# Using U-Bolt for Fixing the Axle of Elevator Deviation Pulleys

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**Abstract**

_Deviation pulleys are used on the elevator traction machines to ensure given distance between the suspension ropes attached to elevator car and counterweight or/and to increase the number of suspension rope falls (roping 2:1 or 4:1). With simple structure, the u-bolts are used widely to fix the axle of these pulleys. In many cases, these bolts are selected or made approximately and it can lead to inadequate selection. This paper presents some results of research concerning the calculation of u-bolts for above mentioned purpose with goal to ensure elevator safe performance. Different angles of contact between the rope and the traction pulley were considered to estimate their influence on the stress in the u-bolt and the standard bolt, then gives some recommendations when choosing or making u-bolts for fixing the deviation pulley axle._

Keywords: U-bolt, Rope deviation pulley, Elevator

## 1. Introduction

Fig. 1 presents a typical configuration of electric elevator with traction drive. The car and counterweight are connected to each other by the steel ropes through traction and deviation pulleys. The traction pulley is mounted on the output shaft of the motor or the reduction box and transfers power to the ropes, so the car/counterweight can move up and down. The deviation pulleys are mounted on the traction machine to fulfill the given distance between suspension ropes at the car and the counterweight, also on the car/counterweight to increase the number of rope falls, which leads to increase of the rope diameter and dimensions of the traction machine, and also to decrease of the speed of the car (with the same speed of traction shaft, comparing with the case of roping 1:1). For this reason, the configuration (b) in Fig. 1 is used widely for gearless traction elevator (i.e. traction machine without reduction box).

The axle position of the deviation pulleys can be fixed by the bearing housings or by the u-bolts. In the traditional method, the pulley is assembled steady with the axle, and the axle terminals are mounted with the bearing housings and the housings are fixed with the bolts (Fig. 2a). Using of the u-bolts is simpler: the axle is mounted to pulley through bearings and its terminals are steadily fixed to the structure by the u-bolts (Fig. 2b). Because of simple forming and mounting, recently the u-bolts have been used widely in different structures such as rope terminals, automobiles, pipelines, ventilators... Some specific cases of using the u-bolts are analyzed [1, 2], but the method of adequate selection of the u-bolts are not shown.

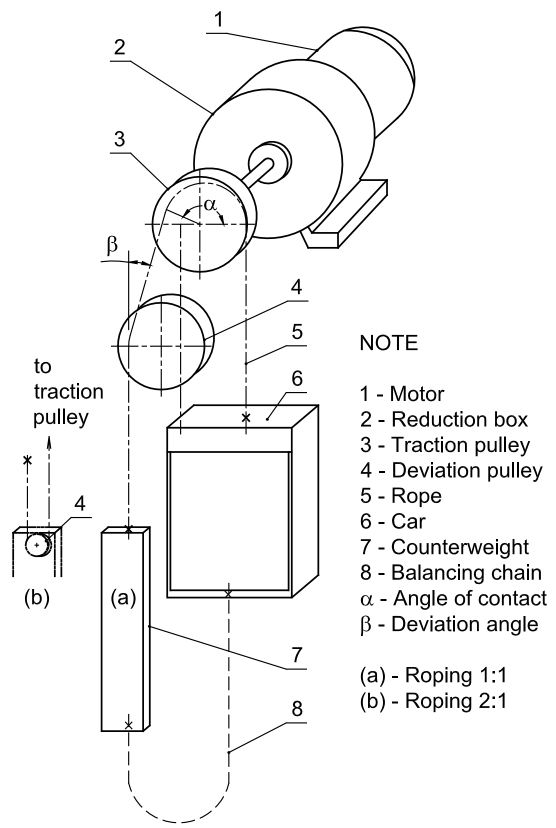


**Fig. 1.** Typical electric elevator with traction drive

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In the present study, the loads and stresses in bolts/u-bolts for both above mentioned cases are analyzed. The angle of contact between the rope and the traction pulley varies from 130 to 170 degrees. The results can help to choose the suitable u-bolts for safe fixing of the axle of deviation pulleys.

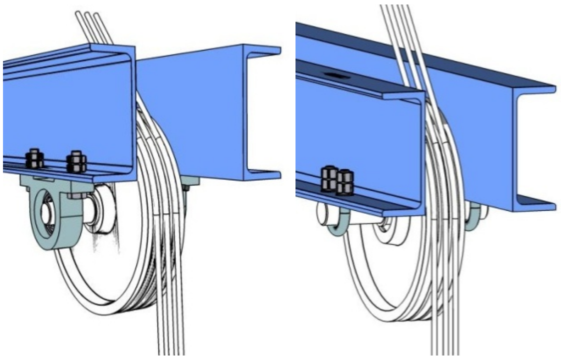
## 2. Loads acting on the bolt and u-bolt connection

The tension forces in the ropes transfer to the bolt or u-bolt connection through the pulley axle as shown in Fig. 3. The total force can be split into 2 components, which are the vertical force *G* and horizontal force *R*. The value of *G* and *R* depend on the magnitude of the rope tension and the angle between ropes falls (angle of deviation $\beta$).

Ignoring the friction in the pulley bearings, the sum of tension forces in the ropes for each fall are both equal to the gravity force of the counterweight (Fig. 3). Then the magnitudes of *R* and *G* are determined by formula (1) below

$$R = G_w \sin\beta; \quad G = G_w(1-\cos\beta \tag{1}$$

The role of the counterweight is to balance the sum of car weight and useful load in order to reduce the required power of the motor and to ensure that the ropes cannot slip on the traction pulley. The angle of contact between ropes and traction pulley $\alpha$ is preselected to avoid slipping between ropes and pulley when the elevator is in service or test conditions, and when the car or the counterweight set on the buffers, the traction force must reduce so the car or the counterweight cannot move [3]. It will prevent the car/counterweight of rising over.



(a) (b)

**Fig. 2.** Fixing the position of the pulley axle

The angle of deviation ($\beta$, radians) depends on the angle of contact by the formula (see Fig. 1)

$$\beta = \pi - \alpha \tag{2}$$

The horizontal force *R* can cause slipping of pulley axle. In order to avoid it, the bolts or u-bolts must be tightened, which leads to occur of clamping force, also called preload. The magnitude of preload *P* must produce enough friction to keep the position of the axle, and can specify by

$$P = \frac{kR}{fz} + \frac{G}{z} \tag{3}$$

Where, *z* is the number of preload points, equals to 4 as shown in Fig. 2; *f* is the coefficient of friction of connection members, and *k* is the safety factor for non-slipping requirement.

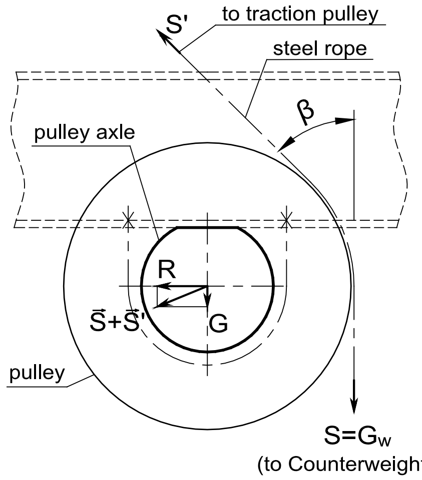



**Fig. 3.** Force acting on the pulley and axle

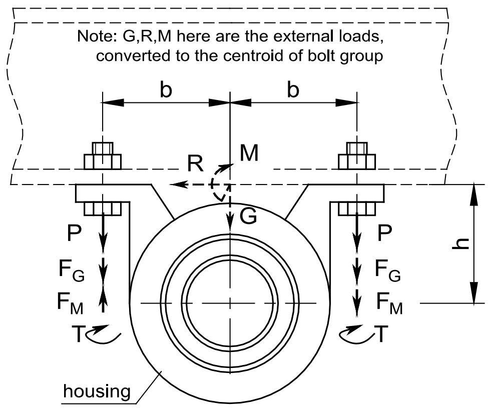



**Fig. 4.** Loads on bolts (standard bolt connection)

Thus, for the case of connection using standard bolts and the pulley is mounted at the middle of the axle, the loads acting to each bolt is shown in Fig. 4. These loads consists of the preload *P*, the portion $F_G$ of external vertical force *G* taken by bolt and the force $F_M$ due to the moment *M* (converted from external horizontal force *R),* and torque moment *T* because of preload [4]. The magnitudes of the loads can be determined as follows

$$F_G = \frac{\chi G}{z}; \quad F_M = \frac{\chi M}{bz}$$
$$M = Rh; \quad T = KdP \tag{4}$$

Where $\chi$ is the stiffness constant of the joint, equal to 0.2 for most bolt (and u-bolt) connection, $d$ is the nominal thread diameter of bolt/u-bolt.

The bolts at the right side in Fig. 4 are the critical ones, and total tension load acting on these is

$$F_{\max} = P + F_G + F_M \tag{5}$$

For the case of using one u-bolt for each terminal of pulley axle, the external loads converted to the centroid of each connection are $R/2$, $G/2$, $M/2$, where $M=R(h+e)$, and because the lower part of the u-bolt plays also the role of clamping member, so the loads acting to the u-bolt can be shown as in Fig. 5. The loads $F_G$ and $F_M$ are specified by

$$\begin{aligned} F_G &= (1-\chi)G/2 \\ F_M &= \frac{R(h+e)/2}{h+r} \end{aligned} \tag{6}$$

Where $h$, $e$ and $r$ are geometric dimensions as shown in Fig. 5.

The calculation diagram in Fig.5 is statically indeterminate, and must solve the problem to find out internal force diagram and then specify the stress in the u-bolt.

Note that the u-bolt is symmetric, so we choose the equivalent structure as shown in Fig. 6, where $X_1$, $X_2$ and $X_3$ are unknown loads, their value are solutions of the following set of equations [5]

$$\begin{aligned} \delta_{11}X_1 + \delta_{12}X_2 + \delta_{13}X_3 + \Delta_{1F} &= 0 \\ \delta_{12}X_1 + \delta_{22}X_2 + \delta_{23}X_3 + \Delta_{2F} &= 0 \\ \delta_{31}X_1 + \delta_{32}X_2 + \delta_{33}X_3 + \Delta_{3F} &= 0 \end{aligned} \tag{7}$$

In these equations, $\delta_{ij}$ is displacement of the structure in the i[th] direction due to unit load in the j[th] direction ("Unit"-condition, i.e. $X_j = 1$), and $\Delta_{iF}$ is displacement of the structure in the i[th] direction due to external loads F ("F"-condition).

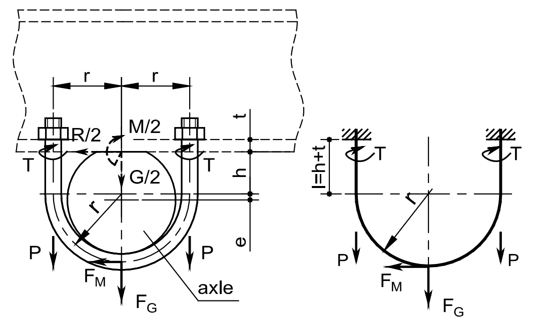



**Fig. 5.** Loads and calculation diagram of the u-bolt

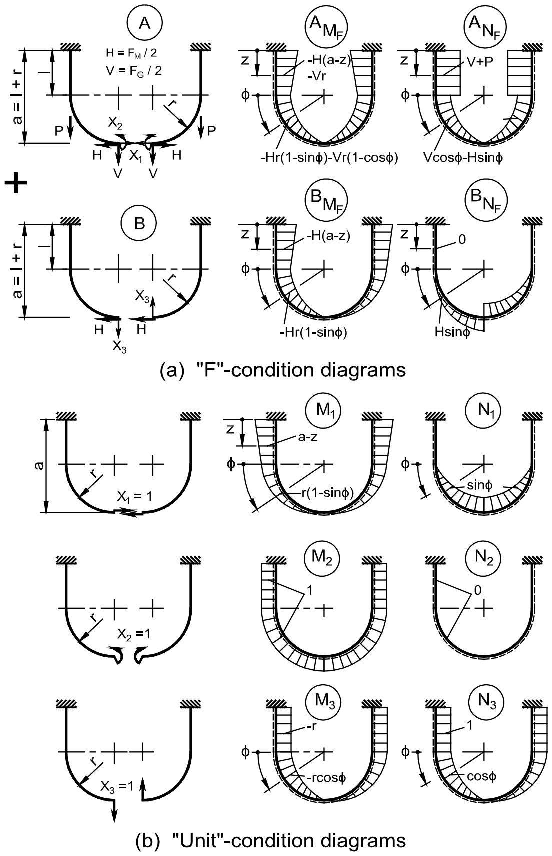



**Fig. 6.** Internal force diagrams to solve statically indeterminate u-bolt

Ignoring the influence of shear force, theses displacements are defined by Maxwell-Mohr formula:

$$\begin{aligned} \delta_{ij} &= \sum\int_0^s \frac{M_i M_j}{EI} ds + \sum\int_0^s \frac{N_i N_j}{EA} ds \\ \Delta_{iF} &= \sum\int_0^s \frac{M_i M_F}{EI} ds + \sum\int_0^s \frac{N_i N_F}{EA} ds \end{aligned} \tag{8}$$

Where $M_{i,j}$, $N_{i,j}$ are internal forces (bending moment, axial force) in "Unit"-condition; $M_F$, $N_F$ are theses ones in "F"-condition (Fig. 6); $E$ is Young's modulus; $I$ and $A$ are moment of inertia and area of the section, respectively.

Substitute the values in the diagrams in Fig. 6 into (8), compute the integrals, note that $ds=rd\phi$ at the curved part of the u-bolt, then the displacements can determine by formulae (9) below. Solve the equations (7) to find out the unknown loads and then can draw the final internal force diagrams of the u-bolt.

$$\delta_{11}=\frac{2}{EI}\left[\frac{1}{3}(a^3-r^3)+(\frac{3\pi}{4}-2)r^3\right]+\frac{2}{EA}\frac{\pi}{4}r$$

$$\delta_{22}=\frac{2}{EI}(l+\frac{\pi}{2}r)$$

$$\delta_{33}=\frac{2}{EI}(r^2l+\frac{\pi}{4}r^3)$$

$$\delta_{12}=\delta_{21}=\frac{2}{EI}(al-\frac{l^2}{2}+\frac{\pi-2}{2}r^2)$$

$$\delta_{13}=\delta_{31}=\delta_{23}=\delta_{32}=0 \tag{9}$$

$$\Delta_F=\frac{2}{EI}\begin{bmatrix}\frac{H}{3}(r^3-a^3)+Vr(\frac{l^2}{2}-al)\\ -\frac{3\pi-8}{4}Hr^3-2(\pi-3)Vr^3\end{bmatrix}$$

$$+\frac{2}{EA}\frac{r}{4}(2V-\pi H)$$

$$\Delta_{2F}=-\frac{2}{EI}\left[Hl(a-\frac{l}{2})+Vlr+\frac{\pi-2}{2}(H+V)r^2\right]$$

$$\Delta_{3F}=\frac{2}{EI}\left[Hrl(a-\frac{l}{2})+\frac{Hl^3}{2}\right]+\frac{1}{EA}Hr$$

### 3. Stress in the bolt and u-bolt

For the connection in Fig. 4, the stresses in the bolts include tensile and torsion, and their maximum values are

$$\sigma=\frac{F_{max}}{\pi d_1^2/4}$$

$$\tau=\frac{T}{\pi d_1^3/16} \tag{10}$$

$$\sigma_{VM}=\sqrt{\sigma^2+3\tau^2}$$

Where, $d_1$ is the minor thread diameter; $T$ is the preload torque moment, see formula (4); $\sigma$, $\tau$ are the tensile and torsion stress, respectively, and $\sigma_{VM}$ is the Von-Mises stress.

For the connection in Fig. 5, the upper parts of the u-bolt are under tensile, torsion, shearing and bending stress. The lower part of the u-bolt is considered as a curved beam and the resultant of tensile and bending stress is [5]

$$\sigma=\frac{N}{A}+\frac{M}{A.g}\left(1-\frac{\rho_0}{\rho}\right)$$

$$\rho_0=\frac{d^2}{4\left[2r-\sqrt{4r^2-d^2}\right]} \tag{11}$$

The nomenclature used in this formula is:

$N$ = Internal axial force;

$M$ = Internal bending moment;

$A$ = Area of u-bolt cross section;

$\rho$ = Radius of examining fiber $(\rho=r+c)$;

$\rho_0$ = Radius of neutral fiber;

$r$ = Radius of u-bolt centroidal axis;

$c$ = Distance from centroidal axis to examining fiber;

$g$ = Distance from centroidal axis to neutral fiber $(g=r-\rho_0)$.

$d$ = U-bolt diameter.

### 4. Results and discussion

Table 2 shows some results, calculated for elevator with rate load 600kg (or 8 persons), weight of empty car 600kg, then the counterweight is 900kg or $G_w$≈9000N. Main parameters of bolt and u-bolt connection are described in Table 1.

**Table 1.** Bolt and u-bolt connection parameters

| | |
|---|---|
| Bolt or u-bolt size and mark | M16x2; 6.8 |
| Minor diameter [6] | 13.55 mm |
| Yield limit | 480 MPa |
| Young's modulus | 200 GPa |
| Coefficient of friction | 0.2 |
| Safety factor for non-slipping | 1.5 |
| Stiffness constant $\chi$ | 0.3 |
| Diameter of axle terminal | 50 mm |
| Other dimensions:<br>Fig. 4: $b=h$;<br>Fig. 5: *e = 2.5; r = 35.5; t = 10; l = 26.25*<br>$h=3\times d_{axle}/8-e=16.25$ | |

**Table 2.** Von-Mises stress in the bolt and u-bolt

| Angle of contact, deg. | Preload, N | Maximum $\sigma_{VM}$, MPa | | |
|---|---|---|---|---|
| | | Bolt | U-bolt | Diff., % |
| 130 | 13731 | (185.5) | (254.1) | 36.9 |
| 135 | 12591 | (170.1) | (232.1) | 36.5 |
| 140 | 11373 | 153.5 | (208.9) | 36.1 |
| 145 | 10086 | 136.1 | (184.6) | 35.6 |
| 150 | 8739 | 117.9 | 159.4 | 35.2 |
| 155 | 7342 | 99.0 | 133.4 | 34.8 |
| 160 | 5907 | 79.6 | 107.0 | 34.4 |
| 165 | 4444 | 59.9 | 80.2 | 34.0 |
| 170 | 2964 | 39.9 | 53.3 | 33.6 |

*Note:*

*1. The results in the parentheses are not satisfied (if the safety factor is 3 when the preload is not verified).*

*2. For the u-bolt, maximum stress is in the outer fiber of its right end.*

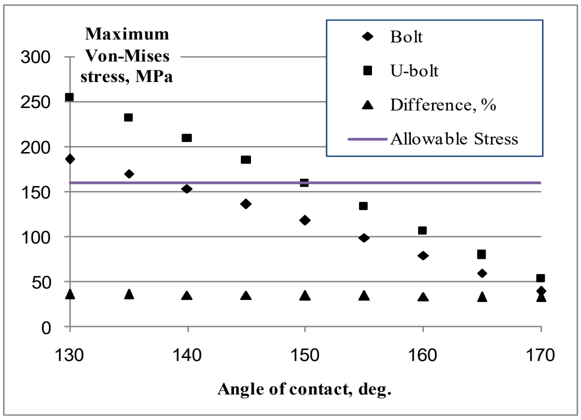



**Fig. 7.** Maximum Von-Mises stress in bolt and u-bolt

The calculation results of u-bolt shows that the maximum Von-Mises stress occurs just under the nut, in the outer fiber of its right haft and the value of stress is greater about 34-40% than the case of standard bolt connection. The reason of it is the significant portion of bending stress, adding to tensile stress due to preload. The value of bending stress is almost equal to the tensile, and shear stress is very small, only about 6% of the tensile and can be ignored.

Furthermore, as shown Table 2, or in Fig. 7, in both cases of using bolt or u-bolt connection, the angle of contact affects clearly to the maximum stress. When the angle of contact decreases, the horizontal force $R$ acting on the pulley axle increases responsively, and it needs greater preload force to avoid sliding of the axle. For the u-bolt connection, increasing of the force $R$ also leads to greater horizontal force $H$ and to greater bending moment. Consequently, the stress in the bolts and u-bolt will increase. When angle of contact decreases from 170 to 130 degrees, the maximum Von-Mises raises almost five times, and it can lead to unsafe condition of the connection. For example, when using bolts M16, grade 6.8, when the angle of contact is less than 140 degrees, the bolt stress exceeds the allowable value, and connection becomes unsafe. Similarly, when using u-bolts with the same diameter and grade, the angle of contact must not less than 150 degrees.

## 5. Conclusion

The bolt and u-bolt connection for fixing the position of deviation pulley on elevator traction machine is analyzed. The critical stress in the bolt or u-bolt depends not only on its dimensions, but significantly on the angle of contact between the rope and traction pulley. So, in order to choose the adequate size of bolt or u-bolt, it is necessary to consider the followings:

The diameter of bolt or u-bolt must be selected accordingly with the angle of contact. Ignoring the influence of contact angle can lead to unsafe connection, especially when this angle is small.

When using u-bolt to fix the pulley axle, the u-bolt diameter must be calculated specifically. Taking the same diameter as the bolt in the standard connection can cause the exceeding of stress.

For practical purpose, the u-bolt diameter can be selected as the bolt in the standard connection, but calculated with reduced allowable stress equal to 70% of actual value.

## References

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