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Fatigue Design 2023 (FatDes 2023)

Multiaxial fatigue on cableway installations components: use of the Dang Van criterion based on detail categories of EN 1993-1-9 standard.

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Abstract

In order to predict fatigue lifetime of cableway installations components, EN 1993-1-9 standard (Eurocode 3) is commonly used. However, EN 1993-1-9 is based on a major hypothesis : stress state has to be uniaxial. But for some components, this uniaxial hypothesis is not verified (for example : fixed grip of chairlift submitted to horizontal tightening stress and vertical load stress, or chairlift structure stressed by gravity and lateral shake when passing a tower). It then appears important to use a fatigue criterion taking into account multiaxial stress state. Our research work proposes to apply for fatigue study the Dang Van criterion, which takes into account multiaxial stress state. Results are then compared to Eurocode SN curves, representing a huge experimental database on uniaxial fatigue, that we propose to use in multiaxial fatigue thanks to an appropriate recalibration. The scientific originality of this work lies in the justification of that Dang Van criterion's recalibration. Therefore, a theoretical study ensures that our use of Dang Van's multiaxial criterion is still consistent with the Eurocode SN curve even if these SN curves are experimentally performed under uniaxial stress state. Finally, that hitherto unpublished use of the Dang Van criterion makes it possible to consider the entire database of detail categories defined in NF EN 1993-1-9, by generalising their use for components under multiaxial fatigue.

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Keywords: multiaxial fatigue ; cableways installations ; Dang Van criterion ; Eurocode 3 ; detail category

1. Introduction

1.1. Eurocode 3 part 1-9 (standard EN 1993-1-9): a fatigue analysis criterion commonly used in cableway installations

EN 1993-1-9 standard (or Eurocode 3 part 1-9) edited by AFNOR (2005) is commonly used to predict fatigue lifetime of cableways installations throughout the European Union (EU), see in particular EN 13796-1 art. 6.3.3.2. edited by AFNOR (2017). This standard lies on the application of generalized Wöhler curves or S-N curves giving the maximum cyclic stress range against the number of cycles to failure for various constructional details such as rolled, bolted or welded steel section connections (see tables 8.1 and 8.2 of EN 1993-1-9 (AFNOR, 2005)). These Eurocode S-N curves are based on the compilation of numerous experimental results, for example by Böller and Seeger (1987). Each constructional detail is associated with a "detail category" $\Delta\sigma_c$. $\Delta\sigma_c$ refers to the maximum stress range with a 75% confidence level and 95% probability of survival at 2 million cycles taking into account the standard deviation, sample size and residual stress effects (see NOTE 1 under Figure 7.2 of EN 1993-1-9. Eurocode S-N curves are defined by equations (1a) and (1b), as shown below:

$$\Delta\sigma^m \times N = \Delta\sigma_c^m \times 2 \times 10^6 \text{ with } m = 3 \text{ for } N \leq 5 \times 10^6 \quad (1a)$$

$$\Delta\sigma^m \times N = ((2/5)^{(1/3)} \Delta\sigma_c)^m \times 5 \times 10^6 \text{ with } m = 5 \text{ for } 5 \times 10^6 \leq N \leq 10^8 \quad (1b)$$

This method is highly appropriate for components subjected to uniaxial normal stress variation. It is generally applied in the principal stress frame, taking into account $\Delta\sigma$ the normal stress variation. However, this method has its limitations, as it does not take into account possible multiaxiality of stresses, nor a priori the effects of an average stress, even though these parameters will influence the component's service life. For example, if a chairlift component is subjected to significant variations in multiaxial stresses, e.g. fixed grip of chairlift under horizontal tightening stress and vertical load stress, or chairlift suspension structure stressed by vertical gravity and longitudinal and lateral shake when passing a tower, fatigue analysis using the EN 1993-1-9 method may be inappropriate.

1.2. The Dang Van criterion: a physical criterion derived from Continuum Mechanics to take into account the multiaxiality of a state of stress

Another type of criterion is based on the critical plane approach. The general principle of this category of criteria is to describe damage based on the determination of the most stressed plane, i.e. the plane where a crack is most likely to appear and/or propagate for any given point on a part, called the critical plane. Most criteria using this approach, such as Crossland's or Matake's criterion, involve the same parameters and are fairly similar; however, the Dang Van's criterion is widely recognized in the literature and takes into account multiaxiality as well as average stresses but requires S-N curves as reference.

Dang Van criterion is a local and instantaneous criterion that therefor must be applied at each node and at any time, to obtain an estimate of the lifetime (see Dang Van et. al (1989), Dang Van and Papadopoulos (2014)). The Dang Van criterion is considered verified locally if inequality (2) is verified, i.e. in general in analytical form over time and space, if equation (3) is verified:

$$\|\tau(\vec{n}, t)\| + \alpha_{(N)} \cdot p(t) \leq \theta_{(N)} \quad (2)$$

$$\max_{\vec{n}} \left[\max_t \left[\frac{\|\vec{\tau}(\vec{n}, t)\| + \alpha_{(N)} \cdot p(t)}{\theta_{(N)}} \right] \right] = 1 \quad (3)$$

With:

- $p(t)$ ($= p_h(t)$ in Figure 1) : hydrostatic pressure over time (one-third of the stress tensor trace).
- $\|\tau(\vec{n}, t)\| = \tau_{hd}(t)$ in Figure 1: re-centered shear stress amplitude over time and space orientation.
- $\alpha_{(N)}$ and $\theta_{(N)}$: the characteristic material parameters, which depend on the number of cycles N. Generally, the parameters $\alpha_{(N)}$ and $\theta_{(N)}$ are determined with S-N curves obtained with a ratio $R=-1$, where $R=\sigma_{\min}/\sigma_{\max}$ (see appendix A). We will see later that the originality of our work consists in calibrating the Dang Van criterion with a ratio $R=0$. For $R=-1$: $\alpha_{(N)} = 3(\tau_{-1}/\sigma_{-1} - 1/2)$ and $\theta_{(N)} = \tau_{-1}$; where σ_{-1} is the number of fatigue limit cycles under symmetrical alternating tension-compression and τ_{-1} the fatigue limit under symmetrical alternating torsion.

The Dang Van criterion can be summarised in a diagram as shown in Figure 1:

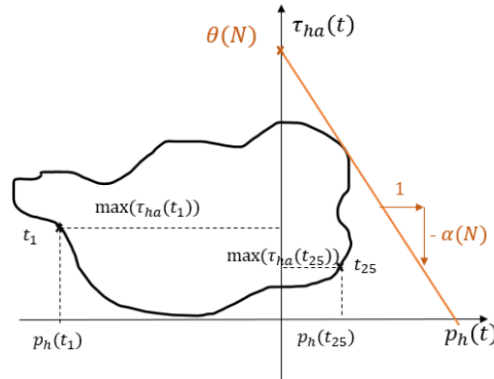


Fig. 1. Dang Van diagram: loading path and criteria $\alpha_{(N)}$ et $\theta_{(N)}$ derived from S-N curves

Calculating the shear amplitude is complex and optimization of the computation time is still a subject of current scientific research, see Fauvin et. al (2020) and Agard et. al (2022).

The Dang Van criterion requires a database of Wöhler curves (S-N) and while advanced methods exist (thermo-metallurgical calculations) and are effective (cf. Giraud et al. 2020), most manufacturers lack the capacity to perform such analysis quickly. The authors propose to use the readily available Eurocode uniaxial S-N curves database as a reference for multiaxial fatigue analysis using the Dang Van criterion, with an appropriate calibration.

1.3. Using the S-N curves of Eurocode as a reference for multiaxial fatigue analysis with the Dang Van criterion

Eurocode 3 part 1-9 was originally developed for building and civil engineering construction. Tests to characterise steel sections were therefore generally carried out with a high average stress and then the addition of a variable load (for example, to simulate the permanent load on a bridge and the variable load when a vehicle passes over it). Thus, by defining the ratio $R = \sigma_{\min} / \sigma_{\max}$, a huge number of tests were carried out for ratios $R=0$ or even $0 < R \leq 1$ like in Fisher et al. (1974) for detail category 90. The thesis by Aygül M. (2012) notably shows the conservative results of Eurocode, by comparing Eurocode S-N curves with $R \geq 0$ tests.

Furthermore, EN 1993-1-9 (art. 7.2.1) allows a 40% reduction in compressive stress ranges for non-welded details or heat-treated welds thus indicating that the Eurocode S-N curves have been produced with a ratio of $R=0$ or even $0 < R \leq 1$. Using the Dang Van criterion with classic calibration in $R=-1$, while feasible, would give inappropriate, as too conservative, results. The Dang Van criterion should therefore be calibrated at $R=0$ to optimise use of the data bank provided by the Eurocode detail classes.

2. Material & Method

2.1. General

All fatigue analyses according to Eurocode are performed in the principal stress frame (σ_I, σ_{II}) and all fatigue analyses with the Dang Van criterion are performed in the local fixed frame of the rosettes considered (σ_{xx}, σ_{yy}) with a non-zero a priori value of τ_{xy} .

2.2. Theory and preliminary results: Dang Van Criterion calibration for $R=0$.

The number of cycles required to verify the Dang Van criterion was obtained through iterations using the algorithm developed by Camara et al (2018) and adapted by Poyet (2022) under Scilab 6.1.1.

The fundamental principle of the Dang Van criterion is that it must be perfectly consistent with the S-N curves on which it is based. At the end the calibration, the Dang Van criterion applied to a uniaxial tensile/compressive stress with zero minimum stress ($R=0$) gives the exact same results as the Eurocode methodology for the chosen detail category.

The reasoning described in Figure 2 is used to determine the values of $\alpha_{(N)}$ and $\theta_{(N)}$ for $R=0$. A uniaxial tensile-compressive stress with mean stress $\sigma_0 > 0$ is applied to the criterion, then a torsional stress with mean stress τ_0 is applied to the criterion. For ease of reading, in Figure 2, $\alpha_{(N)}$, $\theta_{(N)}$, $\sigma_{0(N)}$, $\tau_{0(N)}$, which are functions of the number of cycles N at the fatigue limit (crack initiation or fracture), are denoted by α , θ , σ , τ .

$$\begin{array}{l}
 \left(\begin{array}{ccc} \sigma_0 + \sigma_0 \cos(\omega t) & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{array} \right) \Rightarrow \max_t(p(t)) = \frac{2\sigma_0}{3} \text{ and } \max_{\bar{n}}(\max_t[\tau(\bar{n}, t)]) = \frac{\sigma_0}{2} \\
 \frac{\max_{\bar{n}}(\max_t[\tau(\bar{n}, t)]) + \alpha \max_t(p(t))}{\theta} = 1 \Rightarrow \frac{\frac{\sigma_0}{2} + \alpha \frac{2\sigma_0}{3}}{\theta} = 1 \quad (*) \\
 \left(\begin{array}{ccc} 0 & \tau_0 + \tau_0 \cos(\omega t) & 0 \\ \tau_0 + \tau_0 \cos(\omega t) & 0 & 0 \\ 0 & 0 & 0 \end{array} \right) \Rightarrow \max_t(p(t)) = 0 \text{ and } \max_{\bar{n}}(\max_t[\tau(\bar{n}, t)]) = \tau_0 \\
 \frac{\max_{\bar{n}}(\max_t[\tau(\bar{n}, t)]) + \alpha \max_t(p(t))}{\theta} = 1 \Rightarrow \frac{\tau_0}{\theta} = 1 \quad (**) \\
 (**) \text{ and } (*) \Rightarrow \alpha = 3 \left(\frac{\tau_0}{2\sigma_0} - \frac{1}{4} \right) \quad (***)
 \end{array}$$

Fig. 2. Calibration of Dang Van criterion for $R=0$

2.3. Experimental setup on a GMM's chairlift

On-site stress measurements were carried out during tests on May 18, 2022 on the Gimar Montaz Mautino (GMM) four-seater ChairLift with Fixed grip (CLF4), known as the "Petit Combet", located in Bernex ski resort, Haute-Savoie department, French Alps. These measurements were carried out by CETIM laboratory, on behalf of GMM and in the presence of STRMTG Notified Body 1267 in charge of the CE certification of the CLF4 according to the European Cableway Installations Regulation (EU) 2016/424. Extensometric measurements at a speed of 2.5 m/s and fatigue analysis according to Eurocode (uniaxial hypothesis) were carried out in compliance with article 6.3.3.2 of EN 13796-1, see Maniouloux and Renaux (2022), Vital and Charrot (2022a, 2022b), Causse and Laporte (2022a, 2022b), following tree load cases :

- Load Case 1 (LC1): eccentric half-loaded vehicle at station entrance,
- Load Case 2 (LC2): empty vehicle bypassing sheave (U-turn in station),
- Load Case 3 (LC3): full loaded vehicle in line (meaning passing through all the towers between bottom and top stations).

15 strain gauges were distributed over the entire structure of the chairlift vehicle, for a total of 29 acquisition channels. In the present research work, only the two following rosettes are studied: R16 located on the hoop, and R35 located on the fixed attachment close to its embedding in the cable (see Figure 3).

The acquisition unit used is an HBM QX1615 (313316-313317) with a TH7 temperature control unit.

The sampling frequency is 600 Hz.

The detail categories used are:

- 160 for the hoop of the chairlift structure in steel S355.
- 430 for the fixed grip, as it is a solid forged part made of the noblest alloy steel (34CrMo4) according to the results of the scientific report Handbook MMPDS-05 published by Washington, D.C.: Federal Aviation Administration, (2010), with an added safety margin on the truncation limits (174MPa instead of 413MPa) and constant amplitude limits (316 MPa instead of 371MPa), see Vital and Charrot (2022a) and Causse and Laporte (2022a).

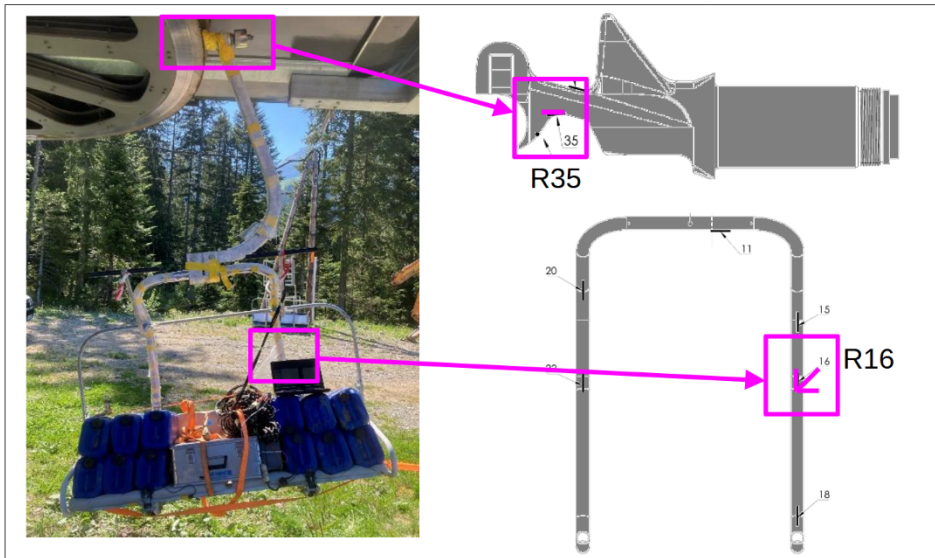


Fig. 3. Chairlift instrumentation setup : Rosette Strain Gauges R35 (fixed grip) and R16 (structure arch/hoop)

3. Results

3.1. Preliminary results

From the Dang Van calibrated at $R=0$, we can simulate an uniaxial load with $R=0$. In these conditions, the input stress and the associated number of cycle calculated by the Dang Van criterion should correspond to the one given by the S-N curve used. Figure 4 shows that the simulation with the $R=0$ calibration (Fig. 4 square) perfectly fits the Eurocode S-N curve of the detail category (Fig. 4 dotted line). This not only shows the effectiveness of the $R=0$ calibration, but also that it was carried out correctly. Conversely, it can be seen that calibrating with $R=-1$ (triangles Fig. 4) gives even more conservative results, emphasizing the benefit of $R=0$ calibration.

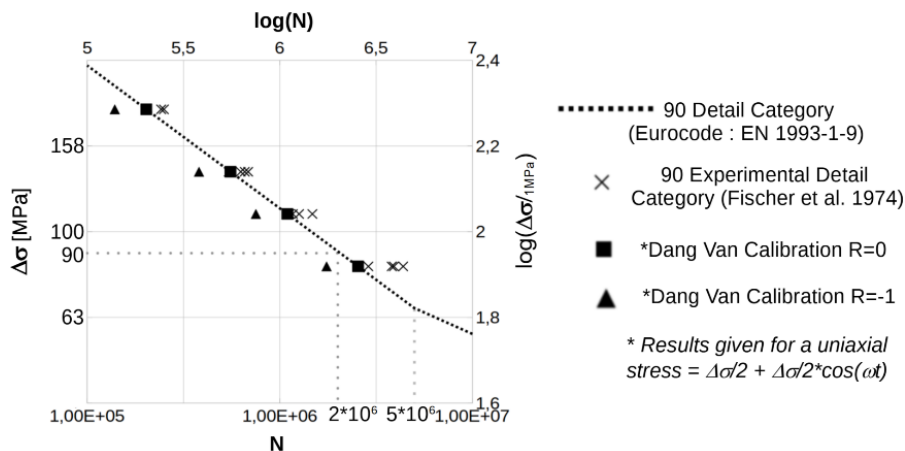


Fig. 4. Comparison of calibrations in $R=0$ and $R=-1$ for the Dang Van criterion based on the Eurocode reference curve for detail category 90

3.2. Theoretical results

Five theoretical Load Cases (LC) were defined, see Table 1, with or without multiaxial stresses, and with or without mean stresses. The Eurocode specifies the same number of cycles for these 5 load cases, whereas Dang Van adapts to each case.

Table 1. Number of Survival Cycles (N) according to Eurocode and Dang Van calibrated at R=0, for detail category 80.

LC	A	B	C	D	E
Stress tensor [MPa]	$\begin{pmatrix} 35+35\sin(\omega t) & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} 35\sin(\omega t) & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} 80+35\cos(\omega t) & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} 35+35\sin(\omega t) & 0 & 0 \\ 0 & -(35\sin(\omega t)) & 0 \\ 0 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} 35+35\sin(\omega t) & 0 & 0 \\ 0 & -(35\sin(\omega t)) & 0 \\ 0 & 0 & 20\sin(\omega t) \end{pmatrix}$
N_E^*	2 985 423	2 985 423***	2 985 423	2 985 423	2 985 423
N_{DV}^{**}	2 985 424	3 675 727	2 330 047	512 725	481 342

* Number of cycle according to Eurocode (EN 1993-1-9) for detail category 80, $\Delta\sigma=70$ MPa ($\gamma_r = \gamma_D = 1$).

**Number of cycle according to Dang Van criterion calibrated with R=0, with detail category of Eurocode as reference S-N curve and load case given in the matrix above

***: For LC B, article 7.2.1 of EN 1993-1-9, which allows a 40% reduction in compressive stress ranges was not taken into account, if so, for memory it would allow 6 460 207 cycles.

For Load Case A (LCA), uniaxial, with R=0, Dang Van and Eurocode thus indicate the same number of cycles. Since both estimations are based on the same S-N curve, for uniaxial loading with R=0, it is quite logical to obtain the same number of cycles (idem as 3.1 preliminary results).

LCB, on the other hand, is a uniaxial load case in R=-1. Dang Van has therefore predicted a higher number of cycles for LCA than for LCB. Indeed, in load case B, the category 80 joint (cross weld) will sometimes be stressed in compression, so the weld will benefit from the beneficial effect of compression, which tends to prevent crack propagation.

LCC is entirely tensile, and has a high mean stress. Dang Van takes this into account and predicts fewer cycles than load cases A and B. This time, the high average stress means that the weld will be subjected to high tension during the cycle. Unlike compression, tension has a destructive effect on fatigue, as it contributes to crack propagation.

Load cases A, B and C show that Dang Van takes average stress into account, whereas the Eurocode does not.

Load case D is the same as A, with bi-axiality. The Eurocode still predicts the same service life. The Dang Van, on the other hand, has significantly reduced the predicted service life.

Load case E shows a tri-axial test, with the Dang Van predicting even fewer cycles.

Using the same database (Eurocode S-N curves), the Dang Van criterion calibrated at R=0 allows consideration of two major phenomena that were neglected in the Eurocode: mean stress and multiaxiality.

3.3. Experimental results

The fatigue study for CE certification of GMM's CLF4 was carried out with a conclusive analysis to EN 13796-1 using a Eurocode-type uniaxial fatigue approach. While this methodology is valid for the vast majority of test results processed for ropeway vehicles (especially those with beam connection structures), some rosettes exhibit significant multiaxial stresses and/or high average compressive stresses (particularly R16 on the seat structure hoop and R35 on the fixed grip) that may not be accurately considered in the Eurocode to predict life expectancy.

The R16 rosette, located in the crook of the hoop, showed strong biaxiality ($(\Delta\sigma_{II}/\Delta\sigma_I) > 37\%$) at the level of tower 9 in descent, full load (P9D_LC3), as well as low shear stress, in the fixed reference of the R16 rosette (see Figure 5). This multiaxiality is quasi-proportional. This result was unexpected, and, in addition to the effects of gravity on the loaded seat, shows a lateral sway when passing the P9 tower on the way down (note that this case was unrealistic and unfavorable, as in the field of use, the chairlift is not designed to be operated at full load full speed...).

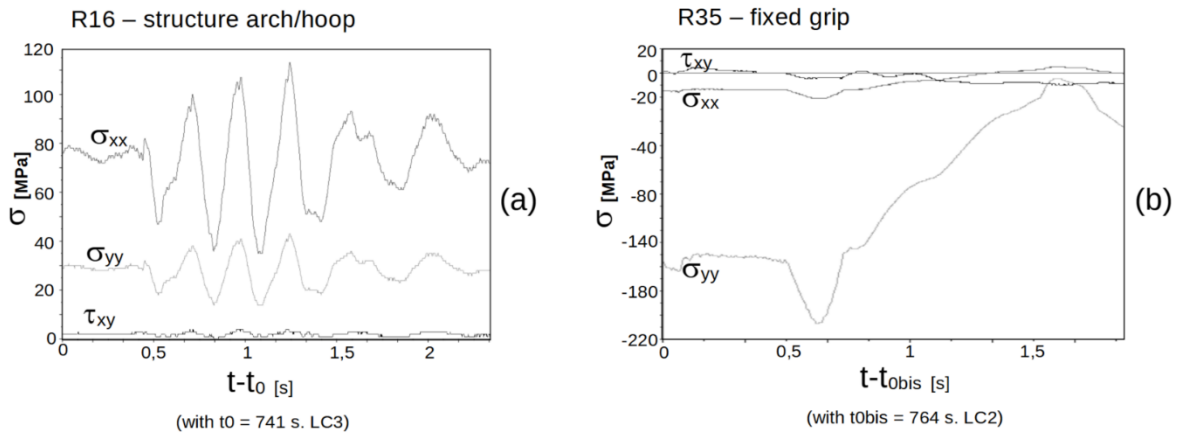


Fig. 5. (a) Rosettes stresses R16 (hoop) when passing tower 9 in descent, full load (LC3), and (b) R35 (fixed grip) when sheave rounding at empty load (LC2).

Based on Dang Van criterion, the R16 stress biaxiality observed reduces the service life of the hoop, since σ_{yy} is positive (of the order of 40% of σ_{xx}) and the target of 5 million cycles set by EN 13796-1 is not reached if we consider a safety coefficient of $\gamma=1.35$ (see Figure 6a and Table 2). The 5 millions cycles are reached only for a safety coefficient slightly higher than $\gamma=1.3255$. However, the value of $\gamma=1.3255=1.15 \times 1.15$, is already a significant safety coefficient, allowing us to take a partial safety of 1.15 combined with a partial safety coefficient for the tension/flexion safety of 1.15, see Weber B. (1999). However, downgrading the γ value under 1.35 is not suitable since it was defined according to statistic considerations. It would be more appropriate to discuss about the reference scenario used for Palgren-Miner summation (see 4. Discussion).

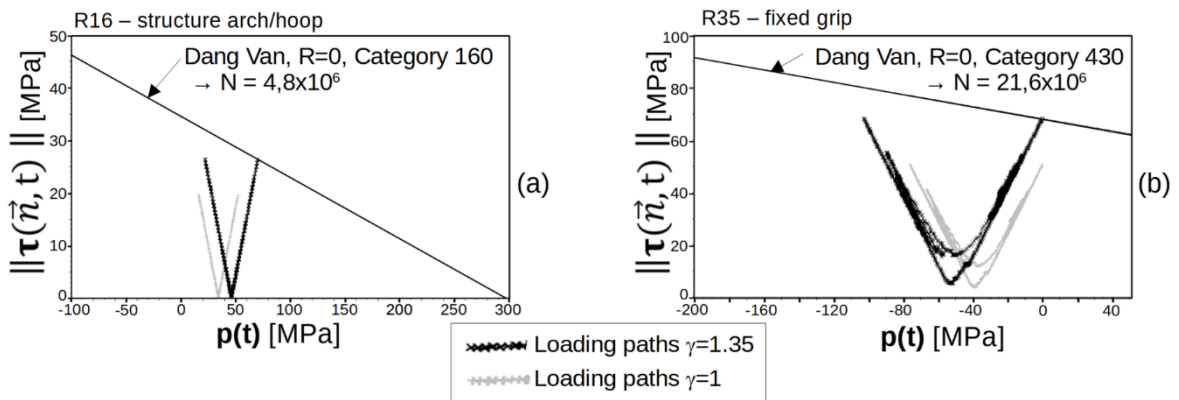


Fig. 6. Dang Van criterion and loading paths for : (a) R16 (hoop) and (b) R35 (grip) corresponding to stress tensor of Fig. 5a resp. 5b.

Table 2. Number of Survival Cycles (N) on the hoop (R16) according to Eurocode and Dang Van calib. in R=0, detail category 160, LC3 (full load in line).

Method	Eurocode	Dang Van (calib. R=0)
Stress tensor [MPa]	$\Delta\sigma_1 = 113 - 35 = 78$	see Fig. 5 a
N (for $\gamma \times \Delta\sigma$ with $\gamma=1$)	39 433 339	20 946 776
N (for $\gamma \times \Delta\sigma$ with $\gamma=1.3255$)	9 637 511	5 177 723
N (for $\gamma \times \Delta\sigma$ with $\gamma=1.35$)	8 794 167	4 800 174

In contrast, for R35 located on the fixed grip, the Eurocode predicts a service life of 11.9 million cycles, while the Dang Van predicts a service life almost twice as long: 21.6 million cycles (see Figure 6b and Table 3).. This is logical, as the low bi-axiality (14%) slightly reduces service life, but the high mean negative stress (-110 MPa) greatly extends service life. Finally, in this case, the Dang Van predicts a longer service life.

Table 3. Number of Survival Cycles (N) for the fixed grip (R35) according to Eurocode and Dang Van calib. in R=0, detail category 430, LC2 (empty vehicle rounding sheave)

Method	Eurocode	Dang Van (calib. R=0)
Stress tensor [MPa]	$\Delta\sigma_{II} = -11 - 208 = 197$	see Fig. 5 b
N (for $\gamma \times \Delta\sigma$ with $\gamma=1$)	53 795 730	96 933 513
N (for $\gamma \times \Delta\sigma$ with $\gamma=1.35$)	11 997 174	21 617 483

4. Discussion

As a prerequisite, whatever the state of stress: we need to identify a detail class in the Eurocode, or even an "equivalent" detail class for forged parts in nobler materials (e.g. using MMPDS-05 edited by Washington, D.C.: Federal Aviation Administration, (2010)).

If the stress state is uniaxial, the application of the Eurocode appears relevant.

If we have a multi-axial stress state, with $\sigma_{II} < 15\% \times \sigma_I$, we can consider the Eurocode application still relevant.

If we have a stress state with $\sigma_{II} > 15\% \times \sigma_I$ in the main frame of reference, then application of the Eurocode, taking into account only σ_I to calculate lifetime, does not appear appropriate. The direct Eurocode fatigue analysis will overestimate lifetime, and it will therefore be much more appropriate to apply a Dang Van criterion as proposed, calibrated at R=0, based on the Eurocode S-N reference curves. This 15% value is a proposal which needs to be further studied and discussed with the cableways installation sector.

On the other hand, if the average stress is zero or negative, Eurocode fatigue analysis will be relevant and even safe (in the case of high average compression, Eurocode will underestimate service life if article 7.2.1 is not applied). On the other hand, in the case of high average tensile stress, the direct results of the Eurocode could underestimate the fatigue life, in which case it would be appropriate to apply a Dang Van criterion as proposed (calibrated at R=0, based on the Eurocode S-N reference curves).

From a theoretical point of view (see Table 1, LC A to E), it is important to note that our work neglected stresses caused by Poisson coefficient ν , although $\nu \approx 0.3$ for steel. This was necessary to initiate the thinking process, but in reality, Eurocode S-N curves takes into account a bit of multiaxial fatigue due to the Poisson coefficient. This should be taken into account to refine this work.

Finally, the Palmgren-Miner summation as proposed in EN 1993-1-9 and EN 13796-1 has to be applied carefully when using the Dang Van Criterion. See Table 4.

Table 4. Partial damage (d) and Palmgren-Miner Damage summation (D) on the hoop (R16, detail category 160) according to Eurocode and Dang Van calib. R=0.

Method	See 2.3 for LC definition	LC1	LC2	LC3* and LC3bis**		D= $\sum d_i$
	N _{wanted}	100 000	500 000	5×10 ⁶ *	2.5×10 ⁶ ** 2.5×10 ⁶ **	
Eurocode and art. 6.3.3.2 of EN_13796-1	$\gamma \times \Delta \sigma$ (with $\gamma=1.35$)	74	24	105		D _E = 0.570
	N _{max}	50.5×10 ⁶	infinity	8.8×10 ⁶		
	d=N _{wanted} /N _{max}	0.002	0	0.568*		
Dang Van	N _{max}	20.1×10 ⁶	infinity	4.8×10 ⁶		D _{DV} = 1,047
	d=N _{wanted} /N _{max}	0,005	0	1,042*		
R=0 calibration $\gamma=1.35$	N _{max}	20.1×10 ⁶	infinity	4.8×10 ⁶	26.3×10 ⁶	D _{DVbis} = 0.621
	d=N _{wanted} /N _{max}	0,005	0	0,521**	0,095**	

* LC3 : according to EN_13796-1 : 100 % worst tower : N=5×10⁶ at P9D

** LC3 bis : more realistic : 50 % worst tower P9D, N=2.5×10⁶ + 50% second worst tower P7D, N=2.5×10⁶.

If the fatigue analysis requires the Dang Van criterion to be applied, then the parameters provided by standard EN 13796-1 (art. 6.3.3.2.2.b3)) for LC3 (loaded, worst pylon in line, 5 million times) are too pessimistic (leading to D_{DV}>1). In this case, a more realistic load histogram should be used (as allowed for bicable aerial ropeway, see art. 6.3.3.2.3 and 6.3.3.2.4). We see that by considering more realistic case LC3bis (in line loaded, worst tower 2.5 million times and second worst tower 2.5 million times) the Palmgren-Miner summation D_{DVbis}<1 is already validated. Note that LC3bis scenario (50%P9D+50%P7D) is still a pessimistic scenario since no down-hill operation is planned on the installation and that up-hill loaded results showed less stressed results. In the end, with a more realistic criterion (Dang Van), it is suitable to apply a more realistic scenario than the penalty package provided by default in EN 13796-1 for fixed grip chairlift, otherwise the assessment of the life time risks being too conservative.

5. Conclusion

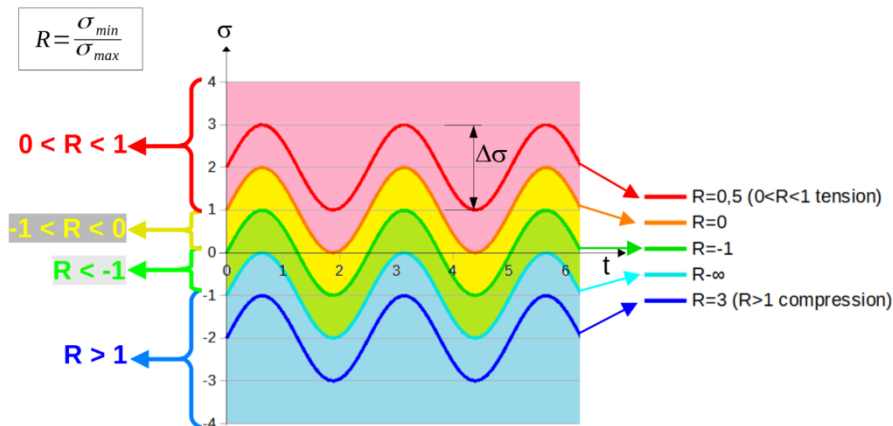
For the vast majority of cases, the Eurocode fatigue analysis provided by EN 13796-1 for ropeway components is relevant. However, for loading cases with multiaxiality of stresses and high mean stresses: the application of the Dang Van criterion, recalibrated to R=0 as shown, before comparison with the Eurocode S-N reference curves, as proposed by us, appears more relevant than the Eurocode for fatigue analysis. Moreover, the proposed method will make it possible to deal with non-proportional loading cases where appropriate. In the future, in order to improve fatigue analysis to the Dang Van criterion for cableway components, the ropeway industry will be able to discuss relevant scenarios to be taken into account, and consider on-site or laboratory multiaxial stress tests to better characterize the reference lifetime under multiaxial-stress state of cableways components.

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Appendix A. schematic representation of the ratio $R = \sigma_{\min}/\sigma_{\max}$



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