

Comparison of Numerical and Theoretical Friction Effect in the Wire Winding for Reinforced Structures with Wire Winding

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Abstract—In the article, the wire winding process for the reinforcement of a pressure vessel frame has been studied. Firstly, the importance of the wire winding method has been explained. The main step in the design process is the methodology axial force control and wire winding process. The hot isostatic press and wire winding process introduce. With use the equilibrium term in the pressure vessel and frame, stresses in the frame wires analyzed. A case study frame was studied to control axial force in the hot isostatic press. Frame and them wires simulated then friction effect and wires effect in elastic yoke in the simulation model considered. Then theoretical and simulate resulted compare and vessel pressure import to frame because we assurance wire wounded not received to yielding point.

Keywords—Wire winding, Frame, stress, friction.

I. INTRODUCTION

IN order to enhance and control forces yield of working pressure in the under pressure structures, we can apply the winding method which is so useful. Winding causes a primary stress to provide remained pressure on the structural wall to encounter (oppose against) the tensile stresses arising from the internal pressure under working conditions which is one of the principles of the enhancing techniques in the winding structures. Under pressure vessels are included in the structures which use this technique. Utilities of the primary stress in the vessel is both reducing the current stress in the structures and the vessel is under working pressure, reducing the thickness of the vessel shell to a maximum specified stress of design [1].

Including those structures that require the primary stress by winding, are the vessel and the frame of the hot isostatic press machine. In this paper we aim to design the frame, laying stress by winding in this structure, and studying the numeric results of the friction effect between its winding layers.

Enhanced structures by winding method include many advantages of which we can mention bellow:

- The structure safety does not depend on its size.
- The stress is computable at each point of the winding.
- The high ratio of resistance to weight due to the thickness of wire layers has the maximum allowed resistance, and

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also the concentrating stress points and therefore the cracks caused by fatigue will disappear.

- Cost saving.

And also another merits like the excellent resistance to corrosion, easy manufacturing, no limit in size and impact resistance [1].

In the 19th century, for the first time Langrich used the winding method to enhance the gun rifle and later this method was used in other applications too. In vessel winding analysis mainly based on the assuming of compound vessel for the tank itself and assuming of each wire as a thin-wall tank too will be analyzed. Fryer analyzed the winding structures in assume of a composite tank and required equations [2]. Various methods has been provided for winding the under pressure vessels and they had individual analyses in order to improve the winding method that each one covered the other one to gain the best method. Langrich [3] executed winding based on the wire winding tension through all of the layers. Maximoph [4] explained that wire winding should be done in a way which the same shear stress applies to all layers. Also in all of the computations the friction between wire layers is ignored by default and it's clear from the previous subjects.

II. WINDING METHOD APPLICATION

Primary tension lying is used in various cases such as solid fuel rockets, floating structures in deep areas, static and moving saving tanks and to design under high pressure vessels [1], hot isostatic press [5] and metal forming dies [6] which executes by the winding method.

Also in the high pressure chemical reactors the spiral twisting of steel bands together or grooved strips is used to tolerate the longitudinal and tangential loads.

In winding the wires or flatbed strips under tension are contiguously twisted around the core in tangential, longitudinal, spiral or the combination of these three. If the layers of wires are twisted tangentially, tolerates only the tangential and radial stress and if it is wound spiral, part of the longitudinal load is absorbed by the wire layers.

In hot isostatic press that is using a gas in high pressure and temperature to press the parts in a special vessel, applied pressure in the vessel is isostatic which this under pressure vessel improved by winding method and controls the tangential and radial forces due to pressure.

This pressing method is used for different applications such as: in the parts, casting to resolve the flaws, strength, toughness, fatigue resistance and fatigue life [7], and

recovering the elongation percentage and impact strength in the aluminum alloys by this hot press [8], also removes all of the tiny holes in the turbine blades and it is possible to retrieve the life of the under creep or fatigue part to the life of a new part [7].

One of the most important components of mentioned devices is the under pressure vessels that was improved by winding method and safety is the most important issue in this design. Its axial force is controlled by the frame structure which includes two up and down Yokes and two pillars. The axial force created by the internal pressure in the vessel is transferred to the Yokes, in this way the axial force by winded wires under stress is inhibited around the frame structure. Using the winding method in the vessels and structures of the frame is so applicable since the high safety [5], low weight and dimension, omitting causing stress concentration points and the simplicity of calculation.

III. STRESS ANALYSIS IN THE WINDING FRAME STRUCTURE

In this section we analyze the stress of the structure frame to control the vessel axial force that assumed P for the working pressure, R for the external radial and L for the vessel length. As seen in Fig. 2, the frame structure as a structure controlling the axial force due to the internal pressure of the vessel including two pillars, two up & down Yokes and wire winding which this frame structure can be used to control the vessel axial force in different systems [9].

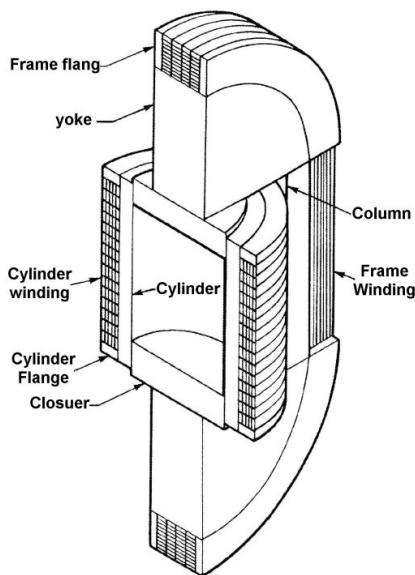


Fig. 1 Wire winding frame for axial force control of vessel [9]

A. Design of Winding Structure Frame

Pre-tension value required in the frame according to the ASME standard [9] should be large enough to keep the Yokes in 105% test hydrostatic pressure in mechanical touch with each other. Due to the working pressure in the vessel, required pre-tension value in the frame equals to at least 1.25 times more than working pressure multiple to minimum ratio of

yielding strength of the considered material in the vessel of test temperature to the yield strength in design considered temperature. The first assumption of the stress analysis in the frame structure is the yoke radius during loading and winding (rigid body assumption) remain fixed and the friction between layers is passed up in order to safety which exists in practice. These calculations is done according to the fixed shearing stress tension [4] and using the equilibrium relationships between the winding frame structure and vessel, and the winding tension of the wire layers computed in case of no friction between layers and will be compared by the simulation results in case of friction exists between layers.

B. The Analysis Method of the Tension among Winding Layers in Structure Frame in Case of No Friction between Layers

To compute the tension in working conditions without friction when the frame is placed under vessel working pressure, the pressure affects the up & down Yoke and pressure caused by the pre-tension will be released and a uniform shear tension τ is created in all wire layers. Assuming layers winded and pre-tension created in pillars, the radial tension (S_{rt}) is zero in the highest layer of wire and using the Teresca criterion tangential tension of that layer (S_{tt}) is as follows:

$$S_{tt} = 2 \times \tau - S_{rt} \quad (1)$$

Tangential force of the tangential tension in this layer is:

$$f_2 = S_{tt} \times 2 \times b \times t \quad (2)$$

Which t is the wire cross-section width and b is the width winded. This force due to the tangential tension affects the lower layer and the radial tension of lower layer is gained by the bellow equation:

$$S_{rt} = \frac{f_2}{[2 \times (r_3 - i \times t) \times b]} \quad (3)$$

Thus according to (1) the tangential tension in each layer and by (3) the radial tension in lower layer, in this order all radial & tangential tensions from the highest to the lowest layer is gained.

In case which only the internal pressure affects on the wire layers and existing force in different wire layers will counter the vessel pressure. Assuming the frame winded and by means of balance between frame and wire layers radial tension in the highest layer (layer 40th) is zero (S_{rp}) and the length of this wire layer due to pressure is as bellow:

$$l_w = 2\pi(r_3 - 0.5 - i) + 2(l_c - 2\delta) \quad (4)$$

R_3 is the sum of Yoke radius and the number of wire layers or h and I layer numbers, σ is the changes of the pillar length

due to the pre-tension of pillars by winding:

$$\delta = \frac{345 \times l_c}{2 \times E_c} \tag{5}$$

Tangential tension of the highest layer due to the length changes in pillar by the same wire layer is according to the following equation:

$$S_{tp} = \frac{4 \times \delta \times E_w - \nu \times S_{rp}}{l_w} \tag{6}$$

and the force yield by tangential stress of the same layer is:

$$f_s = S_{tp} \times 2 \times b \times t \tag{7}$$

which this force affects the lower layer and the lower layer radial tension is like bellow:

$$S_{rp} = \left[\frac{f_s}{2 \times (r_3 - i \times t) \times b} \right] \tag{8}$$

Using (4) & (6), the length of each layer and the tangential stress of the same layer are gained. Also using the equation 8 the lower layer radial tension is gained so in this procedure tangential and radial of all layers to the lowest one will be computed.

If only the stresses in condition of under internal pressure is reduced from the working pressure, gained stresses is in case which no pressure exists in the vessel and only wire layers are wound around the frame:

$$S_{tu}(i) = S_{ti}(i) - S_{tp}(i) \tag{9}$$

$$S_{ru}(i) = S_{ri}(i) - S_{rp}(i) \tag{10}$$

C. The Stresses of Winding the Different Winding Layers

Since the winding stress of the highest layer is equal to the tangential stress on the highest layer (layer 40th) in no load status, in assumption of eliminating the wire layers from top, the outcome force of the tangential stress is gained in this layer:

$$f_1 = 2 \times S_{tu} \times b \times t \tag{11}$$

Assuming to omit the effect of this layer force, some of the column length changes are released:

$$D_c = \frac{f_1 \times l_{c2}}{4 \times a \times b_y \times E_c} \tag{12}$$

$$l_{c2} = l_c - 2 \times \delta \tag{13}$$

The released length change in the same layer is 4 times bigger since the pillar has 4 sides length change:

$$D_w = 4D_c \tag{14}$$

$$l_w = 2\pi(r_3 - i + 0.5) + 2(l_c - 2D_c) \tag{15}$$

From (16) the stress due to length change in wire layers is gained that using the length change in pillar, by means of tangential stress equation (9) will cause pre-tension in pillar and by following this process and remove each layer the stress due to the length change of that layer is gained. If this is added to the tangential stress in no load status of the same layer, the winding stress is gained in each layer.

$$S = \frac{E_w \times D_w}{l_w} \tag{16}$$

$$S_{wr}(i) = S_{tu}(i) + S(i) \tag{17}$$

D. Study the Friction Effect between the Wire Layers on Winding Force

As mentioned above the friction between layers is ignored in winding stress calculations cause of safety but in practice this effect exists and here we check the ruling equations on the friction effect in winding layers.

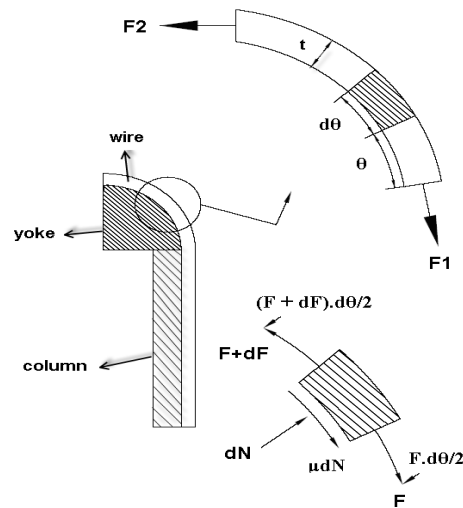


Fig. 2 Friction effect on the wire winding layers

If F1 was the wire tension force in where the wire goes out of the Yoke (to the column) and F2 the wire tension tangential force on the Yoke wall, it shouldn't cause a tension more than tensile strength of wire material. The relative values F1 and F2 can be computed by the approximate method in bellow:

By writing the force balance through the radius and in part

which is curved, we have:

$$\sum F_r = 0 \Rightarrow dN = (F + dF) \cdot \frac{d\theta}{2} + F \cdot \frac{d\theta}{2} \Rightarrow dN = F \cdot d\theta \quad (18)$$

Force balance through the around of wire is as bellow:

$$F + dF = F + \mu \cdot dN \Rightarrow \left. \begin{aligned} dF &= \mu \cdot dN \\ dN &= F \cdot d\theta \end{aligned} \right\} \Rightarrow dF = \mu \cdot F \cdot d\theta \quad (19)$$

By integrating of two sides of the equation:

$$\int_{F_1}^{F_2} \frac{dF}{F} = \mu \cdot \int_0^\theta d\theta \Rightarrow \ln \frac{F_2}{F_1} = \mu \cdot \theta \Rightarrow \frac{F_2}{F_1} = e^{\mu \cdot \theta} \quad (20)$$

As you can see wire tension tangential force on the yoke wall is more than the wire tension force where the wire goes out from the yoke which is due to the friction effect and is dependent to the coefficient of friction and the winding angle, and will cause an increase in winding force value on the top of yoke which will be compared to theory results in simulation section.

IV. STRESSES ANALYSIS OF A TYPICAL FRAME STRUCTURE OF THE HOT ISOSTATIC PRESS SYSTEM

Our main objective is to analyze stress in designed frame for the vessel of the hot isostatic press system that we are to discuss in this part. Real dimensions of the wound vessel as an entry to the question include the working pressure of 250Mpa, external radius of 165mm and length of 650mm. According to the frame conditions, winding design and the economic conditions, geometric dimensions should be computed in a way to minimize the winding weight and required wire layers. By minimizing the length of the required wire, the sample dimensions are: $b_y = 130\text{mm}$, $a = 70\text{mm}$, $b = b_y - 10 = 120\text{mm}$ which 5mm is intended of each side of the winding to metal covering the number of winding layers are $h = 40$ and the yoke external radius is $R_2 = 247\text{mm}$.

The wire using to wind is accorded to the ASM-A905 standard [10] that has square cross-section $1 \times 4\text{ mm}$ and the yield stress 1100Mpa and the elasticity module 195Gpa. The frame structure is made of steel 1/6580 or 1/6582 that has the yield stress about 700-1000Mpa and the elasticity module 200Gpa [11]. From the part A (The calculation of frame designing) pre-stress that should be made in the frame pillars to persist against the vessel pressure is 345Mpa.

A. The Stress of the Wire Winding Layers in no Friction Status

Wires should be wound by means of a device that the stress in wires could be exactly controlled. Wire winding method is in spiral way to the brim wound around the yoke. Also the internal stress in wires should vary larger in lower layers to lower value in the upper layers because the lower layers in affection of the pressure in the upper layers release an amount of their internal stress [3].

Fig. 3 shows the winding stress value in the frame wound layers in which the friction between wire layers from the top layer to the bottom is ignored and the stress value in top layer is 693Mpa and in the bottom is 650Mpa.

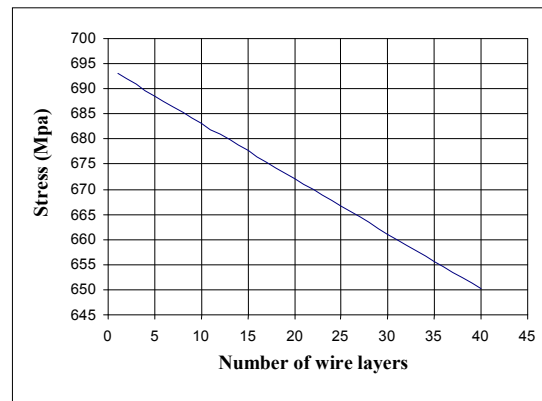


Fig. 3 The stress of wire winding layers in no friction status

The remarkable point in wires' winding is due to the small size of wire, by a relatively low force and applying a relatively low torque you can change these stresses in different layers.

V. SIMULATION OF A FINITE ELEMENT WINDING FRAME WHEN FRICTION EXIST BETWEEN LAYERS

In order to simulate by means of the ABAQUS software to ease the modeling we simulate a quarter of the frame structure according to the designed frame dimensions, and the characteristics of frame materials and wire is according to the selected material in design. The simulation is two dimensional and flat laying stresses [12].

To roll the frame, at first we roll each layer under the its special stress through one row beside each other to the width of winding area (120mm) and after winding one layer next layer is rolled on the previous one under its special stress and so on till all layers are wound around the frame structure, we have done this in our simulation.

Winding each layer under stress will cause the length change in that layer. Due to gaining the winding stress and the length of each layer in the theoretical calculations, according to the bellow equation we can approach the length change in each layer under the stress of the same layer:

$$\sigma(i) = E \varepsilon(i) = E \frac{\delta(i)}{\ell(i)} \Rightarrow \delta(i) = \frac{\sigma(i) \times \ell(i)}{E} \quad (21)$$

A. Comparison of the Winding Stress in Friction State between Layers and No Friction

In Fig. 5 shows the stress value in finite element model of the wire winding layers in frame structure of wire after applying the length change to each layer and the friction coefficient between layers.

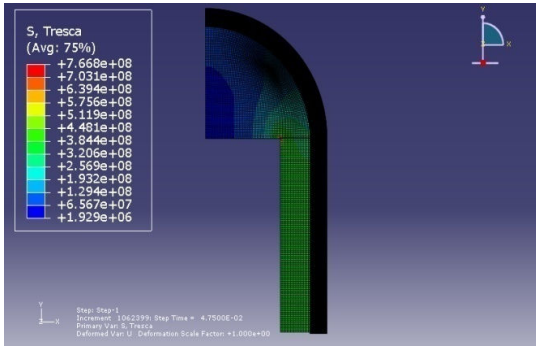


Fig. 4 Simulation frame after applying the length change

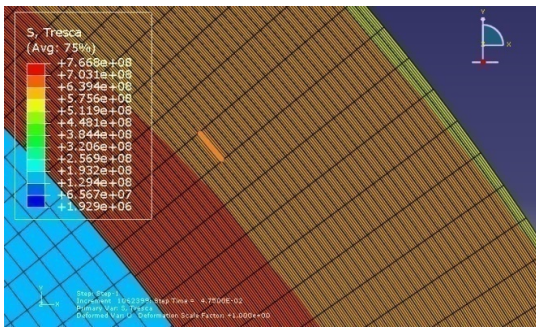


Fig. 5 Simulation frame when the stress of wire winding layer in friction status

Fig. 6 shows the Tresca stress due to simulating in the frictional state and no friction and the winding stress.

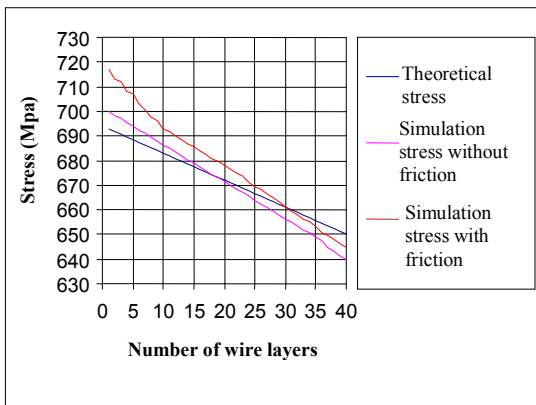


Fig. 6 Comparison between simulation stress in friction status and no friction status with theoretical stress

As you see the stress value of simulation increases at the top of the yoke at winding the wire layers when friction exists and at each layer in compare with no friction state, stress value increases about 11Mpa that is tangible and should be considered. While practical winding the wire layers around the designed frame structure for the vessel of the hot isostatic press system the stress increase should be considered in order to be able to overcome the friction force between wire layers that is produced during winding.

B. Created Simulated Stresses in the Frame Structure after Wire Winding

As shown in Fig. 5 simulating created stresses in wire layers in no friction state cause the pre stress in pillar that its value is 338Mpa that according to the theoretical calculations the created pre stress value in pillars is 345Mpa that has a little difference. Also in theoretical calculations to gain the equilibrium equations between frame and winding stabilizing the yoke radius in the time of loading and winding (rigid yoke) is considered as an assumption [5], but in the simulation, yoke is considered elastic and the stress affection on the wire layers is studied in no friction state and by friction. By considering yoke non elastic and after winding in no friction state, stress varies from 0 to about 450Mpa where yoke and pillar are in touch and at other parts of the yoke is up to 150Mpa which shows after winding however the pre stress is created in pillar will cause the stress in the yoke too that violates the constancy assumption of yoke radius during loading.

In the frictional mode stress increment due to the friction between wire layers affects on the created stress value in the pillar and the stress value created in pillar is 345Mpa that is increased in compare with the no friction state which is 338Mpa.

As you see in Table I simulated stress values created in column and up & down yoke are increased in frictional state in compare with the no friction mode which is due to the stress in wire layers of friction.

TABLE I
COMPARISON OF SIMULATION STRESSES IN THE FRAME STRUCTURE

Column stress in friction status	yoke stress in no friction status	Column stress in friction status	Column stress in no friction status
250Mpa	150Mpa	345Mpa	338Mpa

C. The Simulating Stresses of the Wire Layers after Applying the Vessel Pressure to the Frame

As you can see in Fig. 7 after applying the vessel pressure to the yoke (250Mpa) and applying this force to the wire layers through the yoke created stresses values is maximum in the wire layers on the first five layer and maximum created stress value in the first layer is 830Mpa and in the 40th layer is 677Mpa that has a long distance to wire submission stress (1100Mpa) which shows when wire layers are rolled over the frame structure under winding stresses obtained from theory addition to create required pre stress value in pillars, if it will be under the vessel working pressure too, they can bear the vessel axial force and wire layers would not be fractured.

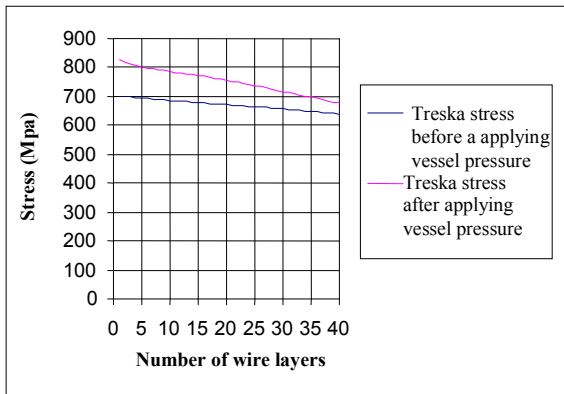


Fig. 7 Comparison of Treska stresses from wires simulation before and after applying vessel pressure

According to the principle of basic laying stress by winding method, this article attempts to provide theoretical equations to gain winding stress of wire layers in the frame structure and by studying a sample and simulating its limited element in different states consider the subject carefully and results of this article is as below:

1. Stress analysis is done in the frame structure and the winding layers according to the geometric equilibrium equations between vessel and frame.
2. Considering the friction between wire layers in the limit element model, a comparison was done between the winding layers stress of the designed frame of a hot isostatic press system with and without friction, and winding stress was done that shows the friction between layers cause to increase the winding stress and it should be considered in the calculations.
3. By considering the yoke elastic in finite element model layers affect on the yoke shows that yoke radius in the time of winding will not be stable.
4. By applying the vessel working pressure to the frame structure in the finite element model, maximum stress that will be created in the wire layers is less than wire submission value and controls the axial force of vessel.

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