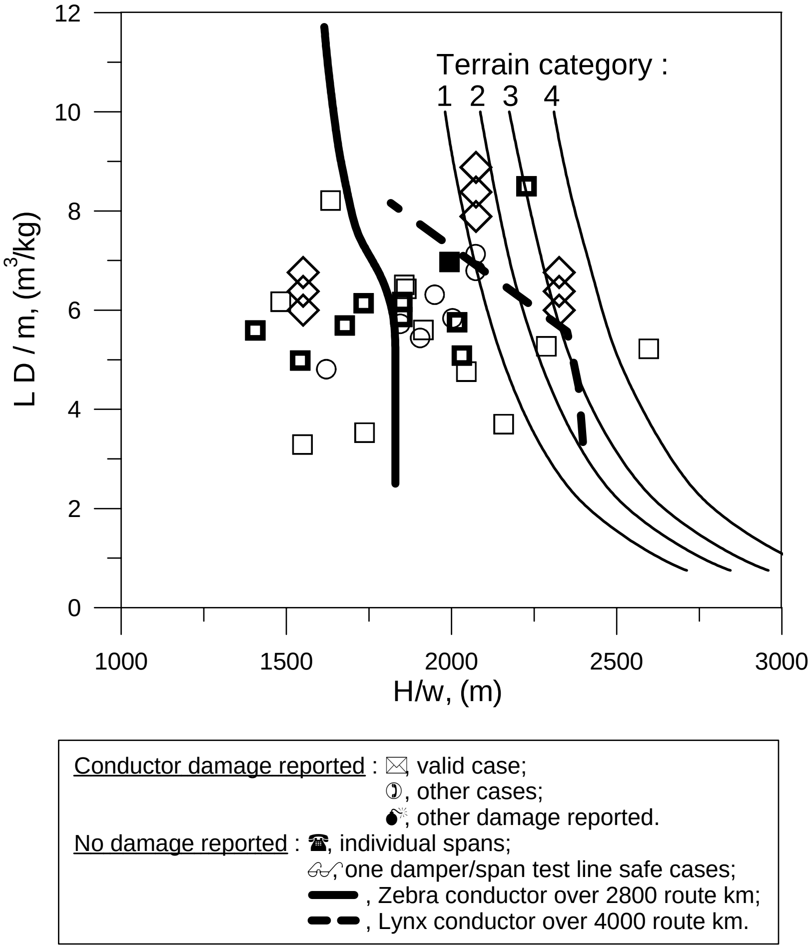

Figure 5.3 Available field experience regarding damped single conductor lines in relation to estimated safe boundaries.

Task Force Recommendations

As explained above, the Task Force has resolved to provide guidance to conductor safe design tension with respect to Aeolian vibrations in terms of two parameters: the tension parameter *H*/*w*, the ratio of horizontal tension *H* in the span to conductor weight *w* per unit length and the span parameter, *LD*/*m*, the ratio of actual span length *L* times conductor diameter *D* to conductor mass *m* per unit length. The tension *H* refers to initial horizontal tension before any significant wind and ice loading and before creep, at the average temperature of the coldest month on the site of the line.

The Task Force recommendations are depicted in Fig. 5.4 in the form of four sets of curves, each one set associated to a particular terrain category described in the legend. The corresponding information is provided in Table 6.3 in algebraic form. Terrains have been divided into four categories according to their general characteristics. Should there be any doubt about real terrain category, the lowest category should be selected.

The basic Safe Design Zone - No Damping applies to undamped and unarmoured single conductors, as already shown in Section 4. This zone is defined in terms of the *H*/*w* parameter only and it is unlimited in the *LD*/*m* parameter.

The Safe Design Zone - Span End Damping constitutes a zone where full protection of single conductors against Aeolian vibrations is assuredly feasible by means of one or more Stockbridge-type damper(s) set up at span extremities. Hence, within the limits of this zone, Aeolian vibrations should not be a constraint on design tension.

For line parameters falling in the Special Application Zone, Aeolian vibrations may or may not be a constraint and it is recommended that line designers determine the availability of adequate protection before finalising the design.

This guide applies to all round wire, concentric lay, overhead electrical conductors shown in Table 5.3.

Table 5.3 Conductor types to which recommendations apply.

Metal Combination	Common Designation	IEC Designation
All 1350-H19	ASC or AAC	A1
All 6101-T81	AASC or AAAC	A2
All 6201-T81	AASC or AAAC	A3
1350-H19 / Steel	ACSR	A1/S1A
1350-H19 / 6101-T81	ACAR	A1/A2
1350-H19 / 6201-T81	ACAR	A1/A3

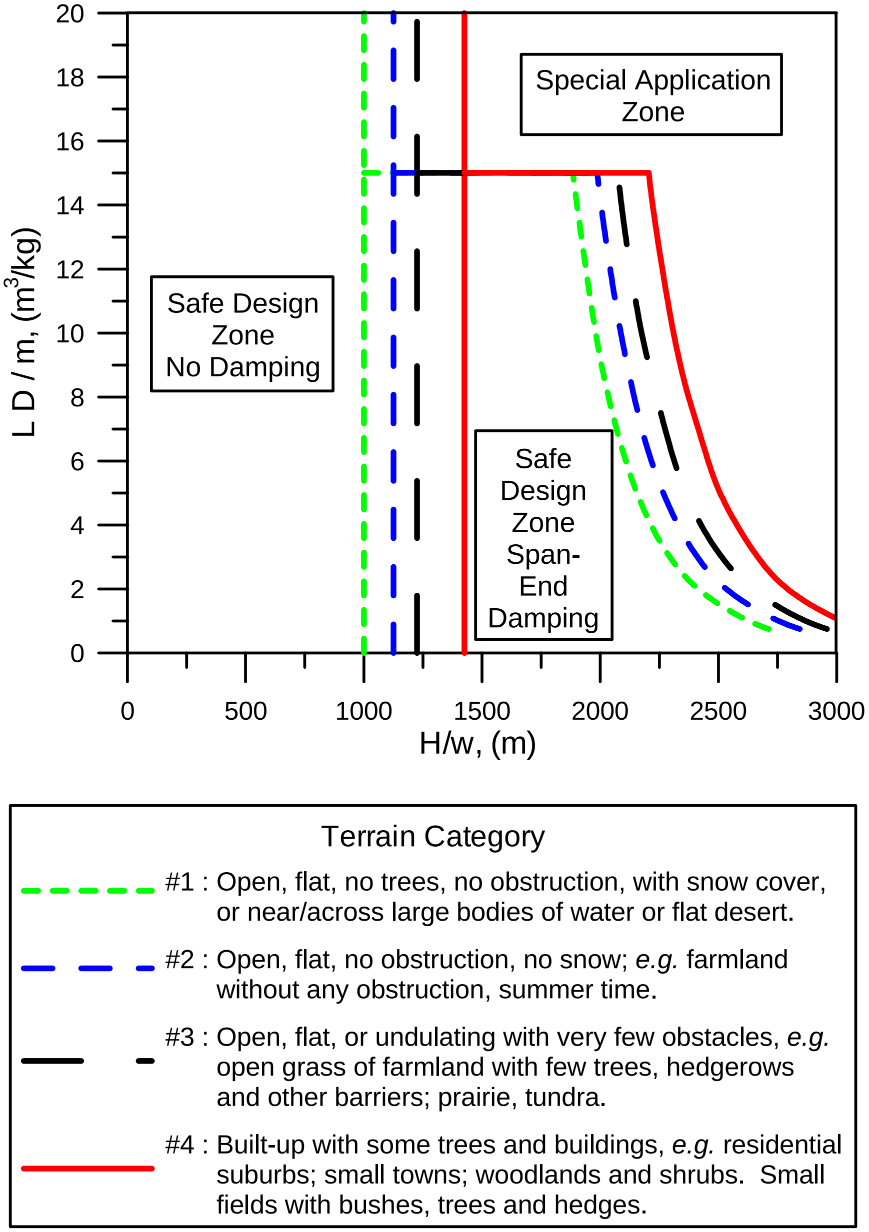

Figure 5.4 Recommended safe design tension for single conductor lines. *H*: initial horizontal tension; *w*: conductor weight per unit length; *L*: actual span length; *D*: conductor diameter and *m*: conductor mass per unit length.

It was resolved to give a uniform recommendation for all types of conventional conductors using aluminium and/or aluminium alloy. Although a lower fatigue endurance of A3 (AAAC) conductors may be surmised from reference [13], there seems to be no well documented field evidence to support a more pessimistic tension recommendation for these conductors.

Existing lines using single conductors strung at a tension exceeding the recommended value for the terrain and span length may require inspection and field measurement. Techniques to perform such vibration measurements have been described previously [19].

It may be noted here that conductors do not get more susceptible to other forms of wind-induced vibrations when tension is increased. As a matter of fact, their propensity to both galloping [27] and wake-induced oscillations [28] (of bundled conductors) has been shown to decrease with increased tension.

Limitations

As mentioned above, the Task Force has focused on Stockbridge-type dampers. It is noted that the "Bretelle" is also used in some countries, helical impact dampers are widely used on earth wires and special designs such as "Festoon" dampers are employed in certain applications such as fjord crossings. However, it was judged not feasible at this juncture to arrive at safe tension recommendations for these types.

The Task Force has used the parameters H/w and LD/m to construct boundaries within which satisfactory performance should be commercially available, often from multiple sources. This statement should in no way be taken to mean that all commercially available dampers will provide such protection up to the limits of those boundaries or that they could provide such protection indefinitely without themselves failing from fatigue. Rather, appropriate field testing or evaluation of available dampers is likely to reveal at least some that do. It falls to the line designer to identify them.

The guidance provided herein should be suitable most of the time. However, special situations require specific attention. Such is the case for extra long spans; for spans often covered with ice, rime or hoarfrost in which case dampers may break up prematurely as a result of galloping and/or excessive Aeolian vibrations; for spans exposed to pollutants that may decrease the fatigue endurance of the conductors; for spans equipped with warning devices and for spans using non-conventional conductors such as compact or high temperature conductors.

Use of armour rods or special supporting devices such as cushioned clamps and helical elastomer-bushed suspensions may justify higher design tensions. Information on safe tension, when these devices are employed should be obtained from their suppliers.

6. BUNDLED CONDUCTORS

The present section aims at recommending safe design tensions for bundled conductor lines. The recommendations cover twin horizontal bundles, triple apex-down bundles and quad horizontal bundles made up of conventional stranded conductors fitted either with damping spacers or non-damping spacers or a combination of non-damping spacers and span-end Stockbridge-type dampers.

Review of Literature

Numerous field tests have demonstrated that bundled conductors respond less to Aeolian excitation than single conductors of the same size and at the same tension as those of the bundle. For example, Fig. 6.1 shows results of simultaneous recordings at Alcoa's outdoor laboratory in1960 [29]. Bundling reduced vibration amplitudes by about half, with and without dampers on the span.

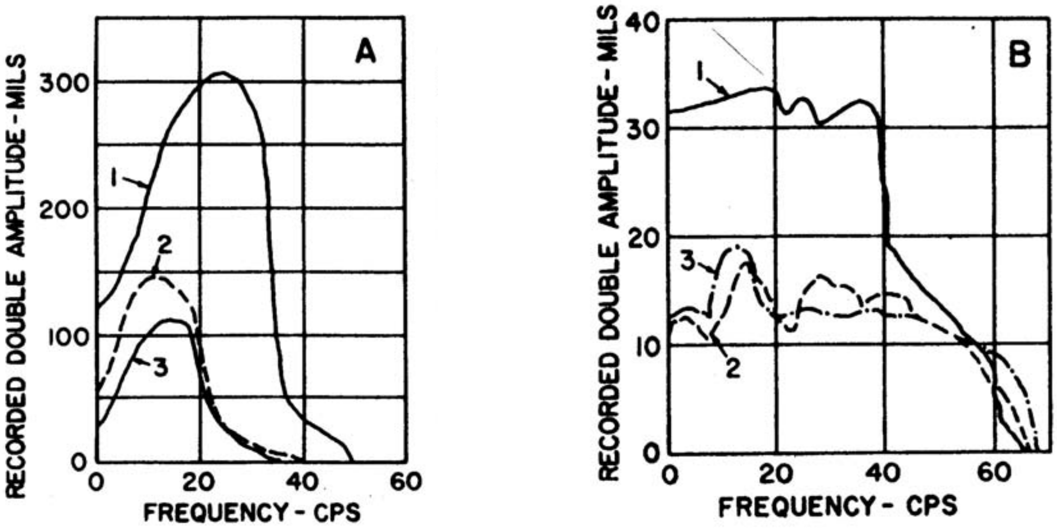

Figure 6.1 Comparison of vibration in single versus bundled conductors
Drake ACSR in 1200-foot span [29]. (MILS ≡ in x 10^{-3}; CPS ≡ Hertz)
1 – Single conductor 2,3 – Subconductors in horizontal two-conductor bundle
A – No dampers B – One Stockbridge damper at end opposite recorder.

Early investigations showed that the reduction in amplitude becomes greater as the number of subconductors in the bundle increases. Leibfried and Mors reported that spans in the Hornisgrinde Test Station displayed, on average, amplitudes in the ratios 4:2:1 in spans with single, twin- and quad-bundles respectively [30]. Liberman and Krukov reported that amplitudes were reduced by factors of 1.5 to 2.5 for horizontal two-bundles, and of 5 to 10 for triple and quadruple bundles [31]. There was some influence by spacer design, but in all of these tests the spacers did not include intentional damping. Thus, the benefits of bundling were attributed to the effects of mechanical coupling among the subconductors interfering with the vortex excitation mechanism.

The effect of intentional damping in spacers was investigated initially by Edwards and Boyd at Ontario Hydro [32]. They found that damping of a certain type reduced amplitudes in a twin bundle by a factor of 5, relative to a comparable single conductor, and by a factor of 20 in a quad bundle. The benefit of damping was confirmed by Diana *et al*. at the Porto Tolle Test Station in Italy [33]. The effect of bundle configuration upon this benefit was investigated by Hardy *et al*. at the Magdalen Islands Test Station of IREQ [34]. Damping in spacers is beneficial in all bundle configurations, but seems greatest in those that have size in the vertical direction, such as triple and quad bundles.

Table 6.1 collects the test conditions and salient data from a number of these field tests.

Review of Field Experience

Table 6.2 summarises some line design variables of 91 bundled conductor lines in North America which have most likely operated for many decades without any Aeolian vibration problem. It comprises 70 twin horizontal bundled lines (2H), out of which 19 lines have been fitted with non-damping spacers (NDS) alone, 48 lines fitted with a combination of such spacers and span-end Stockbridge dampers (NDS+Stk) and 3 lines fitted with damping spacers (DS) alone. The tension parameter *H*/*w* ranged up to 2088 m in the first case, 2959 m in the second and 1937 m in the third.

Table 6.2 also gives details of 14 triple apex-down bundled lines (3AD), out of which one line only has been equipped with NDS, 4 lines with NDS+Stk and 9 lines with DS. This time, the tension parameter *H*/*w* reached 1627 m in the first case, 2056 m in the second and 2096 m in the third.

Finally, Table 6.2 includes 7 quad horizontal bundled lines (4H), out of which 3 are protected by means of NDS+Stk and 4 others by means of DS. In this case, the tension parameter *H*/*w* was set to a maximum of 1488 m and 1937 m respectively.

Table 6.1 Synthesis of field test experience about comparative vibration behaviour of bundled conductors.

Ref.	**Bundle type**	**Nominal conductor H/w (m)**	**Test span LD/m (m^3/kg)**	**Spacer type**	**End damper**	**Amplitude ratio single/bundle**
[29]	Hor. twin	1755	6.3	Articulated	No	>2,1
[29]	Hor. twin	1755	6.3	Articulated	Yes	>1,8
[29]	Hor. twin	1755	6.3	Ball-&-socket	No	>2,7
[29]	Hor. twin	1755	6.3	Ball-&-socket	Yes	>1,9
[30]	Hor. twin	1295	6.5	Various	No	~2
[30]	Hor. quad	1295	6.5	Various	No	~4
[31]	Hor. twin	>1454	6.5	Articulated	No	>1,5
[31]	Hor. twin	>1437	7.5	Articulated	No	>1,5
[31]	Hor. twin	>1730	6.3	Articulated	No	>1,7
[31]	Vert. twin	>1454	6.5	Articulated	No	>1,7
[31]	Vert. twin	>1730	6.3	Articulated	No	>5
[31]	Triple	>1437	7.5	Grouped twins	No	>5
[31]	Hor. quad	>1730	6.3	Grouped twins	No	>5
[33]	Hor. twin	1743	7.2	Rigid	No	>1,3
[33]	Triple	1743	7.2	Damping spacers	No	>5
[34]	Hor. twin	1550	6.8	Damping spacers	No	~2,4
[34]	Triple	1550	6.8	Damping spacers	No	~6,5
[34]	Hor. quad	1550	6.8	Damping spacers	No	~7,7
[34]	Hor. twin	2325	6.8	Damping spacers	No	~3,6
[34]	Triple	2325	6.8	Damping spacers	No	~8,6
[34]	Hor. quad	2325	6.8	Damping spacers	No	~13,0

Table 6.2 Outlook of field experience with bundled conductor lines in North America.

No. of lines	**Bundle type**	**Protection**	**Range of mean LD/m (m^3/kg)**	**Range of initial H/w (m)**
19	2H	NDS	2.19 - 4.63	802 - 2088
48	2H	NDS+Stk	3.14 - 7.27	910 - 2959
3	2H	DS	5.03 - 6.60	1636 - 1937
1	3AD	NDS	5.62	1627
4	3AD	NDS+Stk	6.20 - 6.93	1166- 2056
9	3AD	DS	3.93 - 7.81	1401 - 2096
3	4H	NDS+Stk	6.63 - 7.89	1452 - 1488
4	4H	DS	7.33 - 8.38	1633 - 1937

Determination of Safe Design Tension

As an accommodating reference and benchmark, the safe design tensions that were recommended previously for undamped single conductors (conductor system #1) and single conductors fitted with Stockbridge dampers (Stk) at the span extremities (system #2) are shown in Table 6.3 for each one of the four terrain categories that were then defined.

6.3.1 Unspacered bundled conductors fitted or not with span-end Stockbridge dampers

Unspacered bundled conductors have sometimes been used with the object of reducing their susceptibility to galloping. In such cases, it appears reasonable to use the same safe design tension limits as for equivalent single conductors whether they are undamped (system #3) or damped by means of Stk (system #4), as indicated in Table 6.3

6.3.2 Bundled conductors fitted with non-damping spacers

The Task Force could not find any well-documented, instrumented field test data related to twin horizontal bundles fitted with NDS alone. But field experience suggests that a tension of $H/w = 2100$ m should be safe for terrain category #2, as it could be appreciated for one of the lines in Table 6.2. However, to keep on the prudent side, it was resolved to associate that safe design tension to terrain category #3. The safe design tensions for terrain categories #1, 2 and 4, as shown in Table 6.3 (system #5), were then determined on the basis of terrain category #3 using the same terrain-to-terrain ratio as for the undamped single conductor case.

For triple apex-down bundled lines fitted with NDS, reference was made to comparative field tests [35] carried out at the IREQ test line in Varennes clearly showing such a tension $H/w = 2100$ m to be safe for terrain category #2, applicable to the test station. The safe design tensions for the other terrain categories were determined using the same transposition principle as for the twin bundles. However, as indicated in Table 6.3 (system #8), it was resolved to limit the safe design tension for terrain category #4 to $H/w = 2500$ m as a matter of prudence.

The same absolute limit ($H/w = 2500$ m) was indeed applied to all systems even if they are strung over the roughest terrain.

Table 6.3 Recommended conductor safe design tension with respect to Aeolian vibrations.

Conductor system	Terrain Cat. #1		Terrain Cat. #2		Terrain Cat. #3		Terrain Cat. #4	
	H/w (m)	LD/m (m^3/kg)	H/w (m)	LD/m (m^3/kg)	H/w (m)	LD/m (m^3/kg)	H/w (m)	LD/m (m^3/kg)
1. Undamped single conductor	< 1000		< 1125		< 1225		< 1425	
2. Single conductor with span-end Stockbridge dampers	$< 2615/(LD/m)^{0.12}$	< 15	$< 2780/(LD/m)^{0.12}$	< 15	$< 2860/(LD/m)^{0.12}$	< 15	$< 3030/(LD/m)^{0.12}$	< 15
3. Undamped, unspacered twin, triple & quad bundled conductors	< 1000		< 1125		< 1225		< 1425	
4. Unspacered twin, triple & quad bundled conductors with span-end Stockbridge dampers	$< 2615/(LD/m)^{0.12}$	< 15	$< 2780/(LD/m)^{0.12}$	< 15	$< 2860/(LD/m)^{0.12}$	< 15	$< 3030/(LD/m)^{0.12}$	< 15
5. Twin horizontal bundled conductors with non-damping spacers	< 1725	< 15	< 1925	< 15	< 2100	< 15	< 2450	< 15
6. Twin horizontal bundled conductors with non-damping spacers and span-end Stockbridge dampers	$< 2615/(LD/m)^{0.12}$	< 15	$< 2780/(LD/m)^{0.12}$	< 15	$< 2860/(LD/m)^{0.12}$ < 2100	< 13 > 13 ; < 15	$< 3030/(LD/m)^{0.12}$ < 2450	< 6 > 6 ; < 15
7. Twin horizontal bundled conductors with damping spacers	< 1900		< 2200		< 2500		< 2500	
8. Triple apex-down bundled conductors with non-damping spacers	< 1850	< 15	< 2100	< 15	< 2275	< 15	< 2500	< 15
9. Triple apex-down bundled conductors with non-damping spacers and span-end Stockbridge dampers	$< 2615/(LD/m)^{0.12}$	< 15	$< 2780/(LD/m)^{0.12}$ < 2100	< 10 > 10 ; < 15	$< 2860/(LD/m)^{0.12}$ < 2275	< 7 > 7 ; < 15	$< 3030/(LD/m)^{0.12}$ < 2500	< 5 > 5 ; < 15
10. Triple apex-down bundled conductors with damping spacers	< 2500		< 2500		< 2500		< 2500	
11. Quad horizontal bundled conductors with non-damping spacers	< 1850	< 15	< 2100	< 15	< 2275	< 15	< 2500	< 15
12. Quad horizontal bundled conductors with non-damping spacers and span-end Stockbridge dampers	$< 2615/(LD/m)^{0.12}$	< 15	$< 2780/(LD/m)^{0.12}$ < 2100	< 10 > 10 ; < 15	$< 2860/(LD/m)^{0.12}$ < 2275	< 7 > 7 ; < 15	$< 3030/(LD/m)^{0.12}$ < 2500	< 5 > 5 ; < 15
13. Quad horizontal bundled conductors with damping spacers	< 2500		< 2500		< 2500		< 2500	

Terrain category # 1 : Open, flat, no trees, no obstruction, with snow cover, or near/across large bodies of water or flat desert.

Terrain category # 2 : Open, flat, no obstruction, no snow; e.g. farmland without any obstruction, summer time.

Terrain category # 3 : Open, flat or undulating with very few obstacles, e.g. open grass of farmland with few trees, hedgerows and other barriers; prairie, tundra.

Terrain category # 4 : Built-up with some trees and buildings, e.g. residential suburbs; small towns; woodlands and shrubs. Small fields with bushes, trees and hedges.

H: initial horizontal tension; w: conductor weight per unit length; L: actual span length; D: conductor diameter and m: conductor mass per unit length.

Quad bundles (system #11) fitted with NDS should be somewhat less prone to Aeolian vibrations than their triple equivalents. However, due to lack of accurate information from the field, quad bundles were assigned the same safe design tensions as the triple bundles (system #8).

For all systems using NDS or NDS+Stk (systems #5, 6, 8, 9, 11 and 12), it was resolved, as a matter of prudence, to limit the range of application of the given safe design tensions H/w to spans for which $LD/m < 15$ m^3/kg.

6.3.3 Bundled conductors fitted with non-damping spacers and span-end Stockbridge dampers

Again, the Task Force could not find any well-documented field test data related to bundles fitted with NDS+Stk which could have been used to determine safe design tensions rigorously. However, it appears reasonable and at one and the same time prudent to recommend the same safe design tensions as for either single conductors fitted with Stk (system #2) or bundles fitted with NDS alone (systems #5, 8 and 11), whichever are more permissive. That applies to twin horizontal bundles (system #6), to triple apex-down bundles (system #9) and quad horizontal bundles (system #12) as shown in Table 6.3.

6.3.4 Bundled conductors fitted with damping spacers

To determine safe design tensions of bundles fitted with DS, the Task Force could rely on the results of an extensive program of tests [34] carried out at the IREQ test line in the Magdalen Islands. The test program covered a horizontal twin, an apex-down triple and a horizontal quad bundle of ACSR Bersfort conductors fitted with the same number of DS, staggered in a similar manner, as well as an undamped single conductor of the same type. Each conductor system was tested successively at a nominal tension H/w of 1550 m, 2325 m and 2870 m respectively.

The most relevant results are shown synthetically in Fig. 6.2 in terms of a relative effective amplitude as a function of the tension parameter H/w. The effective amplitudes relate to a single, integrated figure expressing the overall Aeolian vibration response of each system according to a severity or fatigue-damage point of view. The effective amplitudes are then normalized by means of the effective amplitude of the single conductor strung at $H/w = 2325$ m to yield the relative effective amplitudes.

The resultant relative effective amplitudes are plotted as data points in Fig.6.2 which are then related by straight line segments. There are two and three such points for the single conductor on the one hand and each one of the twin, triple and quad bundles on the other hand. It may be observed first that the relative effective amplitude of vibration is from 2 to 4, 6 to 9 and 8 to 13 times less severe on the twin, triple and quad bundles respectively, at the same tension, in comparison to the undamped single conductor.

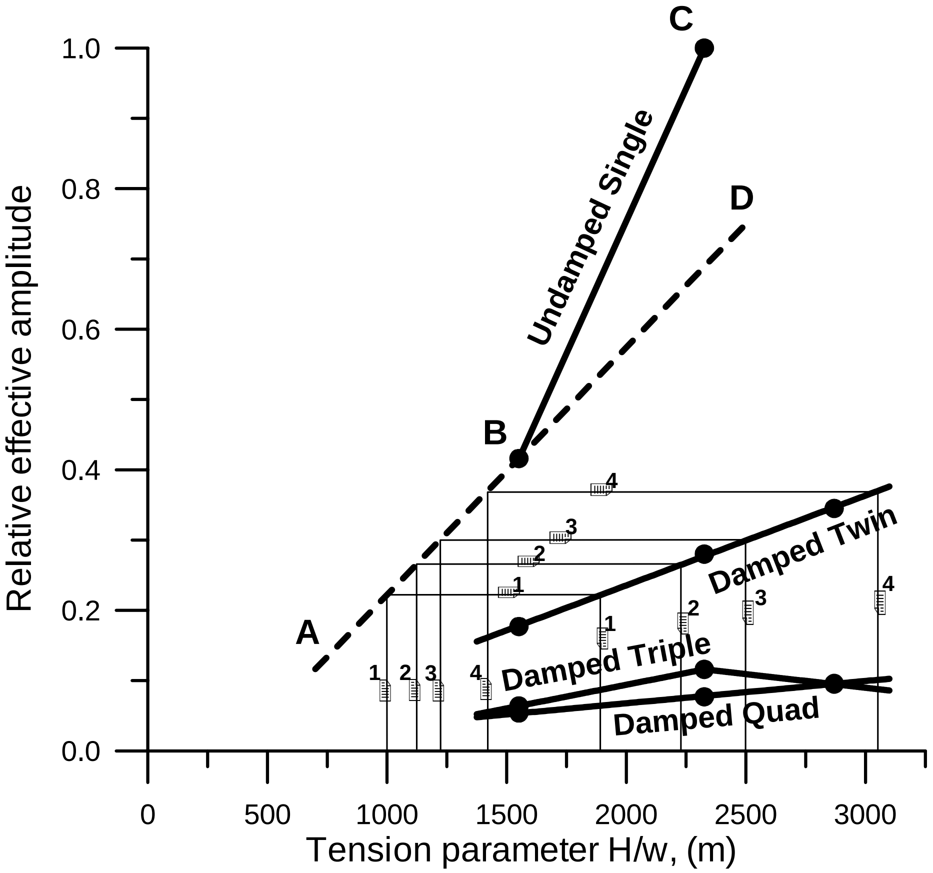

Figure 6.2 Determination of safe design tension for twin horizontal bundled conductor lines fitted with damping spacers on the basis of comparative field test results [34].

In order to proceed further, one would need at least one data point for the undamped single conductor that would stand on the low side of the range of safe design tensions for such a conductor, i.e. 1000 m < *H*/*w* < 1425 m. For lack of such a point from the test program, the IREQ's calculation model [36] was called upon to determine the expected response of the undamped single conductor below data point B in Fig. 6.2, assuming a turbulence intensity corresponding to terrain category 2, as the test site was classified.

Now, if line segment AB is accepted as a reasonable approximation of the actual single conductor response in the range 1000 m < *H*/*w* < 1550 m, one can proceed as follows: for instance, going along arrowed line 2 in Fig.6.2, it may be seen that the relative effective amplitude of the undamped single conductor is expected to stand at about 0.27 when the tension is set at *H*/*w* = 1125 m while for the twin bundled conductors, this amplitude is reached when the tension is set at *H*/*w* = 2200 m. As a result, it looks reasonable to conclude that *H*/*w* = 2200 m may be used as the safe design tension for the twin bundle fitted with DS where *H*/*w* = 1125 m is considered safe for the undamped single conductor.

Strictly speaking, the above procedure for transposing the safe design tension of the undamped single conductor to the twin bundle fitted with DS would be valid only for terrains category 2 as for the test site. However, it was argued that, had the same tests been repeated in other terrains, the effective amplitudes would have certainly moved up or down in absolute terms, but it seems reasonable to assume that they would have moved everywhere in even proportion. As a result, the respective locus for the undamped single conductor and each one of the damped conductor bundles when shown in relative terms would be expected to be approximately unchanged.

To check that assumption to a certain extent, the IREQ computer model for undamped single conductors was run at *H*/*w* = 1500 m, 2000 m and 2500 m respectively for each of the four terrain categories. It could be confirmed that the locus of the predicted, effective amplitude for each terrain category almost coincides when normalized appropriately. Besides, this result makes sense since it is expected that the slope of the line expressing the effective response of any conductor system as a function of the tension parameter *H*/*w* should be determined entirely on structural grounds and not on aerodynamics grounds.

Thus, it appears that Fig. 6.2 could also be used to determine the safe design tensions of twin bundles for the other terrain categories, according to the same transposition procedure. Doing so, it came out that the safe design tensions *H*/*w* = 1000 m, 1225 m and 1425 m for the undamped single conductor in terrain category #1, 3 and 4 respectively translate into safe design tensions *H*/*w* = 1900 m, 2500 m and 3050 m respectively for the horizontal twin bundled conductors (system #7 in Table 6.3) in the same terrain categories. However, in the latter case, the Task Force resolved again to limit the safe *H*/*w* to 2500 m as a matter of prudence.

The above safe *H*/*w* figures are well supported by the results of the test on the twin bundle at *H*/*w* = 2870 m at the test site, in terrain category 2, which indicated a safe condition.

As for the triple and the quad bundles (system #10 and #13), it is clear from Fig. 6.2 that their response is much lower than that of the twin bundle. Using the same transposition procedure as above would lead to quite high safe design tensions even for terrains category 1. Again, the Task Force decided to limit their respective safe design tension to *H*/*w* = 2500 m for any terrain category.

It should be noted that safe design tensions *H*/*w* for bundled conductors fitted with DS are provided in a way independent of the span parameter *LD*/*m* as it was considered that the benefits of damping are usually well distributed over the span length.

Comparison With Field Experience

Figures 6.3 and 6.4 depict the proposed safe design tension limits together with the corresponding field cases in Table 6.2 for the twin horizontal bundles fitted with NDS or NDS+Stk respectively. It will be seen that the proposed limits reflect well field experience.

Such is also the case for both triple apex-down and quad horizontal bundles fitted with either NDS+Stk or DS, as shown in Fig. 6.5.

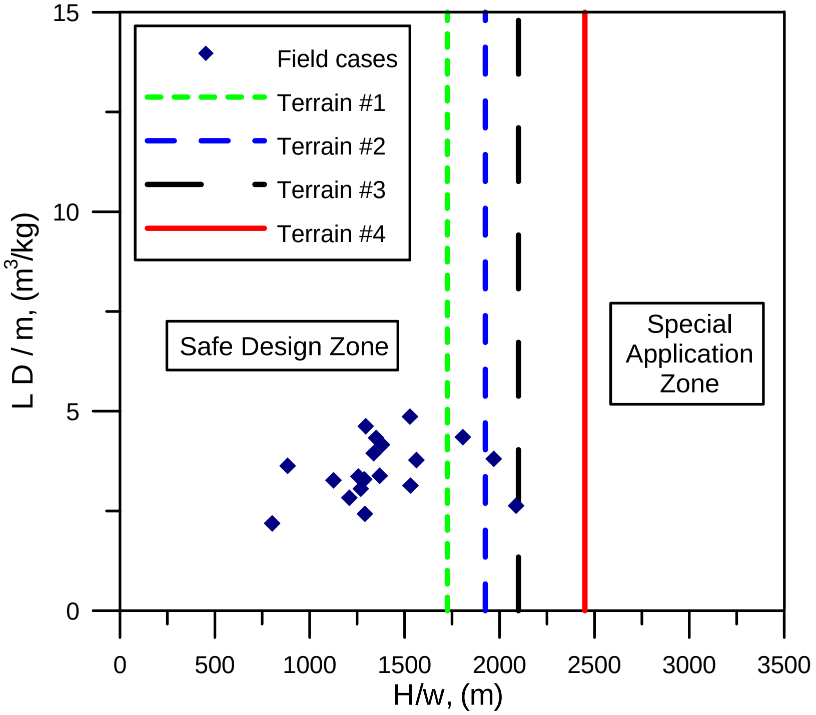

Figure 6.3 Ranking parameters of twin horizontal bundled lines in North America fitted with non-damping spacers in relation to estimated safe boundaries.

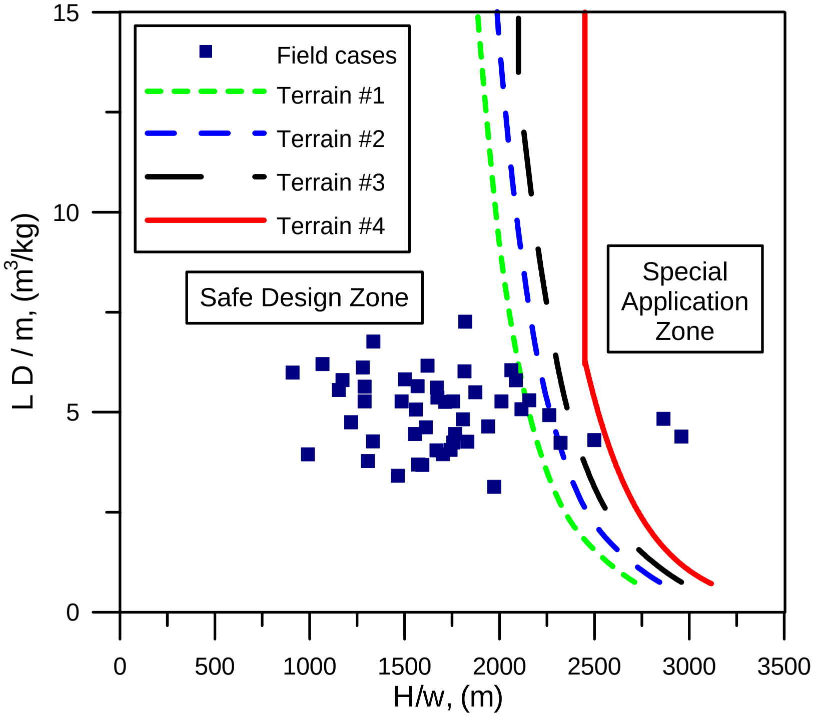

Figure 6.4 Ranking parameters of twin horizontal bundled lines in North America fitted with non-damping spacers and span-end Stockbridge dampers in relation to estimated safe boundaries.

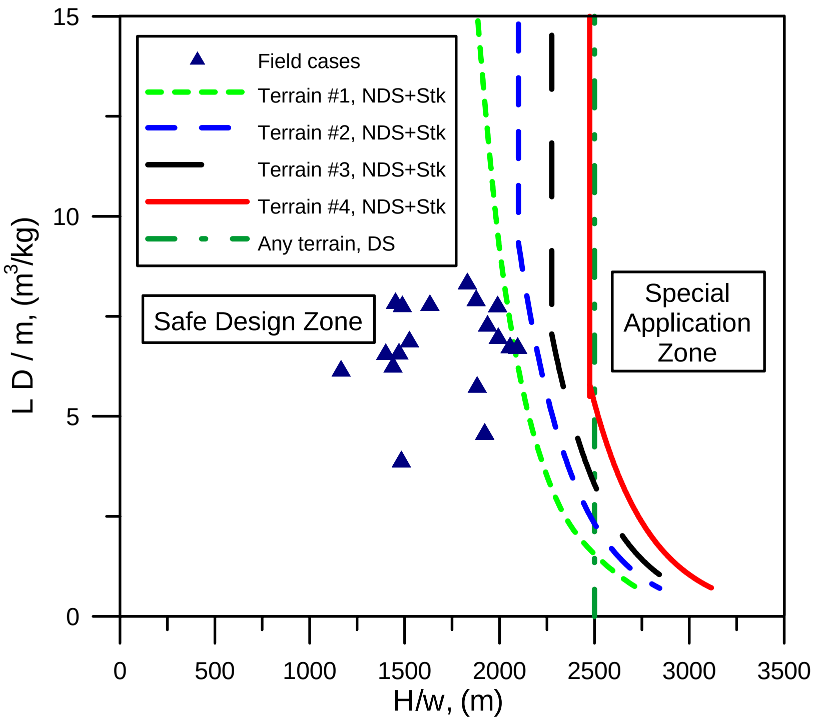

Figure 6.5 Ranking parameters of triple apex-down and quad horizontal bundled lines in North America fitted either with non-damping spacers (NDS) plus span-end Stockbridge dampers (Stk) or damping spacers (DS) in relation to estimated safe boundaries.

Task Force Recommendations

As explained above, the Task Force has resolved to provide guidance to conductor safe design tension in terms of two parameters: the tension parameter H/w, the ratio of tension H to conductor weight w per unit length and, as the case may be, the span parameter LD/m, the ratio of actual span length L times conductor diameter D to conductor mass m per unit length. The tension H refers to initial horizontal tension before any significant wind and ice load and before creep, at the average temperature of the coldest month.

The Task Force recommendations regarding each one of several bundled conductor systems, in addition to two single conductor systems, are summarized in Table 6.3 in the form of simple algebraic expressions, each one associated to a particular terrain category described in the legend. Terrains have been divided in four categories according to their general characteristics. Should there be any doubt about real terrain category, the lowest should be selected.

For some systems, the safe design zones are defined in terms of the H/w parameter only in which case they are unlimited in the LD/m parameter. However in all cases, they constitute zones where full protection of conductors against Aeolian vibrations is certainly feasible by means of a reliable system of non-damping spacers, combined or not with span-end Stockbridge dampers, or alternatively, a reliable system of damping spacers. Hence, within the limits of these zones, Aeolian vibrations should not be a constraint on design tension.

For line parameters falling outside of these zones, Aeolian vibrations may or may not be a constraint and it is recommended that line designers determine the availability of adequate protection before finalising the design.

In the context of this paper, non-damping spacers should be understood as spacers allowing a certain relative mobility of the attachment points with the subconductors in the vertical direction. Lack of such relative mobility may lead to harmful vibration trapping.

This guide applies to all round wire, concentric lay, overhead electrical conductors listed in Table 5.3 supported in conventional metal-to metal clamps.

Use of armour rods or special supporting devices such as helical elastomer-bushed suspensions may justify higher design tensions. Information on safe design tension, when these devices are employed should be obtained from their suppliers.

Limitations and Warnings

The Task Force has recommended safe design boundaries within which satisfactory performance should be available, often from multiple commercial sources. This statement should in no way be taken that all commercially available spacing and/or damping systems will provide such protection up to the limits of those boundaries or that they could provide such protection indefinitely without themselves failing from loosening, fatigue or wear. Rather, appropriate field testing or evaluation of available systems is likely to reveal at least some that do. It falls to the line engineer to identify them.

The guidance provided herein should be suitable most of the time. However, special situations require specific attention. Such is the case for extra long spans; for spans often covered with ice, rime, or hoarfrost; for spans equipped with aircraft warning devices and for spans using non-conventional conductors.

7. REFERENCES

[1] Zetterholm. O.D., “Bare Conductors and Mechanical Calculation of Overhead Conductors”, CIGRÉ Session 1960, Report No. 223.

[2] Fricke, Jr., W.G. and Rawlins, C.B., “The Importance of Fretting in Vibration Failure of Stranded Conductors”, IEEE Trans. on Power Apparatus & Systems, Vol. PAS-87, No. 6, June 1968, pp. 1381-1384.

[3] CIGRÉ Study Committee 22, Working Group 04, “Recommendations for the Evaluation of the Lifetime of Transmission Line Conductors”, Electra No. 63, March 1979, pp. 103-145.

[4] Rawlins, C.B., “Wind Tunnel Measurement of the Power Imparted to a Model of a Vibrating Conductor”, IEEE Trans. on Power Apparatus & Systems, Vol. PAS-102, No. 4, April 1983, pp. 963-971.

[5] Krispin, H.-J., "Parametric Studies: Vibration Intensity of Various Conductors as a Function of Tension and Wind Turbulence", Report CIGRÉ SC22-WG11-TF4-95-6, April 1995.

[6] Hardy, C. and Leblond A., "Estimated Maximum Safe *H*/*w* for Undamped Conductor Spans", Report CIGRÉ SC22-WG11-TF4-95-13, September 1995.

[7] Rawlins, C.B., "Exploratory Calculations of the Predicted Fatigue Life of Two ACSR and One AAAC", Report CIGRÉ SC22-WG11-TF4-96-5, April 1996.

[8] Claren, R., "A Contribution to Safe Design T/m Values", Report CIGRÉ SC22-WG11-TF4-94-10, 1994.

[9] ESDU, “Across-Flow Response Due to Vortex Shedding”, Eng. Science Data Item Number 78006, Oct. 1978, ESDU, London.

[10] Wieringa, “Updating the Davenport Roughness Classification”, J. Wind Engineering & Industrial Aerodynamics, 41-44, 1992, pp. 357-368.

[11] CIGRÉ Study Committee 22, Working Group 01, “Report on Aeolian Vibration”, Electra No. 124, May 1989, pp. 40-77.

[12] International Electrotechnical Commission, IEC 61089 Publication, “Round Wire Concentric Lay Overhead Electrical Stranded Conductors”, June 1991.

[13] Rawlins, C.B., “Fatigue of Overhead Conductors”, Chapter 2 of “Wind-Induced Conductor Motion”, EPRI Transmission Line Reference Book, Electric Power Research Institute, Palo Alto, California, 1979.

[14] Rawlins, C.B., Greathouse, K.R. and Larson, R.E. "Conductor Vibration - A Study of Field Experience", AIEE Paper No. CP61-1090, presented at the AIEE Fall General Meeting, Detroit, MI, Oct. 15-20, 1961.

[15] Dulhunty, P.W., Lamprecht, A. and Roughan, J., "The Fatigue Life of Overhead Line Conductors", CIGRÉ SC22-WG04 Task Force document, 1982.

[16] Doocey *et al.*, "Wind-Induced Conductor Motion", EPRI Transmission Line Reference Book, Electric Power Research Institute, Palo Alto, California, 1979, Chapter 3.

[17] CIGRÉ Study Committee 22, WG11, Task Force 1, "Modelling of Aeolian Vibrations of Single Conductors : Assessment of The Technology". Electra No. 198, December 1998, pp. 53-69.

[18] CIGRÉ Study Committee 22, Working Group 04, "Endurance Capability of Conductors", Final Report, July 1988.

[19] CIGRÉ Study Committee 22, Working Group 11, Task Force 2, “Guide to Vibration Measurements on Overhead Lines”, Electra No. 163, Dec. 1995.

[20] CIGRÉ Study Committee 22, “Guide on the Measurement of the Performance of Aeolian Vibration Dampers for Single Conductors”, Électra No. 76, May 1981, pp.21-28.

[21] Tompkins, J.S., Merrill, L.L. and Jones, B. L., “Quantitative Relationship in Conductor Vibration Damping”, AIEE Transactions on Power Apparatus and Systems, Vol. 75, Pt. III, 1956, pp. 879-894.

[22] Van Dyke, P., Hardy, C., St-Louis, M. and Gardes, J.L., “Comparative Field Tests on Various Practices for the Control of Wind-Induced Conductor Motion”, IEEE Transactions on Power Delivery, Vol. 12, No. 2, April 1997.

[23] Bonneville Power Administration, Specification ETF 60-25.2G, October 1, 1987.

[24] Rawlins, C.B., Greathouse, K.R. and Larson, R.E., “Conductor Vibration – A Study of Field Experience”, AIEE Paper No. CP 61-1090, presented at the AIEE Fall Meeting, Detroit, MI, October 15-20, 1961.

[25] Leblond A. and Hardy, C., “IREQ Predicted Safe Design Tension”, Report CIGRÉ SC22-WG11-TF4-99-6, April 1999.

[26] Rawlins C.B., “Safe Tensions with Dampers”, Report CIGRÉ SC22-WG11-TF4-99-5, April 1999.

[27] Rawlins, C.B., “Analysis of Conductor Galloping Field Observations – Single Conductors”, IEEE Trans. On Power Apparatus & Systems, Vol. PAS-100, No. 8, August 1981, pp. 3744-3753.

[28] Hardy, C. and Van Dyke, P., “Field Observations on Wind-Induced Conductor Motions”, Journal of Fluids and Structures, Vol. 9, 1995, pp. 43-60.

[29] Rawlins & J.R. Harvey, “Improved Systems for Recording Conductor Vibration” Trans. of the AIEE, Transmission and Distribution Committee, Feb. 1960, pp. 1494-1501.

[30] W. Leibfried & H. Mors, “Die Bündelleiter-Vershuchsanlage Hornisgrinde der Badenwerk AG, Karlsruhe”, 1964.

[31] A.J. Liberman & K.P. Krukov, Vibration of Overhead Line Conductors and Protection Against it in the U.S.S.R.”, CIGRÉ General Session, 10-20 June 1968.

[32] A. T. Edwards & J. M. Boyd, “Bundle Conductor Design Requirements and Development of ‘Spacer-Vibration Damper’”, IEEE Transactions on Power Apparatus & Systems, Vol. PAS-84, No. 10, October 1965, pp. 924-932.

[33] G. Diana, M. Gasparetto, F. Tavano & U. Cosmai, “Field Measurements and Field Data Processing on Conductor Vibration (Comparison Between Experimental and Analytical Results)”, CIGRÉ General Session, 1-9 September 1982.

[34] C. Hardy, P. Jahier & S. Houle, “Field Evaluation of Aeolian Vibration of Bundled Conductors”, Canadian Electrical Association Report No. 220T553, December 1990.

[35] P. Van Dyke, C. Hardy, M. St-Louis & J.L. Gardes, “Comparative Practices for the Control of Wind-Induced Conductor Motion”, IEEE Trans. On Power Delivery, Vol. 12, No. 2, April 1997.

[36] A. Leblond & C. Hardy, “Assessment of Safe Design Tension with Regard to Aeolian Vibrations of Single Overhead Conductors”, Proc. of the ESMO 2000 Conference, Montreal, 8-12 October 2000, pp. 202-208.