Dimensioning carrier-components of modern circulating monocable ropeways

A contribution concerning the verification of service strength of carrier components with regard to the operational loads ocurring at stations entry

H. U. Zbil, Inspection body for Ropeways, TÜV Süddeutschland Bau und Betrieb GmbH, Munich

A Introduction

The high transportation capacity of modern circulating ropeways is nowadays generally achieved by raised travelling velocity and increased carrier capacities. Additionally, these days, methods of compact station design are gaining ground for cost reasons. These tendencies make it necessary to damp the carrier´s lateral oscillations within a very short distance after the carrier enters the station.
This contribution raises the following questions: Are verfication procedures nowadays applied to ropeway carrier components such as grips, hangers, cabins still sufficient.

Zbil, Hans-Ulrich
TÜV Süddeutschland Bau und Betrieb GmbH
Zentralabteilung Seilbahnen
Westendstraße 199, D - 80686 München
Tel.: + 49 (0)89 - 5791 - 1971, Fax .: + 49 (0)89 - 5791 - 2022
e-mail: Hans-Ulrich.Zbil@bt.tuevsued.de

May these procedures have to be improved with respect to modern design tendencies in the field of circulating monocable ropeways?

In this context, the essential elements will be discussed that have to be considered and determined in dimensioning of carrier components with sufficient service strength.

B Determining the components strain

The maximum strain on carrier components of detachable monocable ropeways, as a rule, occurs at stations entry. Due to lateral wind, acting on the carrier along the line or passengers, pushing the carrier into a swing during the ride or excentric load arrangements inside the carrier, etc., the carrier does not arrive vertically lined up but with a lateral swing at the stations entry. Especially the carrier´s suspension, the suspension top and the clamping device are subject to high forces, as the entire carrier and especially the clamping device get forced into the support rail and the guide rail within very short time.

Many modern station entries are designed without guide rails for the carriers in order to damp lateral oscillations. Instead the clamping device takes on to smooth down lateral amplitudes being fixed at the rope at one side and at the other side getting led into a funnel-shaped guide rail entering the station. That way the clamping device quickly brings the entire vehicle into vertical line using high forces and momentums at the top of the vehicles suspension.

As the capacity of carriers is increased (carriers for 8, 12 or 15 persons) and the travelling velocity is raised, the level of energies goes up and these high forces and momentums at the suspension of the carrier may even occur at small lateral oscillations.

B1 Investigation of the components strain at the stations entry by experimental measuring

Is it possible to do without experimental examination?

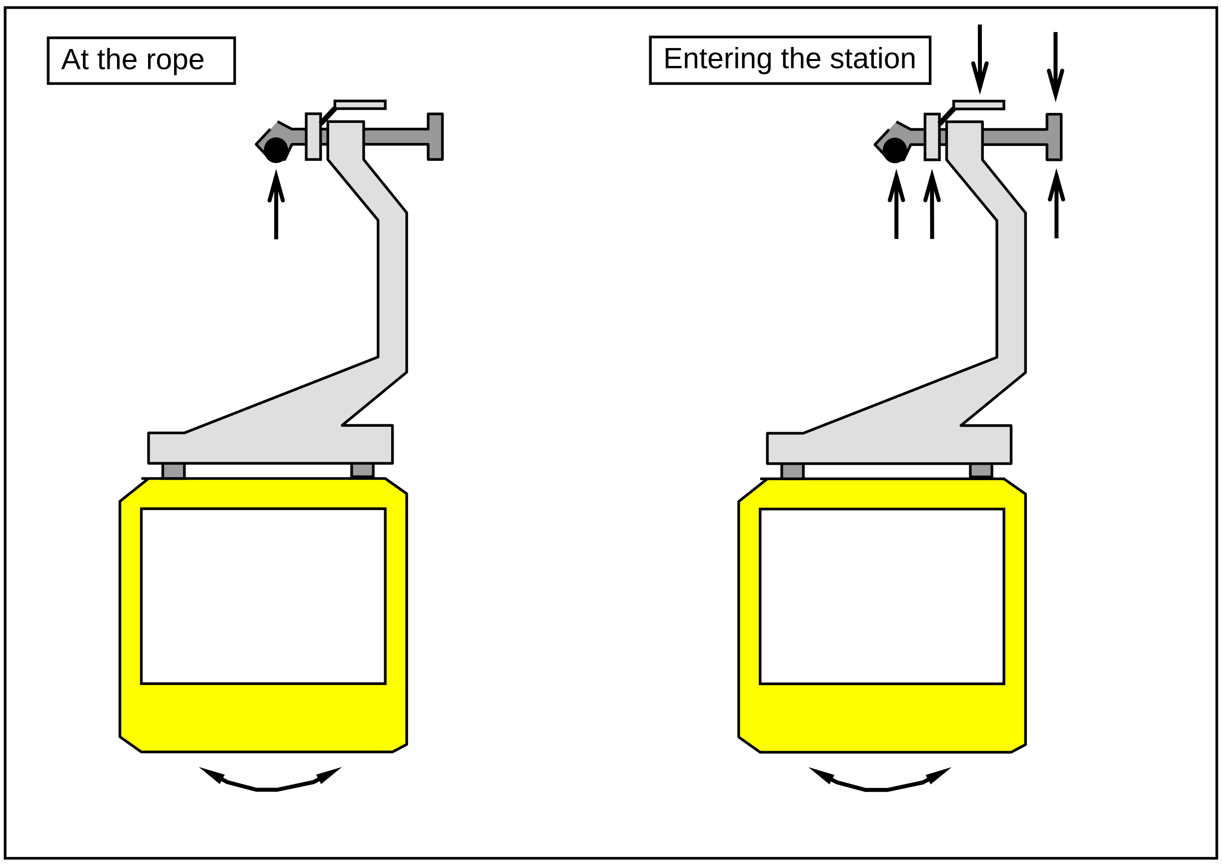
The carrier, being situated on the line, is freely able to swing laterally around the axis formed by the rope.
In contrast with this, the carrier is "firmly fixed" when it enters the station and arrives at the detaching section. Here lateral oscillations are completely blocked. In the moment, the vehicle passes through the stations entry, a multitude of forces acts on the clamping device and forces it into a defined position, like for example the repositioning forces at the guide wheel, the forces of reaction at the suspensions wheels, the positive or negative reaction force from the rope. This represents the situation of a system of forces, which is overdetermined several times. The level of forces within this system is determined by the stiffness of those station components, the carrier´s suspension is in

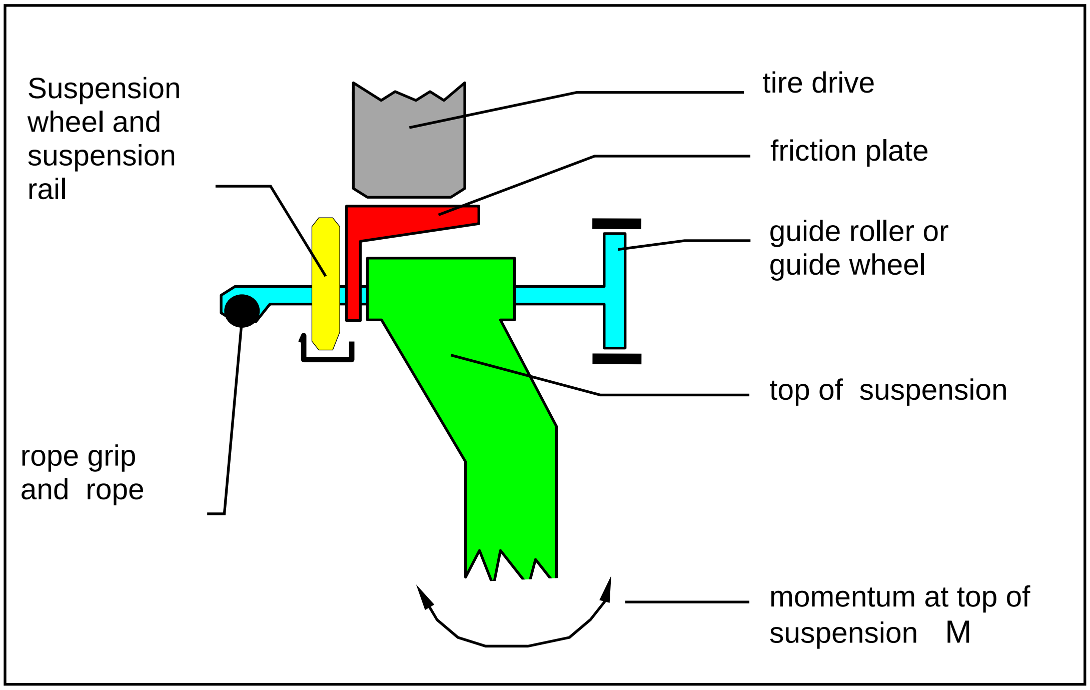
contact with (such as guide rail, entry funnel, suspension rail, detachment rail, tire drive, rope).

To find realistic values of these forces, experimental measuring is extremely helpful. This experimental measuring is necessary, because it can only be replaced by expensive and very sophisticated numeric calculations with dynamic modelling.

How to carry out experimental measuring?

Measuring the loads, carrier components are subject to, has to be carried through all the way from the beginning of the stations entry throughout the end of the deceleration section. On the one hand, this is necessary to find from the measurements the maximum level of forces, ocurring oftentimes even beyond the detaching section. On the other hand, a realistic number of load cycles can be determined only by analysing measurements covering the entire station entering procedure including the deceleration section.





The momentum at the suspension top, which introduces lateral oscillation energy into the hanger suspension axle, is predominantly led out by the guide wheel into the guide rail. Depending on the stiffness and the inertial forces of this guide rail, lateral oscillation energy can partly also be led out through suspension wheels into the suspension rail as well as through the clamping device into the rope or through the friction plate into the tire drive. Depending on the stiffness of the different rails and rail suspensions, the flow of forces and momentums within the clamping device may go different ways. The real forces of carrier components therefore depend on complex interrelations between the station design elements.

It is very difficult to theoretically calculate the stiffness of rails and guiding installations and of dynamic effects within the stations entry section in order to predict the dynamic flow of forces. Until now there is no alternative to experimental measuring the carrier-components strains at the stations entry.

Which parameters and conditions must be realistically simulated during measuring experiments?

The influence of the following operational parameters must be systematically analysed with measuring experiments:

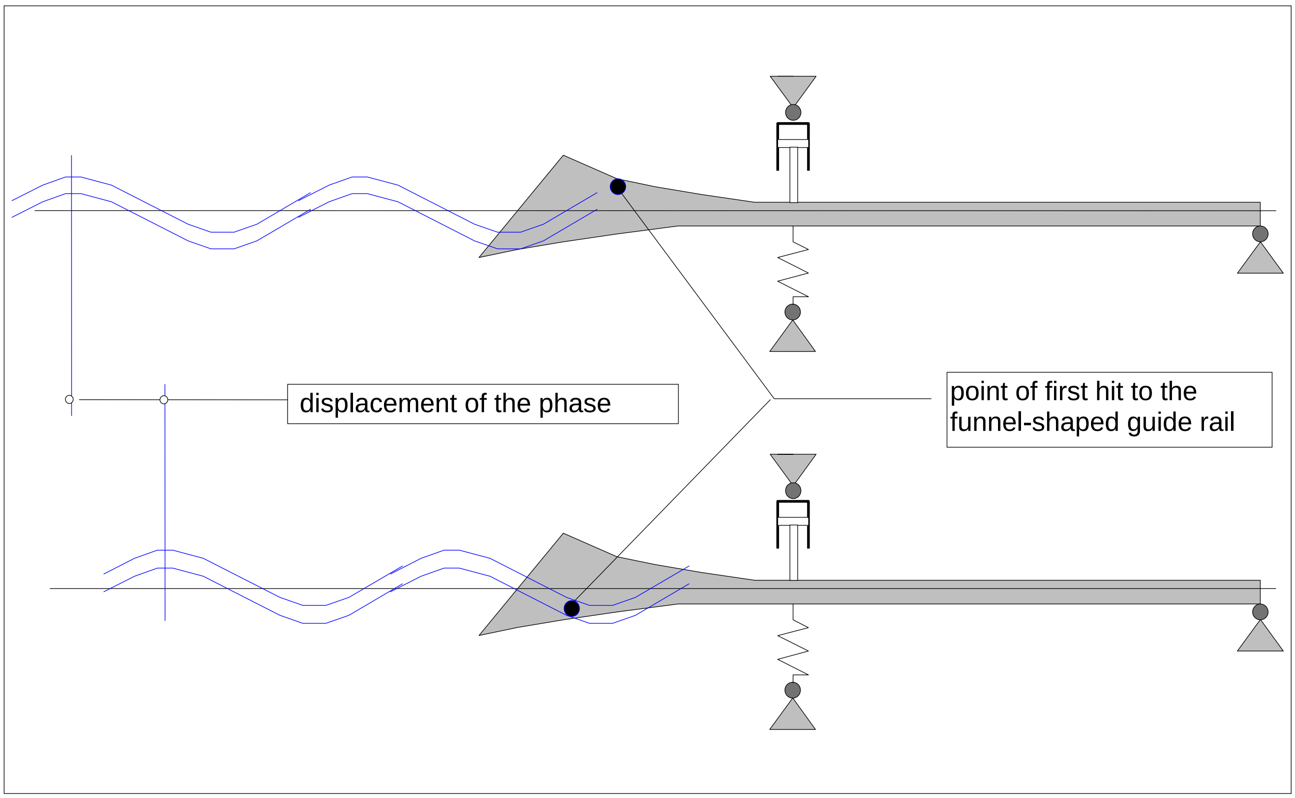
- the influence of different amplitudes of lateral oscillations and of varying phases of the lateral oscillations resulting in different points of first hit to the funnel-shaped guide rail,
- the influence of the variety of loads transported during normal operation (dead loads and persons),

- the influence of the travelling velocity,

- the influence of tolerable wear at all affected components and of rails unfavourably adjusted within admissible tolerances.

<u>The influence of different amplitudes of lateral oscillations and of varying phases of the lateral oscillations resulting in different points of first hit to the funnel-shaped guide rail</u>

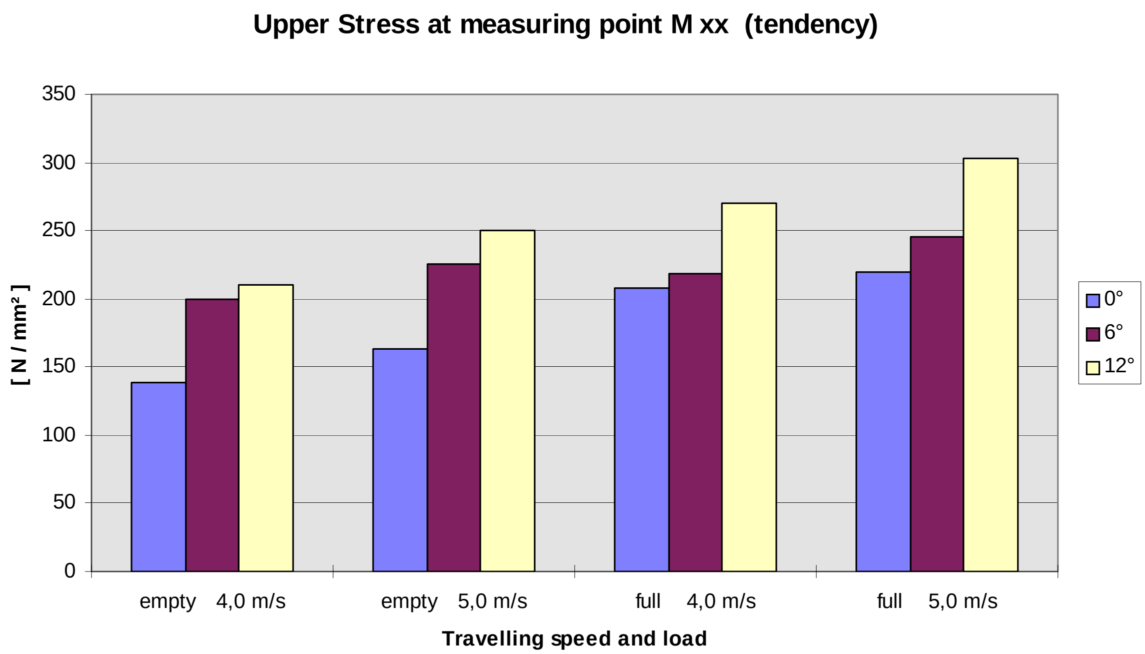
The analysis of experimental measurements carried out at detachable monocable ropeways have shown that the strain on carrier components definitely is not deterministic. Rather, it shows remarkable differences depending on where the guide wheel of a vehicle happens to first hit the funnel-shaped guide rail. In case of a unfavourable situation of hitting, the funnel-shaped guide rail does not damp lateral oscillations, but even enhances them. In that case the forces carrier components are subject to may considerably increase as the vehicle passes through the detaching area.



Therefore the influence of varying phases of lateral oscillations as the vehicle´s guide wheel hits the funnel-shaped guide rail at stations entry has to be examined systematically. With almost the same amplitude of lateral oscillation and at the same load, transported by the carrier as well as the same speed, station entry procedures are repeatedly measured in order to record at least four different phases of lateral oscillation.

With a small series of experiments like this, varying the phases of oscillation, the worst loads will be approximated quite well. It is not absolutely sure, though, that the worst loads will actually be found. This would afford a lengthy and detailed systematic examination with several experiments for each phase of oscillation and small steps in varying the phase. For such a systematic search, computer simulation can be a good help.

As a result, the experimental examination will show important dependencies of dynamic strain figures from operational parameters. The following example shows a tendency how the upper dynamic strain at a certain measuring location depends on travelling speed, load inside the vehicle and amplitude of lateral oscillation.



The efficiency of mechanical installations, used to damp lateral oscillations at the stations entry, nowadays is not yet satisfactory. These mechanical damping devices should be improved in order to reduce material strain, showing up at carrier components.

<u>The influence of loads transported during normal operation (dead loads and persons); Categorising loads into load groups</u>

The situations which occur most frequently during normal operation, are the empty carrier and the partly loaded carrier. Especially the partial load, possibly having an excentric load arrangement inside the carrier, causes high strain at the station entry. Experimental measuring of strain in carrier components therefore may not be limited to fully loaded vehicles, but must also comprise the empty carrier as well as the partly loaded vehicle with excentric load arrangement inside.

Example for categorizing into five load groups (load group 0 to 4) for a carrier for 6 passengers:

	load group 0 empty	1 light	1 light	2 half	2 half	3 heavy	4 full
number of persons in carrier	**0**	**1**	**1**	**3**	**3**	**5**	**6**
positionning of load	**---**	**excentric inner side**	**excentric outer side**	**excentric inner side**	**excentric outer side**	**center**	**center**

As some experiments have shown, the way of loading the vehicles, persons instead of dead loads like concrete, which is normally used for experimental purposes, has a small, negligible influence on the experimental results.

<u>The influence of the travelling velocity</u>

The maximum speed (nominal speed) for which a ropeway installation is designed, in general is used only in those cases, when a waiting period of a big crowd has to be avoided and maximum transportation capacity is needed. During the year this maximum transportation capacity is not used very frequently and therefore it may be interesting to experimentally examine the components' strain not only at nominal speed but also at the reduced speed most frequently set.

Nowadays most detachable circulating ropeways are designed for a nominal speed of 5 m/s. For energy and wear reasons, these installations are run at this speed only a couple of hours a day. For some installations, which are operated during the summer season, the nominal speed even is not used for several months and instead the transportation velocity is, for example, set to 3.5 m/s. As some measurements of strain at carriers components have shown, the influence of low speeds may be quite considerable.

<u>The influence of tolerable wear and of rails disadvantageously adjusted</u>

Experimental measuring the components' strain is frequently carried out at the new ropeway installation, at which all parts at the station entry are new and properly adjusted. Through the years though, the wear and tear of parts (such as reels, tires, linings at the top of carrier hangers) and changed adjustments (such as guide rail, spring cushioning at the carriers joints) may lead to unfavourable conditions. Within the tolerances given by the ropeway manufacturer, the influence of these changes inevitably occurring during the ropeway's lifetime, should be considered and experimentally examined.

B2 Frequency numbers of common loads during normal operation

How frequently during the entire lifetime are carriers entering the stations for example being partly loaded ?

How many load cycles are to be expected throughout the years for the kind of strain, occurring for example at a fully loaded vehicle ?

<u>1. Frequency criterion for the filling grade of vehicles</u>

The average filling grade of a ropeway is the relation of the number of persons actually transported in each direction within a certain period, to the number of persons that theoretically could have been transported, if all vehicles that actually left the stations within that period would have been completely full. This quotient, called filling grade, gives a first impression of the carriers' use. At most ropeways it ranges from 15% to 25% for the vehicles going uphill. The filling grade is very easily calculable from the countings of passengers actually transported and the countings of vehicles entering the stations.

This filling grade though, does not yet show how frequently the ropeway vehicles are conveyed empty, partly loaded or full. For the purpose of classification into the above mentioned load groups (empty, light, half, heavy, full), very simple statistics can be used, regarding only vehicles that are not empty. For example it can be counted how frequently the load inside a carrier that is not empty, fits into one of the load groups.

Example for frequencies of loaded vehicles going uphill at a circulating ropeway with vehicles for 6 passengers:

load group	empty	light	half	heavy	full
number of persons in vehicle	0	**1**	**2 or 3**	**4 or 5**	**6**
relative frequency	0	**10 %**	**40 %**	**35 %**	**15 %**

From this relative frequency, which shows how frequently a vehicle is taken by one passenger, by two or three passengers and so on, in combination with the filling grade the absolute numbers of frequencies for the different load groups can be derived. From these statistics it may for example become evident, that 60% to 85% of all station entries go off with empty carriers.

2. Frequency criterion for lateral oscillations within the load groups specified

The more load is inside the vehicle, the better is the stability of the vehicle. Empty vehicles will be pushed into a lateral oscillation by wind much more easily than fully loaded vehicles.

Furthermore there are some facts, which determine the frequency of lateral oscillations:

- Criterion for subjectively switching off the ropeway

  Those amplitudes of lateral oscillations, which occur repeatedly during normal operation, because the operator at the station considers them to be "tolerable", have to be separated from those amplitudes of lateral oscillations, which practically do not occur, because the operator turns off the ropeway as they appear and before the vehicle enters the station. The ropeway manufacturer has to determine the level of amplitudes up to which lateral oscillations are absorbed with shock effects remaining within tolerable bounds and therefore may occur regularly at the stations entry during normal operation. Beyond this determined level of amplitudes the stations operator on duty has to reduce the travelling velocity or to turn off the ropeway in order to avoid damage. Depending on the type of ropeway system there are different levels of "tolerable" amplitudes of lateral oscillations. Commonly the heavier and the wider the vehicles are and the higher the travelling speed is, the lower are the tolerated amplitudes.
  The operator must be given clear directives, which lateral oscillations to tolerate and which not and therefore to turn off the ropeway.

- Lateral amplitudes at vehicles with partial load excentrically arranged inside

  Carriers, which are loaded only half or even lesser during normal operation, oftentimes show a constant lateral amplitude because of an excentric load arrangement inside. Lateral oscillations, as they are generated by wind for example, are then overlying this constant amplitude. This has as a result that for partly loaded vehicles the level of lateral amplitudes is higher than for the fully loaded.

- Lateral amplitudes generated by wind

Here the individual topographic conditions of the ropeway are of special importance. Nevertheless the influence of wind can be categorised as well by finding typical lateral effects the way they are regularly generated by wind close to the stations. An example of a ropeway with vehicles for six passengers is given below. In this example it is assumed that 80% of normal operation is done under the influence of wind speeds that cause the empty vehicle to move 2.3° laterally, the full vehicle 1° laterally. Further 20% of the normal operation at this example ropeway are assumed to be done under the influence of wind speeds which cause the empty vehicle to move 6° laterally, the full loaded one only 2.6°. Furthermore the example assumes, that lateral amplitudes caused by higher windspeeds, exceed the determined limit of tolerable lateral amplitudes and the operating staff has to reduce the ropeway speed in case they occur.

Example: Limits of tolerated lateral amplitudes at a ropeway with six-passenger cabins for a travelling velocity of 4 m/s:

- empty and partly loaded vehicle (≤ 50% load): 9°,
- heavy or fully loaded cabine (> 50% load) : 6°.

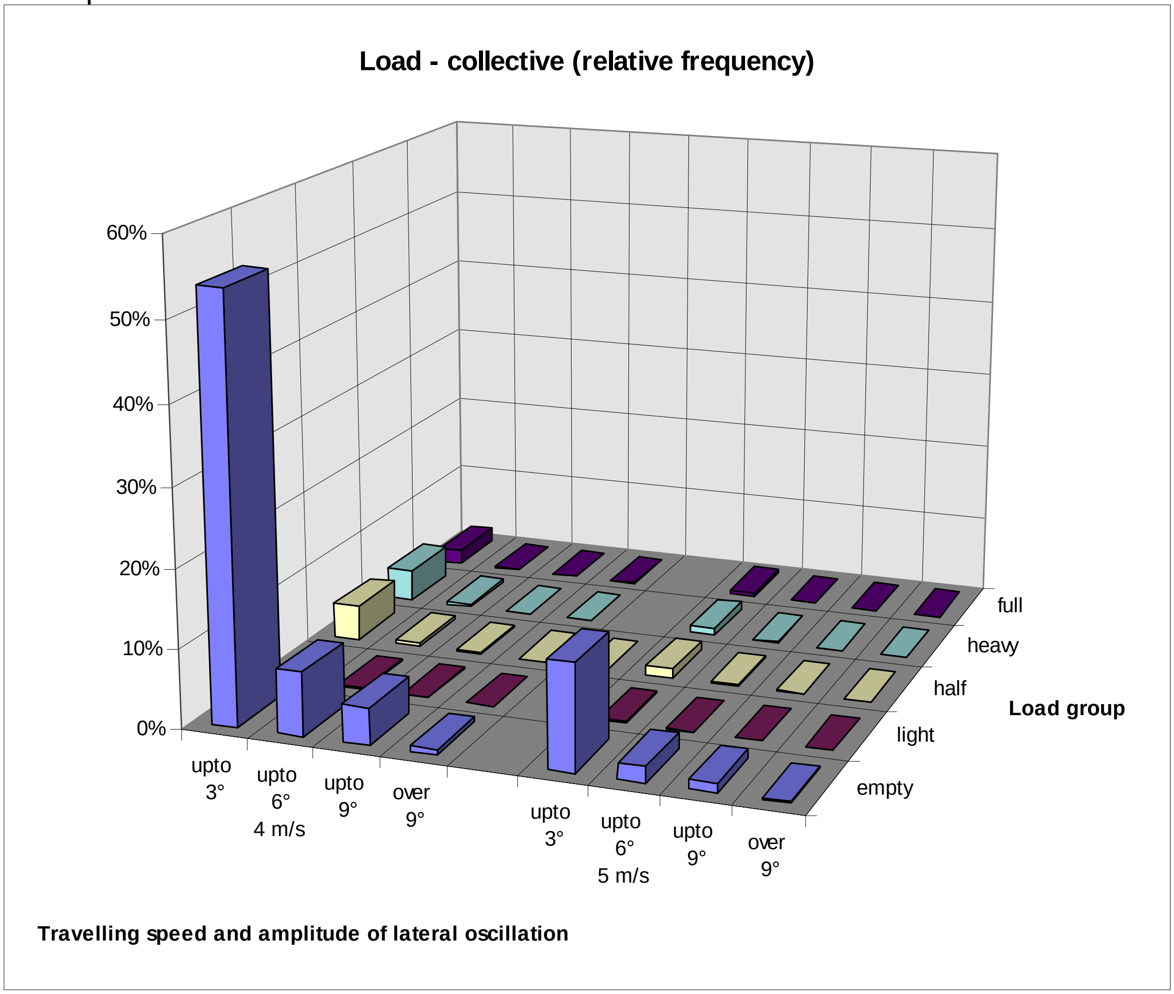
From these criteria, the characteristic frequencies can be combined for each type of ropeway system.

Example for relative frequencies of lateral amplitudes at the above mentioned example ropeway with cabins for 6 passengers:

frequencies of lateral amplitudes		**empty**	**light**	**half**	**heavy**	**full**
number of persons in this load group		0	1	2.5	4.5	6
	amplitude of lateral oscillation					
	0° to 3°	80.00%	78.00%	85.00%	90.00%	95.00%
	3° to 6°	12.00%	13.00%	10.00%	9.00%	4.50%
	6° to 9°	7.00%	7.50%	4.00%	0.50%	0.30%
	over 9°	1.00%	1.50%	1.00%	0.50%	0.20%
	sum	100.00%	100.00%	100.00%	100.00%	100.00%

From these relative frequencies in combination with the above mentioned criteria for the filling grade, the absolute frequencies of lateral oscillations can be derived.

Example of a load-collective:



A very realistic strain collective thus can be formed by first determining the carrier components' strain and the numbers of occurring load cycles at every station entering procedure by experimental measurements and second determining the absolute frequency of lateral oscillations according to the scheme described above.

C The process of verifying sufficient service strength

1. Verification procedures applied today

Verification procedures for carrier components nowadays are based on laboratory experiments in which the entire carrier is subject to a fatigue test in order to find out how the whole unit reacts under uniaxial vertical pulsing.

The fully loaded vehicle herewith undergoes 5 million cycles of a load, corresponding to the double of the nominal load (mass of the entire vehicle plus nominal load). In laboratory the vehicle is fixed at the rope bed of the grip in the clamping device. The clamping device itself though is not completely fixed or blocked for these experiments in contrast to the real conditions at the detachment section inside the stations entry.

Therefore, this kind of experiments does not comprise reality like forces and momentums and consequently does not contain the strain that occurs when lateral oscillations are cushioned under the influence of detachment forces within the station entering section.

The fatigue test has the advantage, that all carrier components completely get subject to the loading and therewith also those sections or crossections, for which a calculation to verify service strength was not specially executed. Beacause of this advantage, it is better not to do without fatigue tests. It is decisive for the quality of fatigue tests, though, that the loading of all examined components is done reality like.

Why does the amplitude of load-alternation, like it is applied at laboratory fatigue tests today, not represent the components' strain for station entering procedures in a reality like manner?

The clamping device is forced into a horizontal position when the carrier arrives at the station entry and passes through the detachment section. In that very moment the clamping device is fixed into horizontal position by the rope, the suspension rail, the tire drive and the guide rail. Whenever the vehicle's energy of lateral oscillations is not yet completely cushioned up to this "section of stiff fixation" of the clamping device, high momentums will go through the hanger top into the hanger axle. The loading of the carrier components at a uniaxial fatigue test in laboratory does not simulate this reality.

- When a partly loaded carrier (half loaded at the inner or outer side) enters the station, the amplitude stresses are higher than the central stress so that, in part, alternating load conditions exist (limit stress ratio $\kappa < 0$), while fatigue tests only study a dynamic load with the limit stress ratio $\kappa \geq + 0$.
- In the fatigue test, no forces are introduced from the suspension wheel axle into the grip, whereas the suspension wheel axle absorbs at least part of the forces of the tyre drive and detachment roller upon station entry without lateral oscillation and, additionally supports the momentum of the hanger top already at very low lateral oscillations.

Laboratory fatigue tests can help to identify critical or dangerous sections within the examined components. Allthough the way how the loading of these components in the laboratory tests is done, is not comparable to the real loading of the carrier components at the stations entry of a ropeway.

2. Calculations Verifying service strength

Which factors have to be considered in verifying the sufficient service strength of carrier components by calculations?

The verification of sufficient service strength is performed by **comparing** the stress to be expected in service with the **fatigue strength** of the components. Additionally, a **safety factor** has to be taken into account.

For determining the components´ strain, the results of experimental measurements of station entering procedures may serve as a basis in the form of a reality like load - collective. The strain at each critical component section as well as the number of load cycles to expect for the entire period of the components use are represented by the strain-collective, described here above.

Recognised standard literature in the field of caculation of service strength supplies the individual form-strength values of the material at every crossection of the component. Therein the individual material properties as well as the form, shape and surface of the material are taken into account (alternating cyclic strength, factors for the influence of size and surface as well as of notch-factors).

It is not permissible to derive the fatigue strength from the results of the fatigue test, among others, for the following reasons:

- An S-N curve cannot be replaced by a fatigue test that is represented by a single point in the fatigue strength diagram. The fatigue test does not yield any information on the probability of failure.
- The force flow simulated in a uniaxial fatigue test does not represent the complex interdependencies characterising the force flow when a carrier enters the station.

Safety factors

In analogy with generally recognised literature [6], the following aspects must not be neglected:

- Uncertainty about the load's volume ($1.10 < f_{un} < 1.30$)

Among others the following effects belong here:

* External loads that appear during the station entering procedure, are superposing inner stresses inside the components, permantently present for example in press fits or weldings.

* The experimental measuring of stress during the station entering procedure normally is done at the brand new ropeway installation at which all parts have no wear and tear and all components are properly adjusted. Throughout the years

worse conditions will appear because of the wear of parts and unfavourable adjustments.

- <u>Uncertainty about the operation mode (1.10 < f_{op} 1.30)</u>

In case that comprehensive experimental examination of the station entering procedures has been carried out, the uncertainty about the operation mode is quite low. Here it has to be considered,

* that the operating staff of the ropeway has to react in case of non tolerable lateral oscillation ocurring. Their subjective behavior, always to have a realisic estimation and always to react in time, has to be taken into account.

* that forming a load collective is always an extrapolation of known conditions into the future. Assumptions about certain frequencies of loads for example are based on experience or estimations. The real operational conditions in the future will differ from these assumptions.

- <u>Indispensability of the component (1.20 < f_{ind} < 1.50)</u>

* The indispensability has to be considered particularly for those carrier components whose failure may result in a carrier fall (single, non-redundant components such as hanger axle and arm).

* The timely identification of a component failure is to be assessed (e. g. visibility of crack formation and propagation). Critical component points that are not accessible for inspection result in a relatively big uncertainty.

The saftey-factor has to be formed from these three factors. It commonly ranges from f_{total} = 1,50 to f_{total} = 2,50.

3. Alternative verification by a series of Wöhler's fatigue tests

Modern ropeways are more and more designed using lesser compact and light-weight elements and components, which only need a minimum of maintenance. Modern designs are characterized by a highly efficient use of the properties of the material. If modern calculation procedures on service strength taking into account adequate safety factors are not successful, it may be necessary, in individual cases, to perform a series of Wöhler's fatigue tests for carrier components and thereby verify the components' behaviour under the loads occurring in ropeway operation.

The way to verify components by a series of Wöhlers' fatigue tests with an specific examination of the components behavior at breakdown or cracking, like automotive and aircraft-industries do, is very costly. But such sophisticated methods under consideration of the dynamic behavior lead to further optimized, compact designs.

D Important questions

Important questions are posed to:

a) the ropeway design-engineer:

- Are all components designed in the way, that is becomes possible to detect any damages or cracks easily, early and with simple methods ?

- Which information has to be given to the ropeway operator so that he will replace the shock absorbing elements in the funnel-shaped guide rail at the stations entry in time?
  How is the ropeway operator able to control sufficient functioning of the damping elements for cushioning lateral oscillations at the stations entry ?

- Which information has to be given to the ropeway operator so that he can avoid not tolerable loads caused by lateral oscillations?
  For this purpose was the influence examined experimentally that results at stations entry for the stress and strain at the carrier components at reduced rope-speed ?

- When the tolerances of wear at ropeway parts and the tolerances of the adjustment of rails were determined, have the special forces been taken into account which appear when the carrier is forced into the „section of stiff fixation" at the stations entry ?

b) the ropeway operator:

- Have the conditions been determined, under which the operator has to reduce the ropeway speed during normal operation ?

- Does the operating staff recognize the tolerances of wear on ropeway parts and the tolerances of adjustment specified by the manufacturer?
  Does the operating staff regularly check the station entering procedures for inadmissable shock effects ?

E Summary

The real strain in the carrier components depends on highly complex, inter-related factors occurring upon station entry. Depending on the stiffness of the guard rails and their suspensions, the forces may take different paths in the grip device.
In this situation high dynamic forces are activated by high carrier masses and high transportation speed. Traditional laboratory fatigue tests do not cover this situation of complex flow of forces.
The efficiency of devices damping lateral oscillations upon station entry was not improved to the same extent as the lateral oscillation energies increased due to higher carrier masses and travelling speeds. Detailed experimental investigations need to be performed for carriers entering stations.

Verification procedures for the carrier components, they way they are conventionally applied today, do not sufficiently consider the special effects and conditions which occur as ropeway carriers pass through the station entry. The form of verification of service strength at the carrier components, which is based on a uniaxial laboratory fatigue test, which has been practised over several decades, is no longer sufficient with respect to development-tendencies in the field of modern ropeway installations. Especially the use of compact and light-weight designs must be taken into account by a detailed calculation method considering carefully reflected safety-factors.

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Dipl. - Ing. Hans Ulrich Zbil
TÜV Süddeutschland Bau und Betrieb GmbH
Zentralabteilung Seilbahnen
Westendstraße 199, D - 80686 München
Tel.: + 49 (0)89 - 5791 - 1971, Fax .: + 49 (0)89 - 5791 - 2022
e-mail: Hans-Ulrich.Zbil@bt.tuevsued.de

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This contribution raises the following questions: Are verification procedures nowadays applied to ropeway carrier components such as grips, hangers, cabins still sufficient?

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In this context, the essential elements will be discussed that have to be considered and determined in the dimensioning of carrier components with sufficient service strength.

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Many modern station entries are designed without guide rails that damp the lateral oscillations of the carriers. Instead, this task is performed by the coupling device that is fixed at the rope at one side and led into a funnel-shaped guide rail at the other side when the carrier enters the station. Thus, the coupling device quickly brings the entire carrier into vertical line using high forces and momentums at the top of the carrier's suspension.

As the carrier capacity is increased (carriers for 8, 12 or 15 persons) and the travelling velocity is raised, the level of energies increases, and high forces and momentums at the suspension of the carrier may even occur at small lateral oscillations.

B1 Investigation of the components' strain at the station entry by experimental measurements

Is it possible to do without experimental examinations?

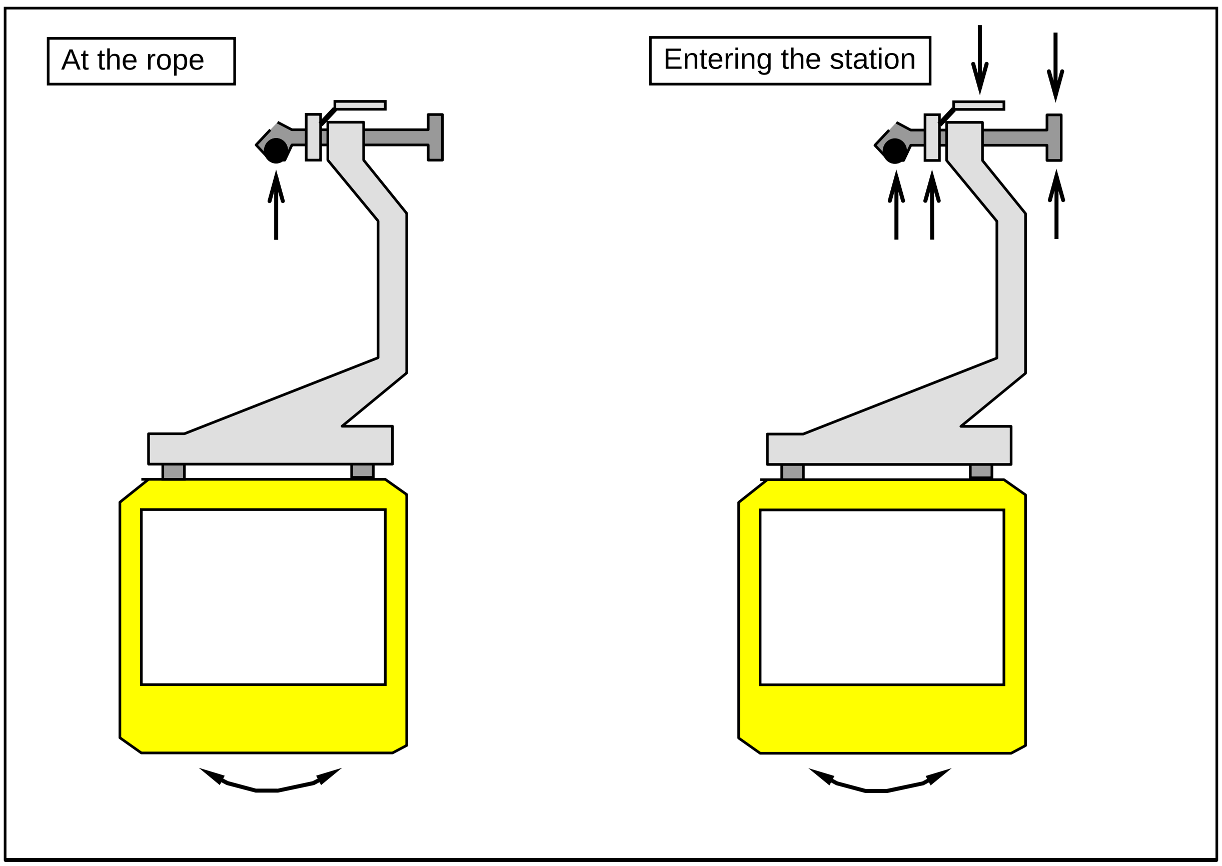
The carrier, while situated on the line, is freely able to swing laterally around the axis formed by the rope.
In contrast thereto, the carrier is "firmly fixed" when it enters the station and arrives at the detaching section. Here, lateral oscillations are completely blocked. In the moment when the carrier passes through the station entry, a multitude of forces acts on the coupling device and forces it into a defined position, e.g. the repositioning forces at the guide wheel, the forces of reaction at the suspension wheels, the positive or negative reaction force from the rope. This represents the situation of a system of forces that is overdetermined several times. The level of forces within this system is determined by

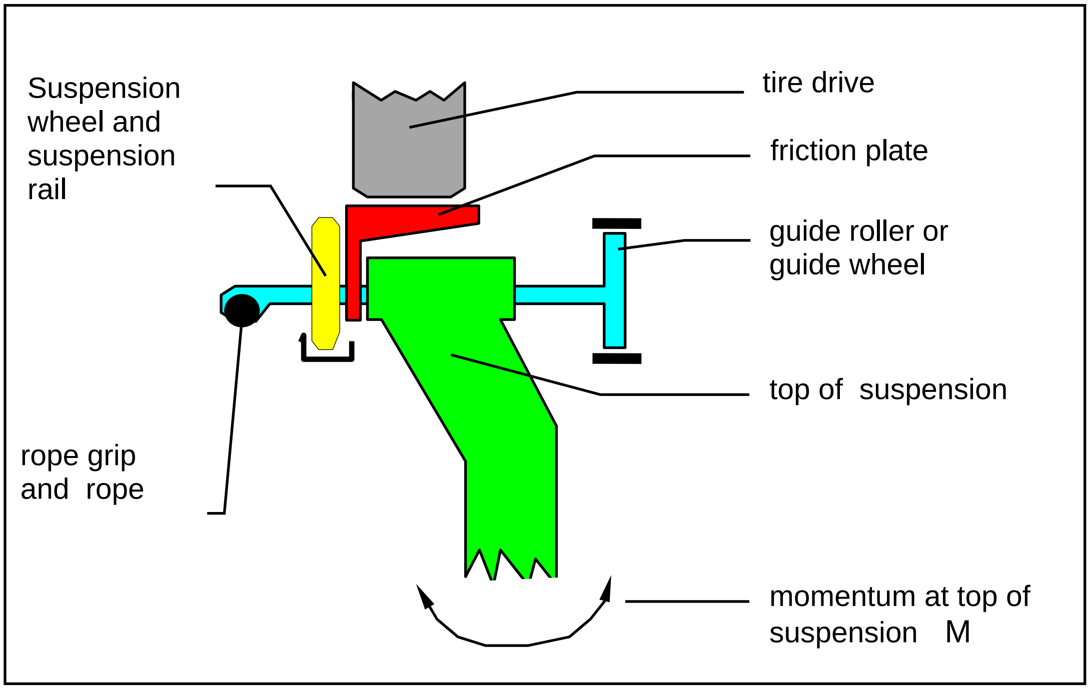
the stiffness of those station components the carrier's suspension is in contact with (such as guide rail, entry funnel, suspension rail, detachment rail, tire drive, rope).

To find realistic values of these forces, experimental measurements are extremely helpful. They are necessary because they can only be replaced by expensive and very sophisticated numeric calculations with dynamic modelling.

How to carry out experimental measurements?

The loads acting on carrier components have to be measured all the way from the beginning of the station entry to the end of the deceleration section. On the one hand, this is necessary to find the maximum level of forces occurring often even beyond the detaching section on the basis of the measurements. On the other hand, a realistic number of load cycles can be determined only by analysing measurements covering the entire station entering procedure including the deceleration section.





The momentum at the suspension top, which introduces lateral oscillation energy into the hanger suspension axle, is predominantly led out by the guide wheel into the guide rail. Depending on the stiffness and the inertial forces of the guide rail, lateral oscillation energy can partly also be led out through suspension wheels into the suspension rail as well as via the coupling device into the rope or via the friction plate into the tire drive. Depending on the stiffness of the different rails and rail suspensions, the flow of forces and momentums within the coupling device may take different paths. The real forces acting on the carrier components therefore depend on complex interrelations between the station design elements.

It is very difficult to theoretically calculate the stiffness of rails and guiding devices and dynamic effects within the station entry section in order to predict the dynamic flow of forces. Up to now, there is no alternative to experimentally measuring the strains on carrier components at the station entry.

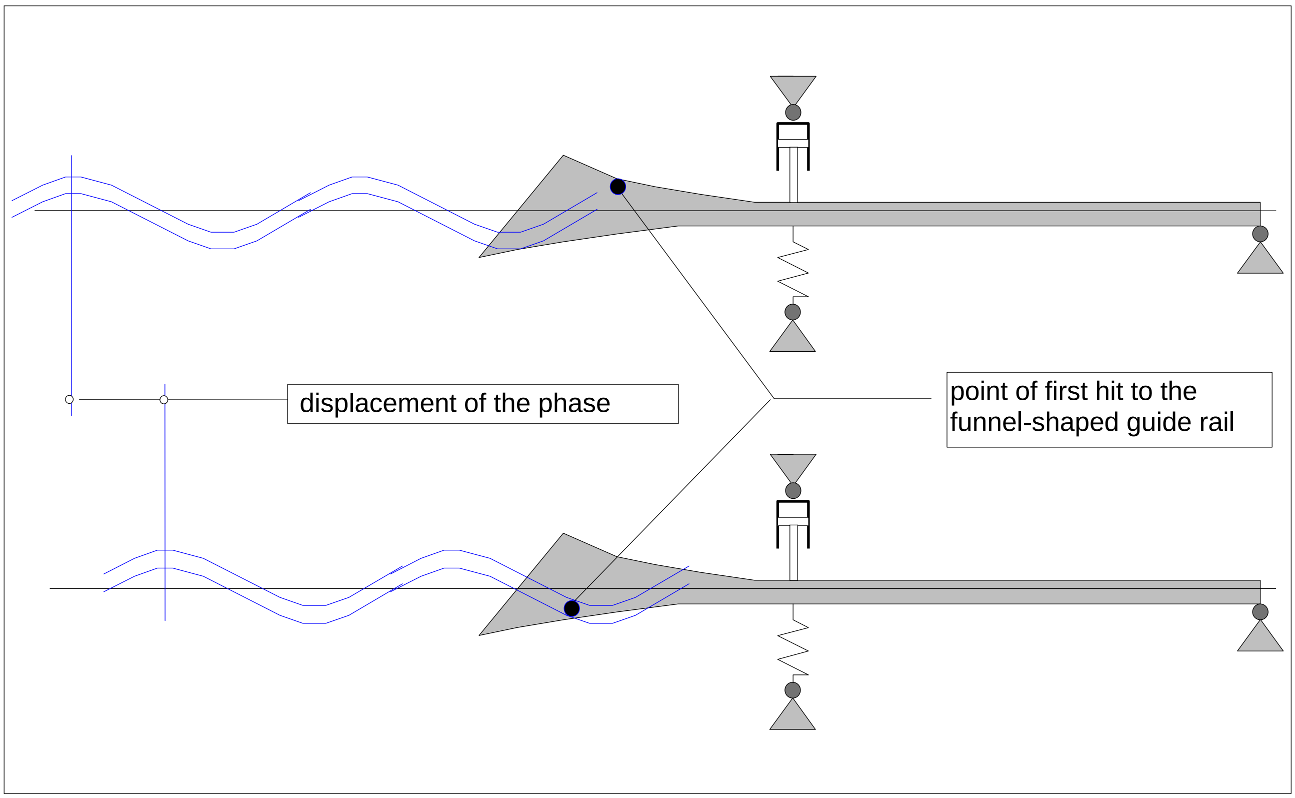
Which parameters and conditions must be realistically simulated during measuring experiments?

The influence of the following operational parameters must be systematically analysed with measuring experiments:

- the influence of different amplitudes and varying phases of the lateral oscillations resulting in different points of first hit to the funnel-shaped guide rail,
- the influence of the variety of loads transported during normal operation (dead loads and persons),
- the influence of the travelling velocity,
- the influence of tolerable wear at all affected components and of rails unfavourably adjusted within admissible tolerances.

The influence of different amplitudes and varying phases of the lateral oscillations resulting in different points of first hit to the funnel-shaped guide rail

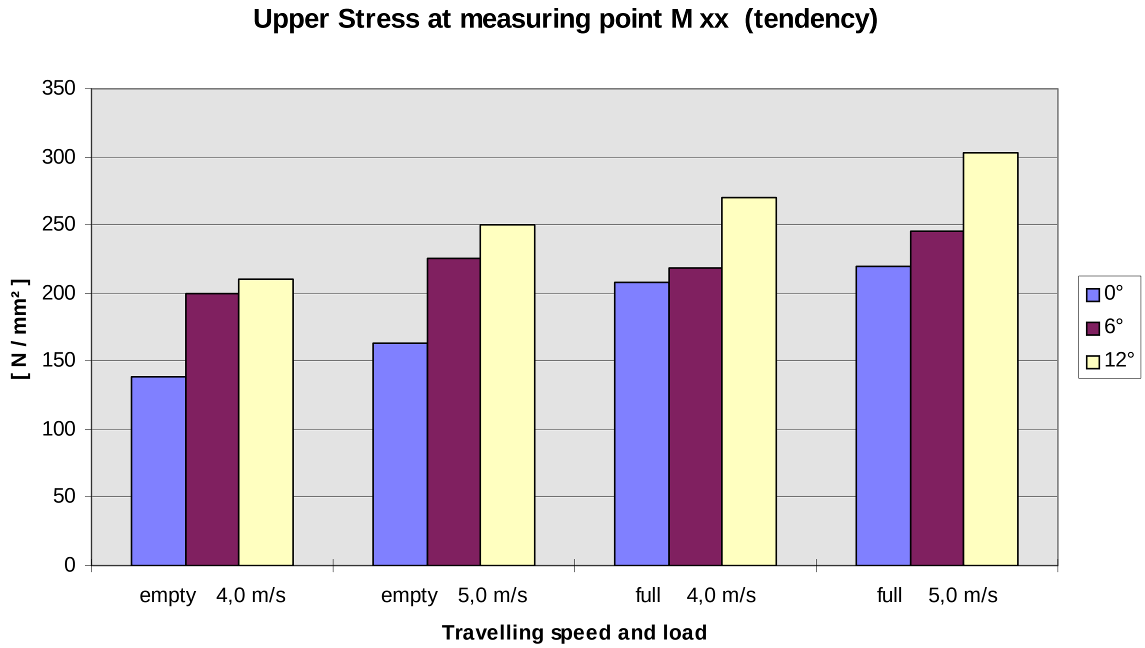
The analysis of experimental measurements carried out at detachable monocable ropeways have shown that the strain on carrier components definitely is not deterministic. Rather, it shows remarkable differences depending on where the guide wheel of a carrier happens to first hit the funnel-shaped guide rail. In case of an unfavourable situation of hitting, the funnel-shaped guide rail does not damp lateral oscillations, but even enhances them. In that case, the forces acting on carrier components may considerably increase as the carrier passes the detaching area.



Therefore the influence of varying phases of lateral oscillations as the carrier's guide wheel hits the funnel-shaped guide rail at station entry has to be examined systematically. With almost the same amplitude of lateral oscillation, the same load transported by the carrier as well as the same speed, station entry procedures are repeatedly measured in order to record at least four different phases of lateral oscillations.

With a small series of such experiments in which the phases of oscillation are varied, the worst loads will be approximated quite well. It is not absolutely sure, though, that the worst loads will actually be found. This would afford a lengthy and detailed systematic examination with several experiments for each phase of oscillation and small steps in varying the phase. For such a systematic search, computer simulation can be a good help.

As a result, the experimental examination will show important dependencies of dynamic strain figures on operational parameters. The following example shows how the upper dynamic strain at a certain measuring location depends on the travelling speed, the load inside the carrier and the amplitude of lateral oscillation.



The efficiency of mechanical installations used to damp lateral oscillations at the station entry is not yet satisfactory. Mechanical damping devices should be improved in order to reduce the material strain of carrier components.

<u>The influence of loads transported during normal operation (dead loads and persons); Categorising loads into load groups</u>

The situations occurring most frequently during normal operation are empty carriers and partly loaded carriers. Especially a partial load, possibly with an eccentric load arrangement inside the carrier, causes high strain at the station entry. Experimental measurements of strain in carrier components therefore must not be limited to fully loaded carriers, but also comprise have to cover empty carriers as well as partly loaded carriers with eccentric load arrangement inside.

Example for categorising loads into five load groups (load group 0 to 4) for a 6-passenger carrier:

	Load group 0 empty	 1 light	 1 light	 2 half	 2 half	 3 heavy	 4 full
Number of persons in carrier	**0**	**1**	**1**	**3**	**3**	**5**	**6**
Positioning of the load	**---**	**eccentric inner side**	**eccentric outer side**	**eccentric inner side**	**eccentric outer side**	**centre**	**centre**

As some experiments have shown, the way of loading the carriers – persons instead of dead loads like concrete, which is normally used for experimental purposes – has a small, negligible influence on the experimental results.

The influence of the travelling velocity

In general, the maximum speed (nominal speed) for which a ropeway installation is designed is used only when waiting periods for a big crowd have to be avoided and maximum transport capacity is needed. In the course of the year, the maximum transport capacity is not used very frequently and therefore it may be interesting to experimentally examine the components' strain not only at the nominal speed but also at the reduced speed most frequently set.

Nowadays most detachable circulating ropeways are designed for a nominal speed of 5 m/s. For energy and wear reasons, these installations are run at this speed only a couple of hours a day. For some installations, which are operated during the summer season, the nominal speed even is not used for several months and instead the transportation velocity is, for example, set to 3.5 m/s. As some measurements of strain at carrier components have shown, the influence of low speeds may be quite considerable.

The influence of tolerable wear and rails unfavourably adjusted

Experimental measurements of the components' strain are frequently carried out at new ropeway installations at which all parts at the station entry are new and properly adjusted. In the course of the years, though, the wear and tear of parts (such as reels, tires, linings at the top of carrier hangers) and changed adjustments (such as guide rail, spring cushioning at the carrier's joints) may lead to unfavourable conditions. Within the tolerances given by the ropeway manufacturer, the influence of these changes inevitably occurring during the ropeway's life should be considered and experimentally examined.

B2 Frequency numbers of common loads during normal operation

How frequently do carriers enter the stations, for example, being partly loaded during their entire life?

How many load cycles are to be expected throughout the years, for example, for the kind of strain occurring at a fully loaded carrier ?

1. Frequency criterion for the filling ratio of carriers

The average filling ratio of a ropeway is the relation of the number of persons actually transported in each direction within a certain period to the number of persons that, theoretically, could have been transported if all carriers that actually left the stations within that period had been completely full. This quotient, called the filling ratio, gives a first impression of the carriers' use. For most ropeways, it ranges from 15% to 25% for the carriers going uphill. The filling ratio can be very easily calculated based on counts of passengers actually transported and counts of carriers entering the stations.

The filling ratio, though, does not show how frequently the ropeway carriers are conveyed empty, partly loaded or full. For the purpose of classification into the above mentioned load groups (empty, light, half, heavy, full), very simple statistics can be used taking into account only carriers that are not empty. For example, it can be counted how frequently the load of a carrier that is not empty fits into one of the load groups.

Example for frequencies of loaded carriers going uphill on a circulating ropeway with 6-passenger carriers:

Load group	Empty	Light	Half	Heavy	Full
Number of persons in a carrier	0	**1**	**2 or 3**	**4 or 5**	**6**
Relative frequency	0	**10%**	**40%**	**35%**	**15%**

Based on this relative frequency, which indicates how frequently a carrier is taken by one passenger, by two or three passengers and so on, in combination with the filling ratio, the absolute numbers of frequencies for the different load groups can be obtained. These statistics, for example, may show that 60% to 85% of all station entries are performed with empty carriers.

2. Frequency criterion for lateral oscillations within the load groups specified

The higher the load inside the carrier is, the better is the stability of the carrier. Empty carriers will be pushed into lateral oscillations by the wind much more easily than fully loaded carriers.

Furthermore, there are some facts that determine the frequency of lateral oscillations:

- Criterion for subjectively switching off the ropeway

  The amplitudes of lateral oscillations that occur repeatedly during normal operation because the operator at the station considers them to be "tolerable" have to be separated from those amplitudes of lateral oscillations that practically do not occur because the operator turns off the ropeway as they appear and before the carrier enters the station. The ropeway manufacturer has to determine the level of amplitudes up to which lateral oscillations are absorbed with shock effects remaining within tolerable bounds and which, therefore, may occur regularly at the station entry during normal operation. Beyond this defined amplitude level, the stations operator on duty has to reduce the travelling velocity or turn off the ropeway in order to prevent damage. Depending on the type of ropeway system, there are different levels of "tolerable" amplitudes of lateral oscillations. Commonly, the heavier and the wider the carriers are and the higher the travelling speed is, the lower are the tolerated amplitudes.
  The operator must be given clear instructions as to which lateral oscillations are tolerable and which not so that the ropeway has to be turned off.

- Lateral amplitudes at carriers with partial load eccentrically arranged inside

  Carriers that are only half or even less loaded during normal operation often show a constant lateral amplitude because of an eccentric load arrangement inside the carrier. Lateral oscillations, such as those generated by wind, are then superimposing this constant amplitude. As a result, the level of lateral amplitudes is higher for partly loaded carriers than for fully loaded ones.

- Lateral amplitudes generated by wind

  Here, the individual topographic conditions of the ropeway are of special importance. Nevertheless, the influence of wind can also be categorised by identifying typical lateral effects regularly generated by wind close to the stations. An example of a ropeway with carriers for six passengers is given below. In this example, it is assumed that 80% of normal operation is done under the influence of wind speeds that cause the empty carrier to move 2.3° laterally and the full carrier 1° laterally. Further 20% of the normal operation of this example ropeway are assumed to be done under the influence of wind speeds that cause the empty carrier to move 6° laterally and the full loaded one only 2.6°. Furthermore, the example assumes that lateral amplitudes caused by higher wind speeds exceed the determined limit of tolerable lateral amplitudes so that the operating staff has to reduce the ropeway speed.

Example: Limits of tolerated lateral amplitudes at a ropeway with six-passenger cabins travelling at a velocity of 4 m/s:

- empty and partly loaded carriers ($\leq$ 50% load): 9°,
- heavy or fully loaded cabin (> 50% load) : 6°.

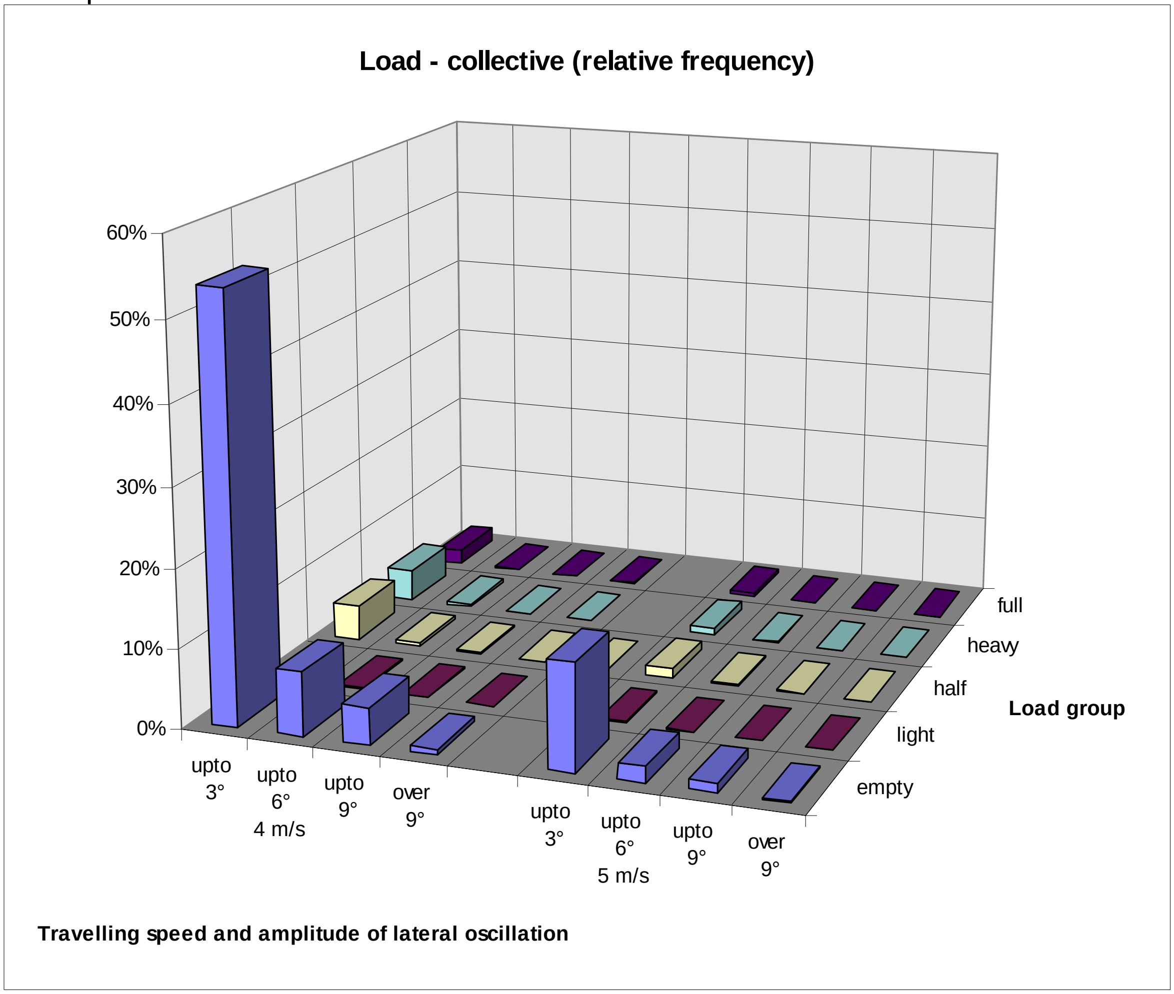
On the basis of these criteria, the characteristic frequencies can be summarised for each type of ropeway system.

Example for relative frequencies of lateral amplitudes at the above mentioned example ropeway with 6-passenger cabins:

Frequencies of lateral amplitudes		Empty	Light	Half	Heavy	Full
Number of persons in this load group		0	1	2.5	4.5	6
	Amplitude of lateral oscillation:					
	0° to 3°	80.00%	78.00%	85.00%	90.00%	95.00%
	3° to 6°	12.00%	13.00%	10.00%	9.00%	4.50%
	6° to 9°	7.00%	7.50%	4.00%	0.50%	0.30%
	over 9°	1.00%	1.50%	1.00%	0.50%	0.20%
	Total	100.00%	100.00%	100.00%	100.00%	100.00%

From these relative frequencies in combination with the above mentioned criteria for the filling ratio, the absolute frequencies of lateral oscillations can be derived.

Example of a load-collective:



A very realistic strain collective can thus be developed by firstly determining the carrier components' strain and the numbers of load cycles occurring in each station entry procedure by experimental measurements and secondly determining the absolute frequency of lateral oscillations according to the scheme described above.

C The process of verifying sufficient service strength

1. Verification procedures applied today

Verification procedures for carrier components nowadays are based on laboratory experiments in which the entire carrier is subject to a fatigue test in order to find out how the whole unit reacts under uniaxial vertical pulsing.
The fully loaded carriers undergoes 5 million cycles of a load corresponding to the double of the nominal load (mass of the entire carrier plus nominal load). In the

laboratory, the carrier is fixed at the rope bed of the grip in the coupling device. The coupling device itself though is not completely fixed or blocked for these experiments in contrast to the real conditions at the detachment section inside the station entry.

Therefore, such experiments do not comprise reality-like forces and momentums and consequently do not cover the strain that occurs when lateral oscillations are cushioned under the influence of detachment forces within the station entering section.

The fatigue test has the advantage that all carrier components are completely subject to the loading. Hence, it also covers those sections or cross-sections for which special calculations were not performed to verify the service strength. Because of this advantage, it is better not to do without fatigue tests. It is decisive for the quality of fatigue tests, though, that the loading of all examined components is done in a reality-like manner.

Why does the amplitude of load alternation, as applied in laboratory fatigue tests today, not represent the components' strain for station entering procedures in a reality-like manner?

The coupling device is forced into a horizontal position when the carrier arrives at the station entry and passes through the detachment section. In that very moment, the coupling device is fixed into a horizontal position by the rope, the suspension rail, the tire drive and the guide rail. Whenever the carrier's energy of lateral oscillations is not yet completely cushioned up to this "section of stiff fixation" of the coupling device, high momentums will go through the hanger top into the hanger axle. The loading of the carrier components during an uniaxial fatigue test in the laboratory does not simulate this reality.

- When a partly loaded carrier (half loaded at the inner or outer side) enters the station, the amplitude stresses are higher than the central stress so that, in part, alternating load conditions exist (limit stress ratio $\kappa < 0$), while fatigue tests only study a dynamic load with the limit stress ratio $\kappa \geq + 0$.

- In the fatigue test, no forces are introduced from the suspension wheel axle into the grip, whereas the suspension wheel axle absorbs at least part of the forces of the tyre drive and detachment roller upon station entry without lateral oscillation and, additionally supports the momentum of the hanger top already at very low lateral oscillations.

Laboratory fatigue tests can help to identify critical or dangerous sections within the examined components. Nevertheless, the way in which these components are loaded in the laboratory tests is not comparable to the real loading of the carrier components at the station entry of a ropeway.

2. Calculations verifying service strength

Which factors have to be considered in verifying by calculations that the service strength of carrier components is sufficient?

The verification of sufficient service strength is performed by **comparing** the stress to be expected in service with the **fatigue strength** of the components. Additionally, a **safety factor** has to be taken into account.

For determining the components' strain, the results of experimental measurements of station entering procedures may serve as a basis in the form of a reality-like load collective. The strain at each critical component section as well as the number of load cycles to be expected for the entire period of the components use are represented by the strain collective described above.

Recognised standard literature in the field of calculation of service strength supplies the individual form strength values of the material at every cross-section of the component. Therein, the individual material properties as well as the form, shape and surface of the material are taken into account (alternating cyclic strength, factors for the influence of size and surface as well as of notch factors).

It is not permissible to derive the fatigue strength from the results of the fatigue test, among others, for the following reasons:

- An S-N curve cannot be replaced by a fatigue test that is represented by a single point in the fatigue strength diagram. The fatigue test does not yield any information on the probability of failure.
- The force flow simulated in a uniaxial fatigue test does not represent the complex interdependencies characterising the force flow when a carrier enters the station.

Safety factors

In analogy with generally recognised literature [6], the following aspects must not be neglected:

- Uncertainty about the load's volume ($1.10 < f_{un} < 1.30$)

This includes the following effects:

* External loads that appear during the station entering procedure are superposing inner stresses permanently present inside the components, for example, in press fits or welds.

* The experimental measuring of stress during the station entering procedure is normally done at brand new ropeway installations where all parts do not show any wear and tear and all components are properly adjusted. In the course of the years, conditions will deteriorate because of the wear of parts and unfavourable adjustments.

- Uncertainty about the operation mode ($1.10 < f_{op}$ 1.30)

If comprehensive experimental examinations of the station entering procedures were carried out, the uncertainty about the operation mode is quite low. Here, one has to take into account that

* the operating staff of the ropeway has to react when intolerable lateral oscillations occur. Their subjective behaviour, always to have a realistic estimation and always to react in time, has to be taken into account.

* the development of a load collective always is an extrapolation of known conditions into the future. Assumptions about certain frequencies of loads, for example, are based on experience or estimations. The real operational conditions in the future will differ from these assumptions.

- Indispensability of the component ($1.20 < f_{ind} < 1.50$)

* The indispensability has to be considered particularly for those carrier components whose failure may result in a carrier fall (single, non-redundant components such as hanger axle and arm).

* The timely identification of a component failure is to be assessed (e. g. visibility of crack formation and propagation). Critical component points that are not accessible for inspection result in a relatively big uncertainty.

The safety factor has to be established based on these three factors. It commonly ranges from $f_{total} = 1.50$ to $f_{total} = 2.50$.

3. Alternative verification by a series of Wöhler's fatigue tests

Modern ropeways are more and more designed using a few compact and light-weight elements and components that only need a minimum of maintenance. Modern designs are characterised by a highly efficient use of the properties of the material. If modern calculation procedures on service strength taking into account adequate safety factors are not successful, it may be necessary, in individual cases, to perform a series of Wöhler's fatigue tests for carrier components and thereby verify the components' behaviour under the loads occurring in ropeway operation.

It is very costly to verify components by a series of Wöhler's fatigue tests with a specific examination of the components behaviour at breakdown or cracking, as is done in the automotive and aircraft industries. Such sophisticated methods taking into account the dynamic behaviour lead to further optimised, compact designs.

D Important questions

Important questions are posed to:

a) the ropeway design engineer:

- Are all the components designed in a way so that any damages or cracks can be detected easily, early and with simple methods?

- Which information has to be given to the ropeway operator so that the shock absorbing elements will be replaced in the funnel-shaped guide rail at the station entry in time?
  How is the ropeway operator able to check that the damping elements for cushioning lateral oscillations at the station entry sufficiently function?

- Which information has to be given to the ropeway operator so that intolerable loads caused by lateral oscillations can be avoided?
  Were experiments performed in that context in order to investigate the influence of reduced rope speeds on the stress and strain acting on carrier components upon station entry?

- If the tolerances of wear at ropeway parts and the tolerances of the adjustment of rails were determined, have the special forces been taken into account which appear when the carrier is forced into the "section of stiff fixation" at the station entry?

b) the ropeway operator:

- Have the conditions been determined under which the operator has to reduce the ropeway speed during normal operation?

- Does the operating staff comply with the tolerances of wear on ropeway parts and the tolerances of adjustment specified by the manufacturer?
  Does the operating staff regularly check the station entering procedures for inadmissible shock effects?

E Summary

The real strain in the carrier components depends on highly complex, inter-related factors occurring upon station entry. Depending on the stiffness of the guard rails and their suspensions, the forces may take different paths in the grip device.
In this situation high dynamic forces are activated by high carrier masses and high transportation speed. Traditional laboratory fatigue tests do not cover this situation of a complex flow of forces.
The efficiency of devices damping lateral oscillations upon station entry was not improved to the same extent as the lateral oscillation energies increased due to higher carrier masses and travelling speeds. Detailed experimental investigations need to be performed for carriers entering stations.

Verification procedures for the carrier components, as they are conventionally applied today, do not sufficiently consider the special effects and conditions which occur as ropeway carriers pass through the station entry. The verification of service strength at the carrier components based on a uniaxial laboratory fatigue test, which has been practised over several decades, is no longer sufficient with respect to development trends in the field of modern ropeway installations. Especially the use of compact and light-weight designs must be taken into account by a detailed calculation method considering carefully reflected safety factors.

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Dipl. - Ing. Hans Ulrich Zbil
TÜV Süddeutschland Bau und Betrieb GmbH
Zentralabteilung Seilbahnen
Westendstraße 199, D - 80686 München
Tel.: + 49 (0)89 - 5791 - 1971, Fax: + 49 (0)89 - 5791 - 2022
E-mail: Hans-Ulrich.Zbil@bt.tuevsued.de