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High Speed - High Rise Elevators. A Quick Guide

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***Abstract*: This paper highlights the new trends in high-speed elevators and discusses the impact in modern buildings' design, construction, and operation. Additionally, it focuses on the technological innovations and how these are implemented in high-speed elevators. All these implementations are resulting into a modern, comfortable, safe and energy efficient vertical transportation. As these implementations are penetrating, the overall calculations are affected, and new parameters are inserted to an integrated application.**

Keywords: Energy efficiency, roping, safety components, European Norms

INTRODUCTION

The modern trend in city built, that includes tall buildings, would not be feasible without the development of faster and more reliable elevators.
Nowadays the largest metropolitan centers have competed each other in building such buildings which are considered as landmarks that reflect dynamism and financial growth. At the same time, another competition takes place, the one that has to do with the fastest elevator. It seems that Olympic Games moto “citius, altius, fortius” is a constant pursuit of every human activity.
At the present paper we are dealing with the modern trends at high speed – high rise elevators and we are presenting the features that differentiate them from conventional ones, as well as the calculations in such elevators according to the European Norm 81-50:2014 (EN 81-50: 2014).

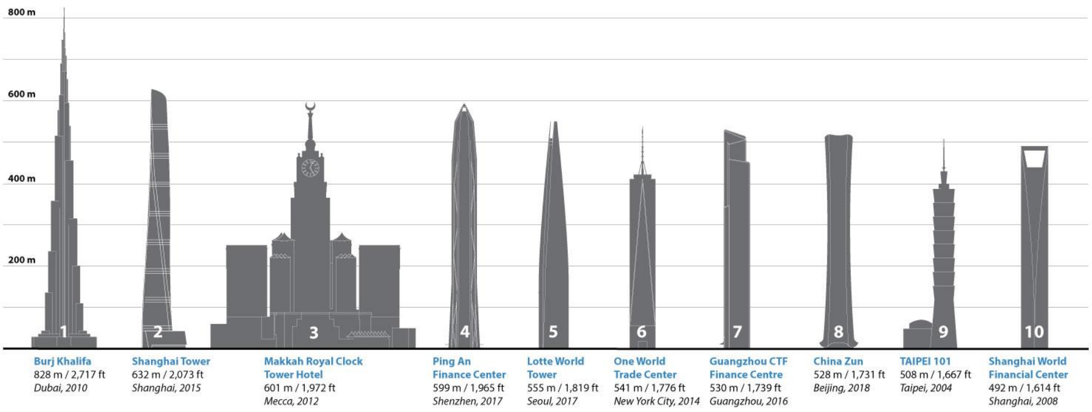
CHAPTER 1. TALL BUILDINGS - HIGH SPEED ELEVATORS

According to the Skyscrapers Center Institute, the tall buildings are discriminated in 3 categories based on their height (h):

Talls	h<300m
Supertalls	h>300m
Megatalls	h>600m

Nowadays, there are 3 Megatalls and 151 Supertalls buildings worldwide.
The following chart shows the 10 tallest-to-tip buildings worldwide, with descending classification as they are referred to the cbtuh.org. The tallest to-tip building is Burj Khalifa, Dubai. Its height reaches 828 meters while the highest floor is on 585 meters. Far East and Middle East countries have plenty of tall buildings while USA follows that pace and Europe lags.
Nowadays, the fastest elevator has a speed of 20 m/s. This elevator is installed by Hitachi in 2016, in the skyscraper CTF Financial Center (#7), 530 m high, located in Guangzhou, China. It needs 43 seconds to travel from the lowest to the highest (95^{th}) floor. The previous record was held by Taipei 101 (#10) elevator, in Taiwan which is travelling with 16, m/s (60,6 km/h) speed, whereas inside the tallest building (Burj Khalifa), the fastest elevator travels at speed of 10 m/s. Elevators at a speed higher than 1 m/s require technologically enhanced parts to meet the demands of a normal operation.
The tests of such improved parts must take place in real conditions. Therefore, the large elevator companies invest in elevator test towers constructions.

Figure 1.1: Top 10 tallest to-tip buildings [1]



Source: https://www.ctbuh.org/

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Table 1.1: The tallest Elevator Test Towers worldwide

A/A	Name	Location	Country	Company	Height (m)	Further notes
1	Thyssenkrupp Testturm	Zhongshan	China	Thyssen	248	Completion year: 2018
2	Thyssenkrupp Testturm	Rottweil	Germany	Thyssen	246	30m of 246 are in deep
3	G1 Tower	Hitachinaka	Japan	Hitachi	213,5	Elevator test with speed up to 18 m/s
4	Hyundai, Asan' Tower	Icheon	South Korea	Hyundai	205	Elevator test with speed up to 18 m/s
5	Mitsubishi, Solaé Test Tower	Inazawa	Japan	Mitsubishi	173	This is the Test Tower with the most floors (40)
6	Shanghai New Research Tower	Shanghai	China	Hitachi	172	
7	Nippon-OTIS Shibayama Test Tower	Shibayama	Japan	Otis	154	The tallest Test Tower between 1998 and 2004
8	National Lift Tower	Northampton	UK	Express Lift Company / Otis	127,45	Since 2015, it is used as the largest drainage test tower
9	OTIS Bristol Research Center	Bristol, Connecticut	ΗΠΑ	Otis	117	
10	Basarab Tower	Bucharest	Romania	-	114	Currently, this tower does not belong to any company. This was built in 1988, for testing the elevators that were going to be installed in "People's House"
	KONE's Tytyri Elevator R & D cer	Lohja	Finland	KONE	333 (in depth)	This Test Tower is completely underground. Elevator test with speed up to 17m/s

Source: https://de.wikipedia.org/wiki/Aufzugstestturm

CHAPTER 2. ELEVATORS' MODERN TRENDS

2.1 Elevators of 1:1 (direct) and 2:1 (inderect) roping

Roping (r) is the ratio of the traction sheave's speed to the speed of the travelling car.

$$r = \frac{U_{sheave}}{U_{car}} = \frac{Sheave\ speed}{Car\ speed}$$

The roping ratios that are commonly used by elevators are 1:1 (direct roping) or 2:1 (indirect roping, 4:1 rarely used).

u_{sheave} = linear speed of traction sheave
u_{car} = lift car speed
P = weight of lift car, chassis, and car door
Q = payload
W = counterweight = $P + \frac{Q}{2}$
T_1 = rope stress at the car lift part
T_2 = rope stress at the counterweight part
F = $T_1 - T_2$ = suspended load
S = $T_1 + T_2$ = static load

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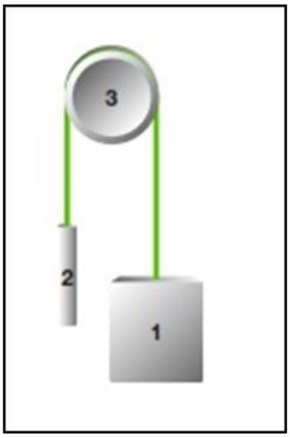
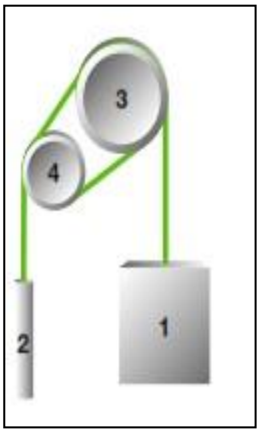
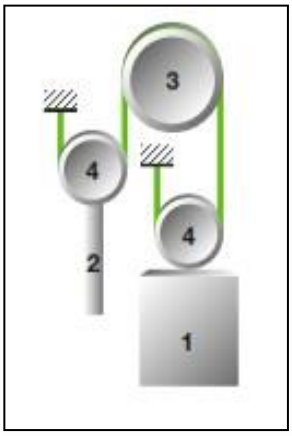
Table 2.1: Roping Types

Table 2.2:

Roping	Roping Illustration		Conditions
1:1 Direct With single or double wrap			$u_{sheave} = u_{car}$ $T_1 = P+Q$ $T_2 = W = P + \frac{Q}{2}$ $F = T_1 - T_2 = \frac{Q}{2}$ $S = T_1 + T_2 =$ $2P + \frac{3Q}{2}$
2:1 Indirect			$u_{sheave} = 2 * u_{car}$ $T_1 = \frac{P+Q}{2}$ $T_2 = \frac{W}{2} = \frac{P}{2} + \frac{Q}{4}$ $F = T_1 - T_2 = \frac{Q}{4}$ $S = T_1 + T_2 =$ $P + \frac{3Q}{4}$

Advantages – Disadvantages of 1:1 and 2:1 roping

A/A	Comparison criterium	1:1	2:1	Notes
1	Ropes' tensile stress	High	Low	2:1 roping has an advantage, due to weight of lift car and counterweight are distributed between the 2 parts of the rope
2	Rope bending	Low	High	2:1 roping falls short due to the multiple use of pulleys
3	Static load at sheaves center	Heavy	Light	2:1 roping has an advantage due to weight of lift car and counterweight are distributed between the 2 parts of the rope
4	Motoring machine stress by suspended load	High	Low	2:1 roping has an advantage due to weight of lift car and counterweight are distributed between the 2 parts of the rope
5	Motor's efficiency	Less efficient	More efficient	2:1 roping has an advantage due to the double rotation speed that requires lower gear ratio
6	Friction's safety limit e^{fa} in case of emergency braking condition (2nd traction condition)	High	Low	2:1 roping falls short due to lower friction (f) coefficient, because of the higher rotation speed.
7	Possibility of lift car's undesirable suspension when counterweight is stalled (3rd traction condition)	Low	High	2:1 roping falls short, due to smaller T_1/T_2 ratio because the lift car load is distributed between the 2 parts of the rope
8	Empty car weight	Light	Heavy	2:1 roping falls short, because to meet the requirements of the 3rd slip condition (EN 81:50), it is required heavier lift car to be installed

9	Compensation chain weight	Not necessary	Necessary	2:1 roping falls short because it requires the use of double weighted compensation chain compared to 1:1 roping
10	Smooth start and stop	Less	More	2:1 roping has an advantage, because the lower suspended load (F) and the use of VVVF inverters provide less electric lag to the motoring start. As a result, there is a smoother start to the motoring machine.
11	Cost	Low	High	2:1 roping requires more expensive equipment

2.2 Machine Room Less Elevators (MRL)

In such elevators, the motoring machine is placed at the headroom of the well. Therefore, there are no space requirements for machine room. To overcome the problem of space narrowness inside the well, gearless motoring machines are developed. The roping ratio is usually 2:1. The first MRL elevator developed in 1996 by KONE (Finland). This model named KONE Monospace [2],[3].

MRL elevators are applied to low and middle rise. At high rise elevators it is preferred to create a separate machine room space, however it is use gearless motoring machines.

Table 2.3: Advantages/Disadvantages of MRL Elevators

A/A	Comparison criterium	Conventional Elevator	MRL Elevator	Notes
1	Machine room space requirements	YES	NO	MRL has the advantage because the machine is located inside the well
2	Headroom of the well	Low	high	MRL has a disadvantage, because the headroom of the must be at least 30 cm to be placed the motoring machine
3	Difficulty in maintenance and repairments	Low	High	MRL has a disadvantage due to the space narrowness
4	Guide rail fatigue	Low	High	MRL has a disadvantage because the motoring machine is hanged upon the guide rails causing an additional compressive load

2.3 New types of elevators

New advanced elevators have been developed for more efficient passenger service in tall buildings. These new advanced types are:

- Double Deck Elevators, where 2 separate cars are connected, and they are travelling inside the same well. In this way, the capacity of the elevator is doubled. These cars are not integral, but they can be divided to run independent travels inside the well
- Antiseismic elevators which are detecting the early imperceptible earthquake vibrations that occur within 7 to 30 seconds before the main vibration (P waves). This function leads the passengers to leave the car safely at the closest floor. Then and if the S waves do not exceed a predefined limit, the elevator is set to operational mode.
- Green Elevators, with high energy efficiency. This type of elevators saves significant amount of energy consumption, has low carbon footprint, and returns energy to the indoors energy requirements of the building.
- Jump Elevators, which are useful during the construction phase of a building. That is because the machine room of the elevator can slide to the guide rails and rise the same time with the rise of the building construction.
- Ultra-high speed elevators are shaped aerodynamically to reduce the air resistance, the noise, and the vibrations. Also, aerodynamic shape of the car is useful for the effective setting of the atmospheric pressure inside them to avoid the pain in the passengers' ears.

Smart traffic innovations are applied to modern elevators to achieve shorter standby and travel time. These are:

- Destination Selection System where the passengers are obliged to choose their destination floor before their boarding to the car. Then, an advanced software informs them to go to the more appropriate car for their destination. This innovation causes significant time saving to passengers' service.
- Express elevators which are leading only to specific floors that are defined as sky lobbies. Then, the passengers are transferred to other elevators to reach their destination.

Currently are testing elevators without ropes. At these modern types of elevators, the traction would be magnetic. Moreover, the rotary motors will be replaced by 4 linear motors with permanent magnets, placed to the 4 corners of the elevator cars. This technology is already applied to ultra-high-speed trains.

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CHAPTER 3. PARTS THAT ARE DIFFERENTIATED IN HIGH-SPEED ELEVATORS

3.1 Motoring Machine

A major technological innovation of our times is considered the gearless motoring machine, which is used at high-speed elevators. At these, the traction sheave is connected in-line to the motor, removing the need of reduction gear use. As a result, there are no energy losses, no noise caused by reduction gear, power savings**,** less volume and weight.

Table 3.1: Comparison between geared and gearless elevator motoring machines

A/A	Comparison in	Geared motoring machines	Gearless motoring machines	Notes
1	Reduction gear	YES	NO	
2	Motor type	Asynchronous induction motors with short-circuited rotor	Permanent Magnets Synchronous Motors	
3	Motor's RPM	1500 rpm	50 – 200 rpm	
4	Use of inverter	Optional	Mandatory	
5	Transmission	Angular 90	Linear	
6	Weight, volume, noise, power consumption	High	Low	
7	Efficiency	Low	High	Gearless machines have higher efficiency due to the absence of reduction gear, the use of PMSM and VVVF inverters
8	Longevity	Low	High	Gearless machines have greater longevity because they provide higher torque combined with lower RPMs.
9	Cost	Low	High	

3.1.1 Permanent Magnet Synchronous Motors (PMSM)

Gearless machines are using exclusively PMSM, which can rotate with low-speed equal to the traction sheave's speed. These are multi-polar motors with 3-phase current field coils at the stator only, while in rotor there are permanent magnets instead. They are considered as a great technological innovation and their development is an aftermath of the discovery of new strong neodymium magnets.

Table 3.2: PMSM electric motors vs asynchronous motors

A/A	Comparison	PMSM	Asynchronous motors	Notes
1	Efficiency	High	Low	PMSMs have higher efficiency because they are equipped with permanent magnets rather than three-phase windings. As a result, PMSMs have less resistance heating and less magnetic losses.
2	Energy savings	High	Low	PMSMs have an advantage due to higher efficiency.
3	Motor speed response to inverter variations	Fast	Slow	PMSMs have an advantage because they are electrically self-excited.
4	Noise and vibrations	Small	Big	PMSMs are operating at lower RPMs.
5	Operation in high temperature	Unsustainable	Sustainable	PMSMs fall short because permanent magnets' specifications are massively affected by high temperature.
6	Cost	High	Low	Permanent magnets are costly and generally there is a limited production of PMSMs.

3.1.2 VVVF Inverters

PMSMs are driven exclusively by VVVF inverters (Variable Voltage Variable Frequency), which are setting accurately the motor's rotation speed and torque by modifying properly the frequency and the voltage of the power supply [4]. Therefore, VVVF inverters achieve smooth motor operation both in acceleration and deceleration. Furthermore, VVVF inverters recycle energy, because in generating mode the generated power is destined for inside-building power needs.

The use of VVVF inverters provides to the motors the following advantages

Table 3.3: VVVF advantages

A/A	Advantage	Reason
1	Reduction of motor's heat stress in start mode	Reduced inrush current
2	Reduction of motor's heat stress in operation mode	When the motor is in generating state, the generated power is consumed by an additional resistance, or it is destined for inside-building power needs instead of stressing motor's three-phase windings
3	Increasing the overall number of starts per hour	Because of motor's overall heat stress reduction
4	Correction of the power factor (cosφ=1)	

Furthermore, the use of VVVF inverter offers the whole mechanical installation of the elevator the following advantages:

- Significant energy savings
- Lift car's smooth start and stop
- Better lift car's floor levelling
- Reaching of high speeds during lift car's travel by increasing power frequency (f≥50Hz)
- Reduction of reducer's mechanical fatigue
- Less use of motor's brakes leads in less brake abrasion
- Human rescue through UPS use [5]

3.2 Ropes (Wire Ropes)

The following symbols must be used for the standardized rope designation in the rope certificate [6]:

Rope specs: **13 8 x 19 S – NFC 1370/1770 U sZ**

Nominal Diameter (13mm)

Number of strands (8 strands)

Number of wires per strand (19 wires)

Strand construction (S = Seale)

Core type (NFC = Natural Fiber Core)

Rope grade outer wires/inner wires (N/mm^2)

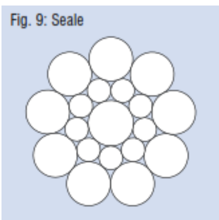
Wire finish (U = Ungalvanized)

Lay (s=lay left hand)

3.2.1 Rope's construction type:

Seale (S) 1-9-9: They have 3 layers consisted by different cross section wires at each layer. However, every wire in a single layer has the same cross section with the other wires that are included in the same layer. The outer layer has thicker wires which are more resistant to abrasion but not to bending fatigue. This rope type is used when it is necessary to last longer rather than not get abrased (e.g., for Elevators without many pulleys)

Figure 3.1



Source: PFEIFER DRAKO, Elevator Products, 2019

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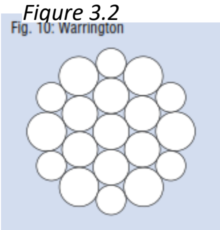
Warrington (W) 1-6-6-6:
The outer layer wires are alternately thick and thin. This feature gives the rope higher flexibility and resistance to bending stress, however it deprives resistance to abrasion compared to Seale ropes. These ropes (W) are used when it is necessary to resist to fatigue bending rather than to outer layer abrasion (e.g., for elevators with many small diameter pulleys or inverse bending pulleys)

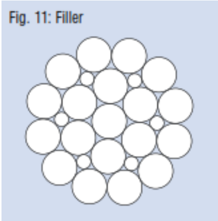
Figure 3.2



Source: PFEIFER DRAKO, Elevator Products, 2019

Filler (F) 1-6-6-12: They combine the advantages of S and W ropes. They include thin wires for higher flexibility, larger fill factor for higher resistance to fracture and thick wires in the outer layer for better traction with traction sheave. Such wires are used at high-speed elevators, where little elongation, large fill factor, higher flexibility, breaking, and flexural strength are required.

Figure 3.3



Source: PFEIFER DRAKO, Elevator Products, 2019

3.2.2 Elevator ropes for tall buildings

Mid and/or high-rise elevators must deal with the following problems:
Ropes' elastic elongation: During passengers' entrance in the elevator, takes place an undesirable drop of the lift car because of the ropes' elastic elongation.
Ropes' plastic elongation (Permanent elongation): Plastic elongation occurs due to the constant tensile that the ropes are submitted. That's because of the weight of lift car and counterweight. Even at the early operation of an elevator, the ropes are elongated plastically
and a after a period, the elongation is so intense and as a result the counterweight drops on the buffer. At this point, it is required to cut part of the ropes. This task is expensive and requires immobilization of the lift car.

3.2.3 Rope Untwist

During the elevator's installation in a tall building, it is possible for the ropes to get untwisted due to their own weight. The untwisted ropes have less resistance to abrasion and their life cycle is significantly decreased. The untwist should be clear and distinguishable. Therefore, the ropes in tall buildings have a colored line drawn along the rope. The manufacturers of ropes constitute that the untwist should not exceed the ½ of a full round every 10m of a rope. Lang type ropes are more liable to such untwist because the individual wires are wrapped around the center of the rope in one direction.
Ropes with the proper specifications and requirements are used in tall buildings. Steel wire core ropes are preferred in this case due to their higher breaking strength and less plastic elongation.

3.3 Compensation chains

The force resulting from the mass of the ropes, acts variably, because it acts either on the part which suspends the lift car or on the part which suspends the counterweight. We do not often concern about the compensation of this variable force in conventional elevators, because it is considered negligible. However, in high rise elevators (>30m) the mass of the ropes is so significant we cannot ignore it. Thus, it is necessary to compensate it.
Compensation chains are used for this purpose. They are installed to connect the down area of the lift car with the down area of the counterweight. For this connection are used riveted tensioning pulleys at the bottom of the well.
According to EN 81-20 5.5.6, for nominal speeds that exceed 3 m/s, it is obligatory to compensate the weight of the suspension ropes [7]. For lower speeds, such means are optional. For lifts whose rated speed exceeds 3,5 m/s there shall be an anti-rebound device as well.
Compensation chains are covered with a flexible plastic PVC material, to insulate the noise of their movement. The choice of the appropriate compensation chain is based on the weight per meter which is desirable to be identical with the total suspension ropes' weight per meter. At 2:1 roping, the weight of the compensation chain should be twice as much the one used for the 1:1 roping.

3.4 Slide guides

During the lift car travel across the slide guides, sometimes it is observed undesirable vibrations, sudden unexpected movement, and noise due to guides' misalignment. At high elevators, these imperfections impact drastically, while in conventional elevators they rarely lead in irreversible situations. Furthermore, the tall buildings are susceptible to climate conditions. In high winds, some high-rise buildings could sway as much as 45cm off center, for a total sway of 1 meter. Extreme temperature variations cause expansion and contraction of the building as well as earthquakes can make the deviate from the vertical line [8]. Thus, the more the structural elements of a building are suffering, the more serious impact that have to lift's installation misalignment.
That is the reason why in high-rise and high-speed elevators are applied roller guides. An elevator car navigates between a pair of rails that are attached to the structure of the building.
The wheels of a guide surround the rail on three sides, helping to control side-to 'side and front-to-back movement. These rollers include three or six roller tyres which are laminated by neoprene rubber. This design has been special engineered to dampen noise and vibration. Moreover, they are spring-loaded to compensate for unbalanced cars or misaligned conditions.

3.5 Mechanical Safety Components

3.5.1 Safety Gear - OverSpeed Governor (OSG)

At high-speed elevators it is required the use of progressive safety gears, both for lift car and counterweight, according to the accepted rule of EN 81-20 [7].

- progressive safety gear for lift car when u > 0,63 m/s
- progressive safety gear for counterweight when u > 1 m/s

Safety gear for counterweight can be replaced by:

- A safety gear for lift car that triggers also in the ascending direction
- A safety device for rope braking
- A safety device for sheave or sheave's axis braking

According to EN 81-20 [7], for progressive safety gear the average retardation in the case of free fall of the lift car with rated load or the counterweight or the balancing weight shall lie between 0,2 g and 1 g (5.6.2.1.3). So, in case that the nominal speed of the lift car is u = 3m/s and the deceleration provided by the safety gear is γ = 0,6g = 6m/s^2, then:

- Braking time is $t = \frac{u}{\gamma} = \frac{3}{6} = 0{,}5$ sec
- Braking space is $S = \frac{u^2}{2\gamma} = \frac{3^2}{2*6} = 0{,}75$ m

The overspeed governor (OSG) should be fly ball type and should be activated when the speed of the lift car exceeds the limit of $1.15u_n$.

When OSG triggers in the up direction, then the tension weight should be bigger compared to the weight that is used for down direction. The bigger the tension weight, the less the rope slipping during the OSG trigger. OSG ropes are fatigued in greater tension; thus, they need to have greater braking strength.

3.5.2 Buffers

At high-speed elevators are used energy dissipation buffers. These are hydraulic buffers consisted of one piston rod, one metallic spring and a cylinder, divided in 2 tubes (inner and outer cylinder) which are communicating through small, drilled holes in the wall of the tube. When the piston rod is pressed, the hydraulic fluid is forced out through the hole and is collected to the outer cylinder. After the buffer has impacted and the piston rod is released, the compressed spring returns the piston rod back to the starting position.

High speed elevators require deeper well than usual, for buffers use [9]. Moreover, for ultra-high-speed elevators are use 3-stage telescopic buffers.

CHAPTER 4. CALCULATIONS OF LIFT COMPONENTS ACCORDING TO EN 81-50

4.1 Guide rail calculation

Guide rails should be dimensioned according to the worst-case scenario i.e., lift car loaded with its full payload. When compensation chain is used, then its weight should be considered in the overall calculations. However, payload is not static, so it is more accurate to consider that it acts off-center of the lift car. That is the reason why EN 81-50 defines 2 different applications of the payload's position in the lift car [10].

1) Payload Q lays $\frac{1}{8}D_x$ off center
2) Payload Q lays $\frac{1}{8}D_y$ off center

For each one of the 2 applications there are 3 conditions that should be examined.

<u>1. Safety gear activation</u>

It is considered that safety gear is triggered, so the overall load applied to the guide rails is multiplied by K_1 factor.

<u>2. Regular operation</u>

It is considered that lift car is travelling with steady speed. The overall load applied to the guide rails is multiplied by K_2=1,2.

<u>3. Car lift load</u>

It is considered that car lift is stopped at a floor level, empty, while the 40% of payload is applied at the car lift entrance.

These conditions are examined to evaluate if the resulting tensions are lower than the maximum permissible tension of the guide rails' material ($\sigma_{max} = 205\,{}^{N}/_{mm^2}$).

1) Bending stress σ_y, Y axis
2) Bending stress σ_x, X axis
3) Compression stress σ_κ and tension stress
4) Combined bending and compression/tension stress and evaluation if it is $\leq\sigma_{perm}$
5) Flange bending stress and evaluation if it is $\leq\sigma_{perm}$
6) Guide rails δ_x and δ_y buckling stress. Maximum permissible deflection = 5mm

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4.2 Calculation of minimum permissible safety factor on suspension ropes

EN 81-50 refers to the minimum permissible safety factors on suspension ropes, considering the specificities that any installation might have [10]:

- The total number of traction sheaves (N_t) and the total number of pulleys (N_p)
- Traction sheaves and pulleys' diameter (D_t, D_p)
- The number of pulleys with simple (D_{ps}) or reserved bends (D_{pr})
- The value of the groove angle γ
- The rope's diameter (d)

EN-50 suggests the method of equivalent number (N_{equiv}) of pulleys, following the steps [10]:

1. Estimation of equivalent number of traction sheaves $N_{equiv(t)}$, considering the value of the groove angle γ (Table 5, par. 5.12.2.2, EN 81-50).
2. Calculation of
   $K=(\frac{Dt}{D_p})^4 = (\frac{Traction\ sheave\ diameter}{Average\ pulley\ diameter})^4$
3. Calculation of the total equivalent number of pulleys $N_{equiv(p)}$
   $N_{equiv(p)} = K * (N_{ps} + 4* N_{pr})$
4. Calculation of the total equivalent number of pulleys and sheaves N_{equiv}
   $N_{equiv} = N_{equiv(t)} + N_{equiv(p)}$
5. Calculation of $\frac{Dt}{d} = \frac{Traction\ sheave's\ diameter}{suspension\ rope's\ diameter}$
6. Final calculation of safety factor S_f, in accordance with N_{equiv} and ratio derived from Fig 10, par. 5.12.3, EN 81-50

From the previous process, we reach to the following conclusions:

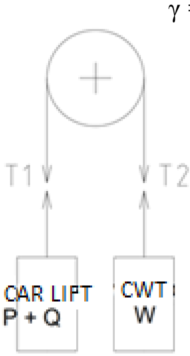
- A traction sheave equals to bigger number of equivalent pulleys compared to a regular pulley. That is because the overall tension in suspension rope is greater in traction sheaves because it is a result of bending stress and wear due to slipping.
- A reversed bended pulley has 4 times larger number of equivalent pulleys from a simple bended pulley.
- The D_t/D_p is affected heavily as the pulleys' diameter gets decreased. That is because in the calculation process this ratio is raised in the 4^{th} exponent.
- The minimum S_f gets increased as N_{equiv} gets increased and as ratio D_t/d gets decreased.

4.3 Traction calculation

4.3.1 Tension calculation at both parts of suspension rope when car lift is accelerating or decelerating

The suspension ropes' traction occurs if the condition $\frac{T_1}{T_2} \leq e^{fa}$ is true.

Where T_1 = rope stress at the car lift part
T_2 = rope stress at the counterweight part
e = 2,71 (natural logarithm's base)
α = angle of wrap of the ropes on the traction sheave
f = friction factor (For sheaves with V groove: $f = \frac{\mu}{sin\frac{\gamma}{2}}$)
μ = friction factor between suspension ropes and traction sheave
γ = groove angle



- The value of slipping limit (e^{fa}) is only affected by angle of wrap a of the ropes and the friction factor f.
- The traction or the slipping of the ropes depends in the tension ratio $\frac{T_1}{T_2}$ of the 2 parts of the ropes.

When the elevator is moving with steady speed or it is stopped, the T values are considered as follows:
$T_1 = (P+Q) *g$ (rope stress at the car lift part, Nt)
$T_2 = W*g$ (rope stress at the counterweight part, Nt)
When the car lift is moving up with acceleration a, then from the 2nd Newton's Law it is:

- $T_1 – (P +Q) *g = (P + Q) *a => T_1 = (P + Q) (g + a)$
- $W*g - T_2 = W*a => T_2 = W*(g - a)$

Table 4.1: Possible situations of car lift movement and the resulting stress values

Situation \ Parts	Car lift part T_1	Counterweight part T_2
Moving up with acceleration	$T_1 = (P+Q)(g+a)$	$T_2 = W(g-a)$
Moving up with deceleration	$T_1 = (P+Q)(g-a)$	$T_2 = W(g+a)$
Moving down with acceleration	$T_1 = (P+Q)(g-a)$	$T_2 = W(g+a)$
Moving down with deceleration	$T_1 = (P+Q)(g+a)$	$T_2 = W(g-a)$

It is observed that when the car lift is moving with acceleration or deceleration the stress that is acted by the masses of car lift and counterweight, they are simulate artificial gravity (g±a) rather than real g.

4.3.2 Evaluation of traction in traction sheave

When a lift is planned to be installed, the traction examination is fundamental. The traction condition is $\frac{T_1}{T_2} \leq e^{fa}$.

Where:

- T_1, T_2 are the forces in the portion of the ropes situated at either side of the traction sheave
- α is the angle of wrap of the ropes on the traction sheave
- f is the friction factor (f = $\frac{\mu}{sin\frac{\gamma}{2}}$)
  - μ is the friction between the ropes and the sheave
  - γ is the groove angle

Traction should be tested at the following conditions through the evaluation of T_1/T_2 ratio:

1st condition: Lift car in the well with 125% of the rated load.

2nd condition: Emergency breaking condition. Traction should be ensured in two sub-conditions.

- Lift car descending at the lowest point of the well, loaded with 100% of the rated load and decelerating due to emergency break.
- Lift car ascending at the highest point of the well, empty and decelerating due to emergency break.

3rd condition: Counterweight stalled condition

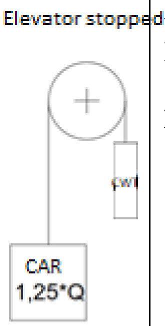
These 3 traction conditions are represented in the following table for both direct and indirect roping. In every table we examine additionally the use of compensation chain which is necessary for high speed – high rise elevators.

It is worthy to be noted that the use of compensation chain improves the traction in every condition and in both types of roping.

The dynamic and kinematic features of traction or slipping are differentiated in elevators with indirect roping because:

- The moving speed of the suspension ropes is double to the moving speed of the car lift
- The deceleration of the suspension ropes is double to the deceleration of the car lift, in case of emergency breaking
- The masses of car lift and counterweight are acting by half at the rope part stress.

Evaluation of traction in direct roping

	Figure	Description	Rope Tension (without compensation)	Rope Tension (with compensation)	Requirement
1 condition μ = 0,10	 	Car lift is stopped at the lowest floor, loaded with the 125% of the payload	T_1 = (P+1,25*Q)*g + M_{rope}*g T_2 = W*g	T_1 = (P+1,25*Q)*g + M_{rope}*g T_2 = (W+ M_{comp}) g	Traction $\frac{T_1}{T_2} \leq e^{fa}$

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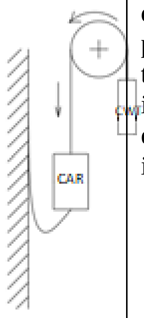
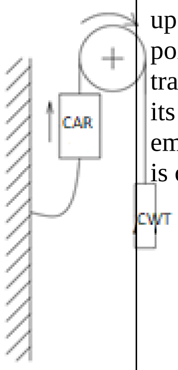
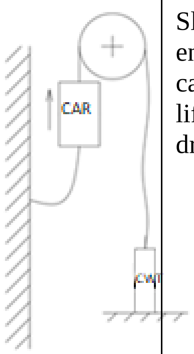
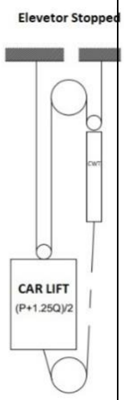
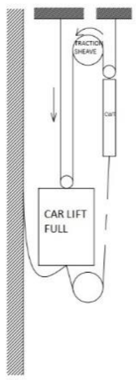
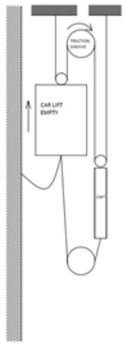
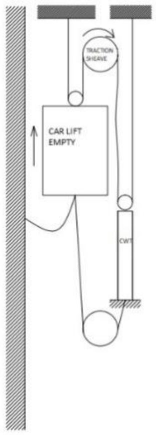
Vol. 10 Issue 11, November-2021

2.1 condition $\mu = \frac{0,10}{1+\frac{u}{10}}$		Car lift is moving down to the lowest point of the overall travel, loaded with its full payload and emergency braking is occurring	$T_1 = (P+Q)*(g+a) + M_{rope}*(g+a)$ $T_2 = W*(g-a)$	$T_1 = (P+Q)*(g+a) + M_{rope}*(g+a)$ $T_2 = (W + M_{comp})(g-\alpha)$	Traction $\frac{T_1}{T_2} \leq e^{fa}$
2.2 condition $\mu = \frac{0,10}{1+\frac{u}{10}}$		Car lift is moving up to the highest point of the overall travel, loaded with its full payload and emergency breaking is occurring	$T_1 = (P+M_{cable})*(g-a)$ $T_2 = W*(g+a) + M_{rope}*(g+a)$	$T_1 = (P + M_{cable} + M_{comp})*(g-\alpha)$ $T_2 = W*(g+a) + M_{rope}*(g+a)$	Traction $\frac{T_2}{T_1} \leq e^{fa}$
3 condition $\mu = 0,20$		Slipping must be ensured, just for the car lift not to be lifted and be dropped sharply.	$T_1 = (P+M_{cab})*g$ $T_2 = M_{rope}*g$	$T_1 = (P + M_{cab} + M_{comp})*g$ $T_2 = M_{rope}*g$	Traction $\frac{T_1}{T_2} \geq e^{fa}$

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 10 Issue 11, November-2021

Evaluation of traction in indirect roping

	Figure	Description	Rope Tension (without compensation)	Rope Tension (with compensation)	Requirement
1st condition $\mu = 0,10$		Car lift is stopped at the lowest floor, loaded with the 125% of the payload	$T_1 = \frac{P + 1.25Q}{2} * g + M_{rope} * g$ $T_2 = \frac{W}{2} * g$	$T_1 = \frac{P + 1.25Q}{2} * g + M_{rope} * g$ $T_2 = \frac{W+M_{count}}{2} * g$	$\frac{T_1}{T_2} \leq e^{fa}$
2.1 case $\mu = \frac{0,10}{1+\frac{2u}{10}}$		Car lift is moving down to the lowest point of the overall travel, loaded with its full payload and emergency breaking is occurring	$T_1 = (\frac{P+Q}{2})*(g+a) + M_{rope}*(g+2a)$ $T_2 = \frac{W}{2}*(g-a)$	$T_1 = (\frac{P+Q}{2})*(g+a) + M_{rope}*(g+2a)$ $T_2 = \frac{W+M_{count}}{2}*(g-a)$	$\frac{T_1}{T_2} \leq e^{fa}$
2.2 case $\mu = \frac{0,10}{1+\frac{2u}{10}}$		Car lift is moving up to the highest point of the overall travel, empty load and emergency breaking is occurring	$T_1 = (\frac{P+Mcab}{2})*(g-a)$ $T_2 = \frac{W}{2}*(g+a) + M_{rope}*(g+2a)$	$T_1 = \frac{P+M_{cab}+M_{count}}{2}*(g-a)$ $T_2 = \frac{W}{2}*(g+a) + M_{rope}*(g+2a)$	$\frac{T_2}{T_1} \leq e^{fa}$

3rd case μ = 0,20		Slipping must be ensured, just for the car lift not to be lifted and be dropped sharply. Motoring machine should not be powerful enough to lift the car lift in this case.	$T_1 = (\frac{P+Mcab}{2})*g$ $T_2 = M_{rope}*g$	$T_1 = \frac{P+M_{cab}+M_{count}}{2}*g$ $T_2 = M_{rope}*g$	$\frac{T_1}{T_2} \geq e^{fa}$

4.3.3 Evaluation of traction in overspeed governor's sheave

The purpose of these calculation is for the OSG's ropes traction to be evaluated. This is necessary, because in case of OSG activation, the ropes must activate the safety gear without slipping.

We name the following symbols:

M_G'= Tension weight (includes OSG sheave and ropes weight)

F_E = Activation force of the safety gear

u_c = car lift's nominal speed

u' = OSG's activation speed (u' = 1,15*u_c)

μ = friction factor between ropes and sheave = $\frac{0,10}{1+\frac{u'}{10}}$

γ = groove angle

f = $\frac{\mu}{sin(\frac{\gamma}{2})}$

α = angle of wrap of the ropes on the sheave, 180° = 3,14 rad

Ropes' traction condition $\frac{T1}{T2} \leq e^{fa}$

We carry out evaluation process whether there is traction in the 2 following situations:

Direction that safety gear acts	Stress in the 2 parts of the ropes	Required tension weight	Required activation force of the safety gear
Down	T_1=M_G'/2 + F_E, T_2=M_G'/2	$M_G' \geq \frac{2F_E}{(e^{fa}-1)}$	$F_E \leq \frac{M_G'}{2}(e^{fa}-1)$
Up	T_1=M_G'/2 T_2=M_G'/2 - F_E	$M_G' \geq \frac{2F_E}{(e^{fa}-1)} e^{fa}$	$F_E \leq \frac{M_G'}{2}(1-e^{-fa})$

It is observed that when safety gear is activated when car lift is moving up, the required tension weight is e^{fa} times bigger to the required tension weight when car lift is moving down.

It is also observed that for given tension weight, the activation force of the safety gear in the up direction must be e^{fa} times smaller than the activation force of the safety gear in down direction.

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