Numerical Test to Determine the Influence of Factors on the Weight of the Multi-layer Rope Reel of the Winch

Truong Giang Duong

Faculty of Mechanical Engineering, Hanoi University of Civil Engineering, Hanoi, Vietnam
Email: giangdt@huce.edu.vn (T.G.D.)

***Abstract*—The winch is the equipment used in many different fields of industry. The drum is an important part of the winch. In the previous study, we designed one personal rescue winch for high-rise building rescue. Its key requirement is to be small and light enough to suit users. Many design factors of drums have not been fully investigated. In particular, the influence and importance of each factor on the drum weight need to be fully evaluated. This article establishes the process and studies the main factors affecting the drum weight of the rescue winch. The main influencing factors are materials and structural parts. This study uses numerical methods with the support of Inventor software. The correctness of the model is verified through the analytical formula. The research results showed that the material is the decisive factor in the drum weight of the winch. For the structure, the drum thickness is the decisive factor. When local stress effects are taken into account, the drum mass can be increased. The research results help us to choose the appropriate method to optimize the drum of the rescue winch in specific conditions.**

***Keywords*—design method, rescue winch, machine design, numerical methods, multi-layer drums**

I. INTRODUCTION

The winch is equipment used in many different fields of industry. Therefore, reasonable calculation and design are always interesting to many researchers. Basic computational studies for mine hoists have also been presented in [1]. Duong *et al.* [2] calculated the design of a rescue winch for the exterior of high-rise buildings, but this type of winch still has a large volume. Wolny *et al.* [3] studied mine hoists to analyze cracks due to fatigue failure. In addition, this study also analyzed stress by finite element method to propose solutions to improve the pulley system on lifting equipment applied in mining. In [4], the friction drum parameters of the winch were optimized to reduce vibration and this study was tested. The study in [5] numerically tested 7 parameters of the gear transmission, using Ansys software to optimize the gear body, resulting in a 10.21% reduction in mass. The parameters of the friction drum of the winch had been rationalized to increase the traction force and reduce the drum weight, the research results allow reducing the weight by up to 50% [6]. This study was applied to farm winch. An overview of winch design improvements to improve working efficiency was given in [7]. This research has analyzed the influencing factors to find the cause of poor performance and the solution to better performance for the entire system. In [8], the stability of the winch drum was studied by the Euler method. The research process in [8] used Ansys software for analysis and found that this is an accurate method, close to the actual stress. The mechanical model of the drum was established in the article [9], according to the winch's actual working conditions to determine the form of load and stress analysis. This study offered a reference method to design a large winch to meet the performance and reduce the number of funeral volumes effectively. Yu *et al.* [10] have provided an important theoretical basis for product design, by applying SolidWorks software to model building and finite element analysis for the model. The maximum drum stress was calculated under the most hazardous operating conditions. Automotive wheel rims have been subjected to static analysis in [11], calculated with different materials, to determine their safety factors. A solid model was created in SolidWorks software, and then loads and stresses were calculated and simulated [11]. Yazdani *et al.* [12] have applied genetic algorithms to optimize a technical problem.

The basis for the detailed design and basic calculation of the winch was presented in [13, 14]. The classical capstan problem in mechanics involves perfectly flexible strings wrapped around a rigid circular capstan, with the frictional interaction between them governed by the Coulomb inequality of static friction [13–15]. Also in the study [15] that developed this problem, this study presented the planar equilibrium of an elastic rod subjected to the final load wrapped around a rigid round bar. The problem has included both frictionless and frictional contact between the rod and the shaft.

The drum is an important part of the winch, as per the above analysis, there have been several related studies. The design process suitable for processing conditions and manufacturing technology will allow rapid application into the product reality. In the previous study, we designed one personal rescue winch for high-rise building rescue. Its key requirement is to be small and light

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enough to suit users [2, 5]. Duong *et al.* [2] have found that the structure of the drum is not reasonable. Many design factors of drums have not been fully investigated [2]. In particular, the influence and importance of each factor on the drum weight need to be fully evaluated.

The purpose of this study is to identify the important factors affecting drum weight. To achieve this goal, the article will present related studies and influencing factors. This study will present the numerical testing process and test results with the help of Inventor software. As a result, the determining factor to the weight of the drum of the rescue winch was determined in [2, 5].

II. Related Studies

A. Geometry Size of Multi-layer Drums

The basic geometric dimensions of the winch drum include drum diameter, drum length, and drum thickness. Other parameters such as the shaft diameter of the drum d_0, length L_0, and diameter D_0 taken according to the structural conditions of the winch and shaft. Drums and rescue winches (as shown in Fig. 1) are multi-layer cables. Based on technical requirements, the geometrical parameters determined initially are as follows.

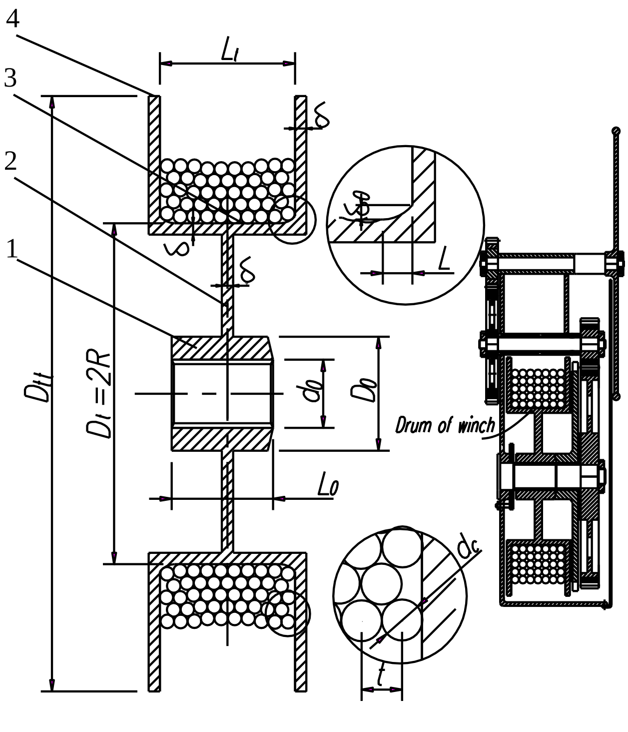


Fig. 1. Rescue winch and geometry parameters of drums. 1- hubs, 2 - drum body, 3 - drum, 4 - drum wall.

Drum diameter is D_t (mm):

$$D_t \geq (e-1)d_c \tag{1}$$

Diameter of a drum wall is D_{tt} (mm):

$$D_{tt} \geq (2n+5)d_c + D_t \tag{2}$$

Number of cable rings per layer is z (round):

$$z = \frac{H + 1.5\pi D_t}{\pi\left(nD_t + d_c n^2\right)} \tag{3}$$

Drum length is L_t (mm):

$$L_t = zt\varphi \tag{4}$$

Drum thickness is δ (mm):

$$\delta \geq 0.01D_t + 3mm \tag{5}$$

where d_c is the cable diameter (mm); e is the coefficient depending on the type and working conditions; n is the number of cable-layers; t is the cable step (mm); φ is the uneven cable coefficient, φ = 1,1; z is the number of cable rings per layers, round; H is the cable length rolled into the drum (mm). The initial calculation and selection results are as in Table I, which is the basis for building the 3D model. The parameters have given for the test H = 30.10^3 mm, d_c = 6 mm, n =5, $t = d_c$ = 6 mm, e =25, d_0 = 30 mm, L_0 = 45 mm, D_0 =50 mm.

TABLE I. Preliminary Selection of Parameters [2, 5]

Parameter	Units	Calculated value	Selection of original design
D_t	mm	$\geq$ 144	150
D_{tt}	mm	$\geq$ 240	260
z	round	$\geq$ 10.86	10.86
L_t	mm	$\geq$ 71.67	72
δ	mm	$\geq$ 4.5	5

B. Pressure Acts on the Drums of Multiple Cable Layers

We consider the model as Fig. 2. Split piece of a drum whose length is one cable step, it's like a flat ring. The sum of the cable tensions of the cable layers on the flat rim is $S_{\max}$, $S_{\max}$ exerts distributed pressure p on the rim and assumes that it is uniformly distributed. To calculate the value of pressure distribution p, separate the element from the area dF on the tangent rim:

$$dF = tRd\varphi \tag{6}$$

The force is acting on the element:

$$dS = pdF = ptRd\varphi \tag{7}$$

Set up finally, we balance the equation along the y-y axis:

$$2S_{\max} = 2\int_0^{\pi/2} ptR\cos\varphi d\varphi = 2Rpt \qquad (8)$$

Finally, we get the formula for calculating pressure p according to the value of cable tension $S_{\max}$ from Eq. (9):

$$p = \frac{2S_{\max}}{D_t t} \qquad (9)$$

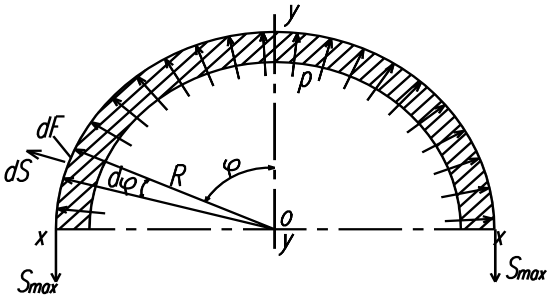


Fig. 2. Model to calculate the pressure acting on the drum.

With multiple layers of a cable, the relationship between the force and strain of each cable-layer is very complicated, so it is difficult to calculate the exact resultant force $S_{\max}$ from cable-layers. In the paper, the approximate calculation method is chosen by adding the factor A_n to account for the pressure increase when the number of cable-layers increases.

$$S_{\max} = A_n S_{\max}^1 \qquad (10)$$

where $S_{\max}^1$ is the cable tension in the case, there is one layer of cable winding on the drum.

Point stress inside the drum:

$$\sigma_I = \frac{-2pD_2^2}{D_2^2 - D_1^2} \qquad (11)$$

Outer surface stress of the drum:

$$\sigma_O = \frac{-p(D_2^2 + D_1^2)}{D_2^2 - D_1^2} \qquad (12)$$

Substituting $D_2 = D_t, D_1 = D_2 - 2\delta$ into Eq. (12), we get the maximum stress for the drum:

$$\sigma_O = \frac{S_{\max}}{(1 - \frac{\delta}{D_t})\delta t} \qquad (13)$$

The value of pressure acting on the drum is calculated in Table II. The coefficient A_n is determined for each case [13, 14]: n =1, A_1 =1; n =2, A_2 =1.2; n =3, A_3 =1.4; n =4, A_4 =2; n =5, A_5 =2.85. The parameters are given in [2]: $S_{\max}^1$ =632 N, D_t =150 mm, t = 6 mm.

TABLE II. PRESSURE ON THE DRUM

n	A_n	$S_{\max}$ **(N)**	p **(MPa)**	σ_o **(MPa)**
1	1	632	1.40	21.79
2	1.2	758.4	1.69	26.15
3	1.43	903.76	2.01	31.16
4	2	1264	2.81	43.59
5	2.85	1801.2	4.00	62.11

III. SURVEY FACTORS AND PROCESSES

A. Influence Factor

The drum structure of the rescue winch (Fig.1) includes hubs **1**, a drum body **2**, a drum **3**, and a drum wall **4**. In which the drum and the drum wall are under direct pressure from the cable. The drum structure of the winch part hubs **1** depends on the assembly with the shaft difficult to change in size. The drum of the rescue winch is made of metal, the different material properties also determine the bearing capacity and weight. Therefore, the problem will examine the main factors including materials for making drums, the structure of the drum body, drum thickness, and structural drum wall with local stress effects.

The goal of the problem is to design a combination of multi-layer cable reels with the smallest possible structure and weight. The conditions for the strength and deformation of the drum satisfy Eq. (14).

$$\begin{cases} \sigma_{\max} \le \dfrac{\sigma_{ch}}{k} \\ f < [f] \end{cases} \qquad (14)$$

where $\sigma_{\max}$ is the maximum stress, Mpa; σ_{ch} is the yield strength of the material, Mpa; k is the factor of safety; f is deformation, mm; $[f]$ is the allowable deformation according to winch structure condition, mm.

Design conditions as in [2, 5] we define the given data. The parameters given for testing are a factor of safety k =1.5 and allowable deformation of the winch drum wall $[f]$=3mm. Cable pressure on the drum p = 4 MPa is the maximum value when the maximum number of layers of rope on the drum n = 5.

B. Survey Process Using Numerical Method

The process of surveying factors in this study is shown in Fig. 3. Numerical methods will be used with the help of Inventor software to investigate the effects of material and structure on displacement and stress. The process of building models and calculating stresses and strains by the finite element method includes the following steps.

Step 1: set up the 3D model and assign boundary conditions, the drum is fixed to the drum shaft and the rotational motion should fix the hole in contact with the drum shaft (Fig. 4).

Step 2: apply evenly distributed force due to the net force of a cable acting on the working length of a drum according to calculated pressure parameters (Fig. 5).

Step 3: mesh the model (Fig. 5).

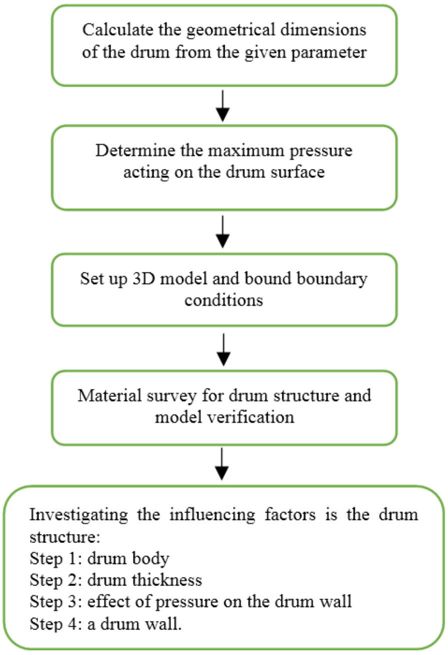


Fig. 3. Survey process.

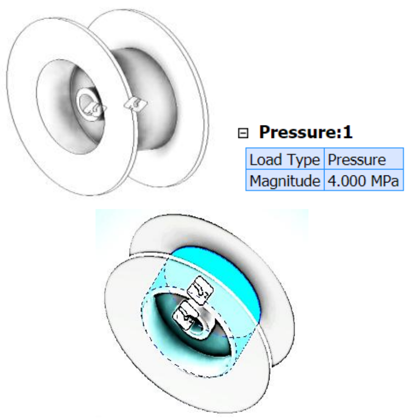


Fig. 4. Boundary conditions.

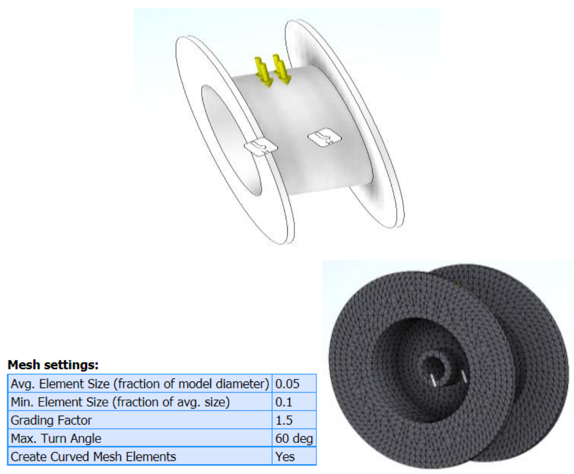


Fig. 5. Distributed force acting on the drum and meshing the model.

TABLE III. MATERIAL DATA FOR DRUM DESIGN

Name	Steel Cast	Aluminum 6061	Magnesium AZ80
Mass Density (g/cm^3)	7.85	2.70	1.82745
Yield Strenggth (MPa)	250	275	275
Ultimate Tensile Strength (Mpa)	300	310	380
Young' Modulus (MPa)	210	68.9	44.8157
Poisson's Ratio (-)	0.3	0.33	0.35
Shear Modulus (GPa)	80.76	25.9023	16.5984
Young' Modulus (g/cm^3)	7.85	2.7	1.82745

IV. SURVEY THE INFLUENCING FACTORS

A. Material Survey for Drum Structure and Model Verification

Three types of materials are investigated: Steel Cast, Aluminium 6061, and Magnesium AZ80. Steel is a material with diverse uses and applications in many fields, especially in industry and mechanical engineering. Aluminium and aluminium alloys are lightweight, high-strength, and flexible, so they are easy to shape and have anti-wear and fireproof properties. The advantages of magnesium alloy are lightweight, high strength-to-weight ratio, high hardness-to-weight ratio, good castability, machinability, and damping. Table III shows the material parameters.

With the geometrical parameters and pressure calculated above, the survey results are as in Table IV and (Figs. 6–8). Calculation results in the model built on Inventor software compared with the results calculated by the Eq. (13) differ by less than 8.1%. This result proves that the calculation model built in the Inventor part will be used for the survey to be correct.

The survey results show that with different types of materials, the different stress values are not large. When the local stress is not considered, the maximum stress is the direct cable winding surface. The factor of safety for strength for steel is 4.23, for aluminium is 4.73, and for magnesium is 4.78. Because the Young Modulus of different materials is much different, the deformation of the drum causes aluminium or magnesium to be larger than that of steel. The largest deformation value is at the drum wall, which does not affect the operation of the drum much. The Magnesium AZ80 drum was reduced by 4.21 kg (76.5%) compared to steel, and the Aluminium 6016 drum was reduced by 0.62 kg (32.5%) compared to steel. Magnesium AZ80 is a material that is also very popular in industrial production. All three of these materials can be used to make drums, but with the requirement that the equipment needs to be as light as possible while still ensuring durability, Magnesium AZ80 was chosen to design the drum and is optimized for the structure. The condition of the problem is to ensure the safety factor k = 1.5, corresponding to the allowable stress $[\sigma]$ = 183 MPa, and the allowable deformation $[f]$ = 3 mm.

TABLE IV. TEST RESULTS FOR DIFFERENT MATERIALS

Material	Stress (MPa)	Error (%)	Disp (mm)	Vol (kg)	Decreased (%)
Steel Cast	59.08	5.1	0.04	5.5	-
Aluminium 6061	58.09	6.9	0.1185	1.91	65.27%
Magnesium AZ80	57.43	8.1	0.1782	1.29	76.65%

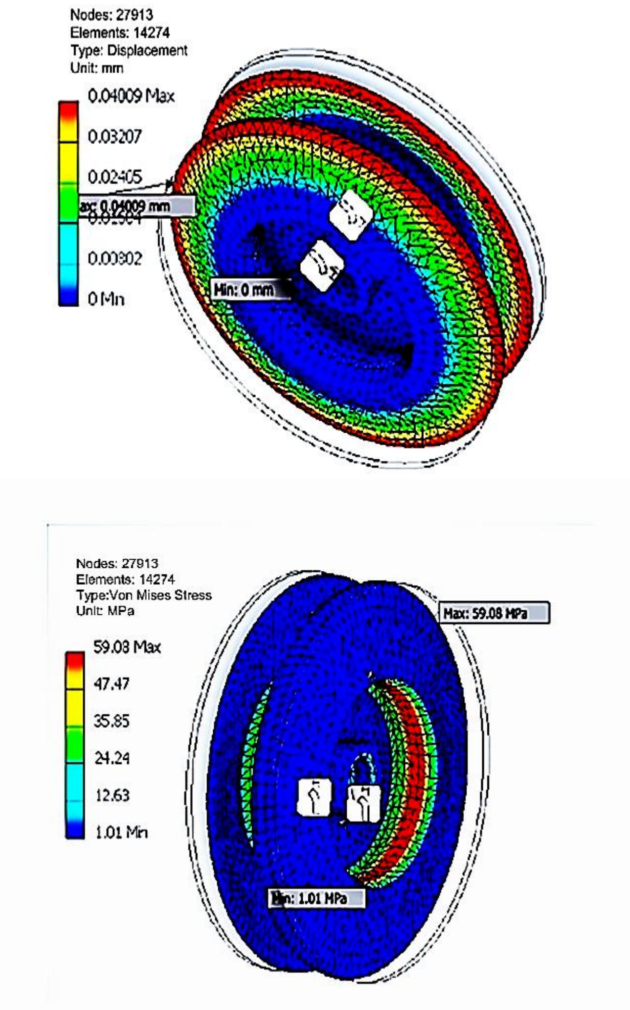
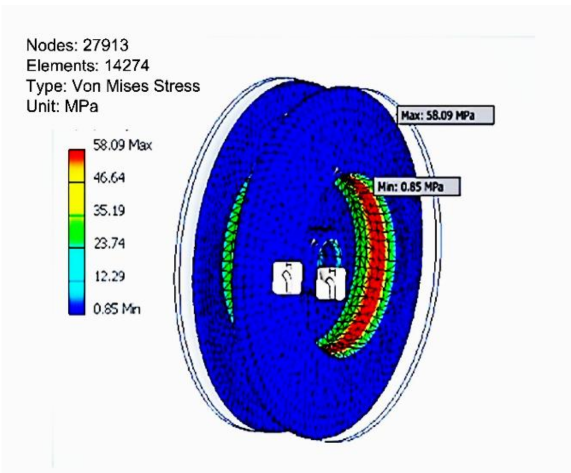


Fig. 6. Displacement and stress with drum made of Steel Cast.



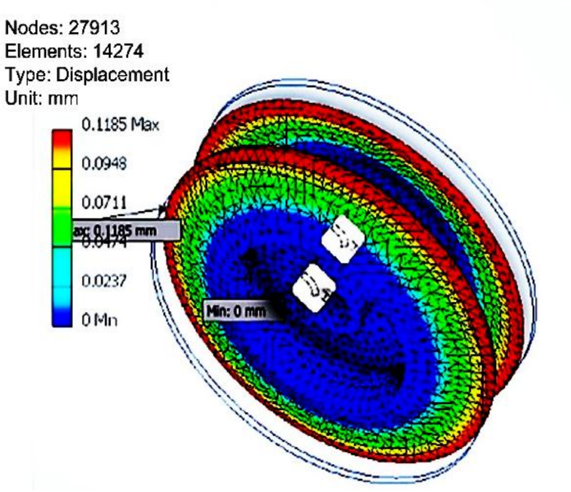


Fig. 7. Displacement and stress with drum made of Aluminium 6061.

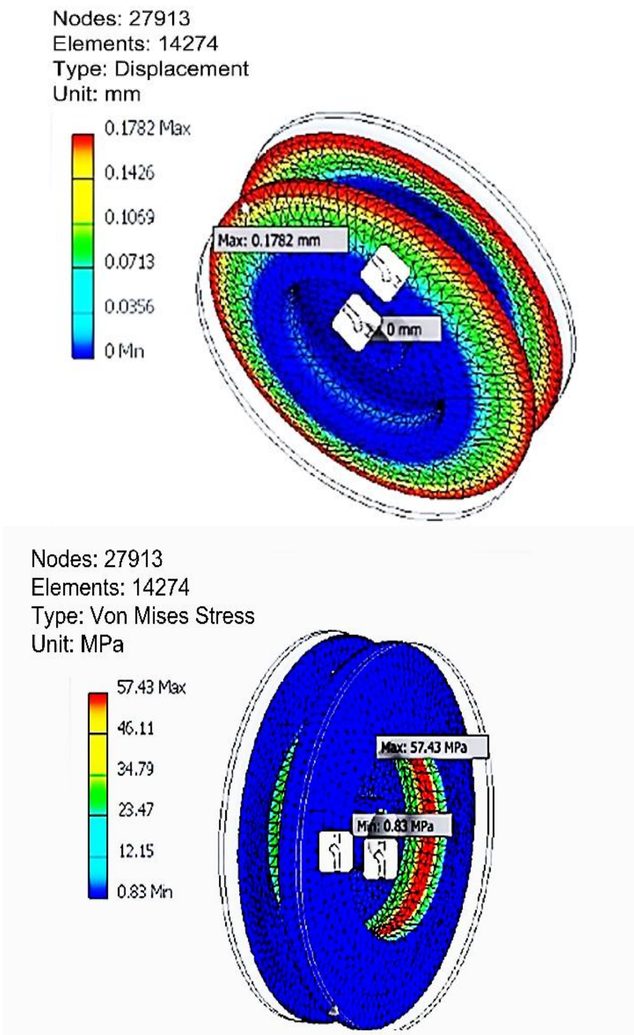


Fig. 8. Displacement and stress with drum made of Magnesium AZ80.

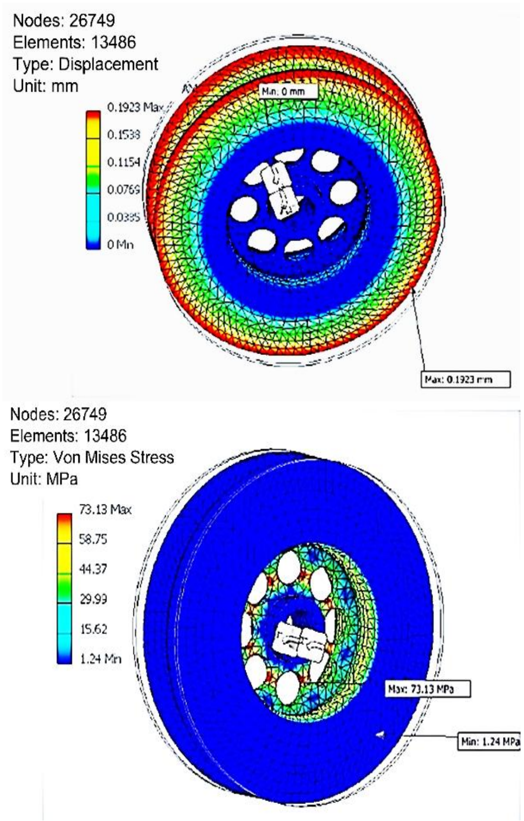


Fig. 9. Stress and displacement at the body of the drum, case 8×ϕ30.

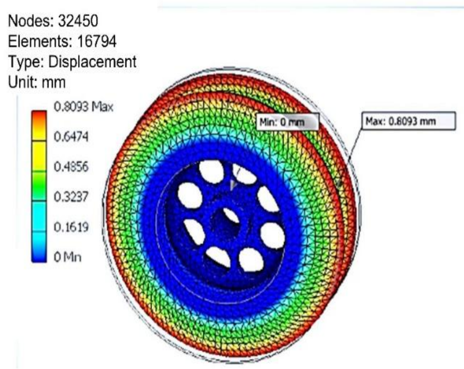
TABLE V. TEST RESULTS OF DRUM BODY

Number of holes ϕ30	Stress (MPa)	Displacement (mm)	Vol (kg)	Decreased (%)
0	57.43	0.1782	1.29	0%
4	57.48	0.1846	1.25	3.1%
6	57.78	0.1902	1.23	4.65%
8	73.13	0.1946	1.21	6.2%

B. Influence of Winch Drum Structure

1) Drum body structure

The reasonable design of the drum body structure creates round holes by technological conditions. The number of holes in the survey cases is 0, 4, 6, and 8 holes (Table V). Calculation results of stress and strain in the case of 8xϕ30 are shown in Fig. 9. The maximum stress when having holes 8×ϕ30 is 73.13 MPa and the deformation is 0.1946 mm, the calculation results show that the mass is reduced by 6.3%.



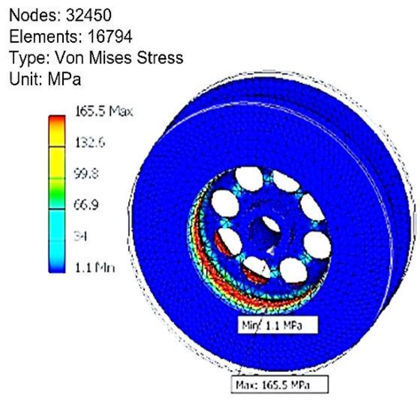


Fig. 10. Stress and displacement, drum thickness δ = 2mm.

2) Winch drum thickness

The next step evaluates the drum thickness according to technology requirements at levels from 5 mm to 2 mm. The test results shown in Table VI show that at the drum thickness of 2 mm as Fig.10, the maximum stress is 165.3 MPa, and the safety factor and the deformation both meet the requirements.

TABLE VI. TEST RESULTS OF DRUM THICKNESS

δ (mm)	Stress (MPa)	Displacement, (mm)	Vol, (kg)	Decreased (%)
5	73.13	0.1946	1.21	0%
4.5	73.65	0.237	1.18	2.48%
2.5	131.5	0.6226	1.021	15.62%
2	165.5	0.8286	0.985	18.59%

3) Influence of pressure on the drum wall

Calculating the pressure acting on the drum wall accurately is relatively complicated; in this problem, we assume as Fig. 11. The pressure distribution on the drum is uniform and the pressure acting on the drum wall is linear, decreasing. The maximum local stress at the edge of the drum wall. To reduce the local stress by creating a bevelled edge with height δ_0 and length L. The height of the drum wall under pressure is:

$$h = nd_c \tag{15}$$

Apply the test to this problem: δ_0 = 5 mm, d_c = 6 mm, n = 5 mm. Survey study with bevelled edge length L increasing from 0 to 10 mm, the stress, and strain decreased. At L = 10 mm, the local stress is 174.4 MPa and the strain is 0.7482 mm (Fig.12), the mass increases by 8% compared to the previous optimal stage (Table VII). Stress and displacement when the length of the corner edge L =10 mm still meet the requirements. However, when L < 10 mm, the necessary safety factor is not guaranteed.

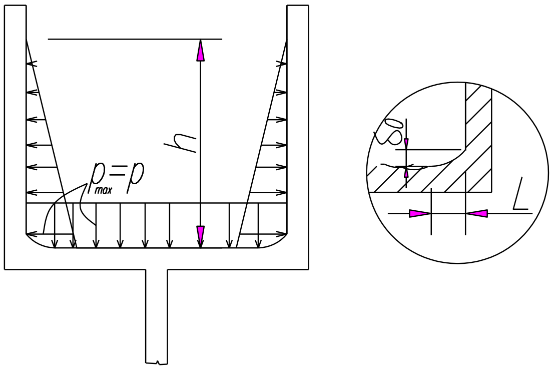


Fig. 11. Pressure acting on the drum wall.

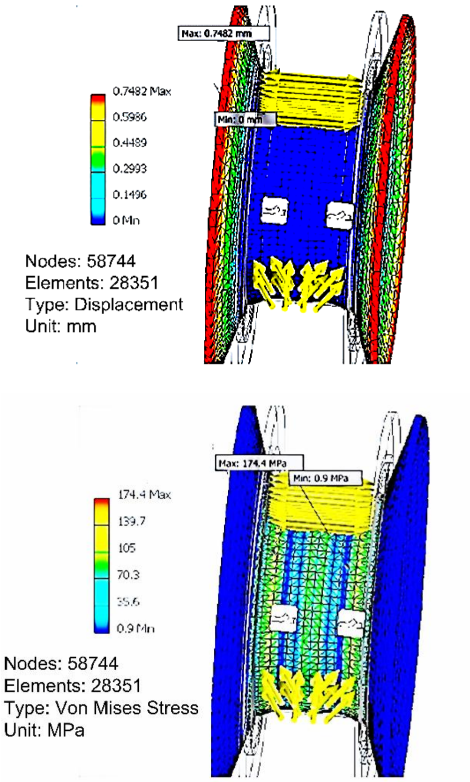


Fig. 12. Stress and deformation due to pressure on the drum wall, L =10 mm.

TABLE VII. EFFECT OF RAM LENGTH L ON LOCAL STRESS DUE TO DRUM WALL PRESSURE

L (mm)	Stress (MPa)	Displacement (mm)	Vol (kg)	Increased (%)
0	525.3	3.197	0.985	0%
10	174.4	0.7482	1.071	8%
Bevelled edge length: L (mm)				

The drum wall structure uses an oval hole with a length of 15 mm and a width of 5 mm to technology requirements. Optimizing the drum wall in cases of creating holes from one round to four rounds, each round has thirty oval holes. According to the maximum structure of four rounds, the calculation results are shown in Table VIII. The maximum stress is 168.5 MPa and the displacement is 0.91 mm (Fig. 13).

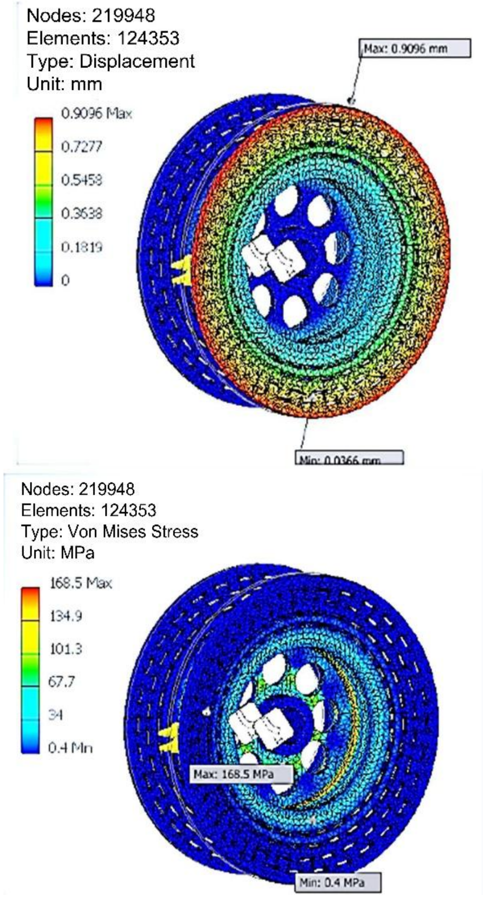


Fig. 13. Stress and strain of the drum wall.

TABLE VIII. TEST RESULTS OF DRUM WALL

Stress (MPa)	Displacement (mm)	Vol(kg)	Decreased from step 3 (%)
168.5	0.91	0.98	8.5%

C. Discussion

In this study, the cable tension in the cable layers is calculated through the coefficients, and the radial pressure on the drum is considered to be uniform on the surface. These calculation assumptions lead to the maximum value of radial pressure that is used to calculate the drum. The calculation result is more secure. This is not exactly correct considering the friction between the layers of the cable, between the drum and the cable, and the capstan effect. When this factor is considered, it will lead to the pressure no longer being evenly distributed, but the problem leads to too complicated numerical simulation. Therefore, in the scope of the problem of assessing the factors of materials and structures affecting weight and stress, the above assumptions are appropriate.

When the drum rolls the cable, the cable layers will overlap. The cable can be wounded unevenly on the drum, then the calculation assumption as shown in Fig. 11 is not appropriate, and the simulation results will deviate from the actual bearing properties. To prevent this, the drum surface will be grooved so that the first layer of a cable is evenly arranged, the following layers use guidance systems.

The calculation model built in the Inventor part used for the survey is correct when compared with the analytical formula in the original solution.

The survey results show that the material for making the drum for the rescue winch is the most important factor affecting weight. The case of using magnesium alloy can reduce up to 76.65%.

The factors related to the drum structure can be compared to the reduction of the surveying process as shown in Fig. 14. The most important factor influencing the drum thickness is 23.64%, but structural factors affecting local stress can only be reduced by 16.97%. The drum body will not be a factor that affects much.

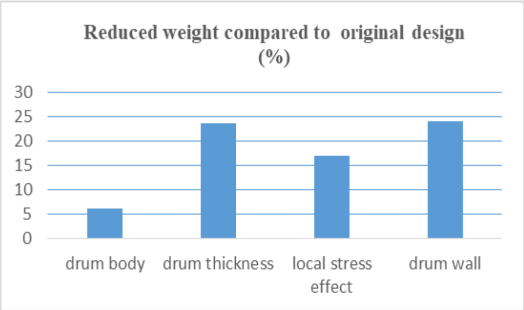


Fig. 14. Survey results of winch drum structure after four steps.

V. CONCLUSION

The article established the procedure and studied the main factors affecting the drum weight of the rescue winch. Materials and structural members are the factors to be examined. This study used numerical methods with the support of Inventor software. The correctness of the model is verified through the analytical formula. The survey and evaluation of the rescue winch in [2, 5] showed that the material is the decisive factor affecting the drum weight of the winch, using Magnesium AZ80 reduced to 76.65% compared to steel. The most important structural factor is the drum thickness, which can be reduced by up to 23.64% compared to the original design with the same material. The influence of local stress causes the structure to increase by 8%, which is only 16.97% compared to the original structure. The drum body has the least effect on weight. The research results help us to choose the appropriate method to optimize the drum of the rescue winch in specific conditions.

In the next research direction, the author will study the sudden stopping of the winch affecting the drum structure. Drum damage due to load changes, and fatigue strength conditions.

CONFLICT OF INTEREST

The author declares no conflict of interest.

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