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RESEARCH ARTICLE

Study on topology optimization of scraper conveyor chain

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Abstract

Silos are structures where grains are stored. In general, for transportation and prevention of wheat from spoiling, some sub-systems can be used in silos. One of these sub-systems is a scraper conveyor that is used to transport the grains in the horizontal direction. Similar to all other systems in engineering, to increase the system efficiency and optimize the required power for the motors, weight reduction is important without sacrificing the safety factor of the system significantly. Topology optimization has been used by mechanical and civil engineers for many years. This study aimed to apply topology optimization to the chain of a scraper conveyor that is used to transport 80 tons of grains per hour in a silo by using ANSYS® Mechanical. In conclusion, a lightweight and material-saving new design for the chain was designed without sacrificing from safety factor significantly.

1. Introduction

Silos are structures where different materials such as grain, cement, and coal are stored inside. In general, rectangular, or cylindrical-shaped silos are constructed to store bulk materials. Agricultural bulk materials must be protected against spoilage and transported to be placed in silos. For that reason, some sub-systems should be implemented for transportation and aeration. A scraper conveyor is used to transport the grains in the horizontal direction. The scraper conveyor system basically includes a chain, pins to connect chains, a welded scraper, and a motor, as seen in Figure 1.

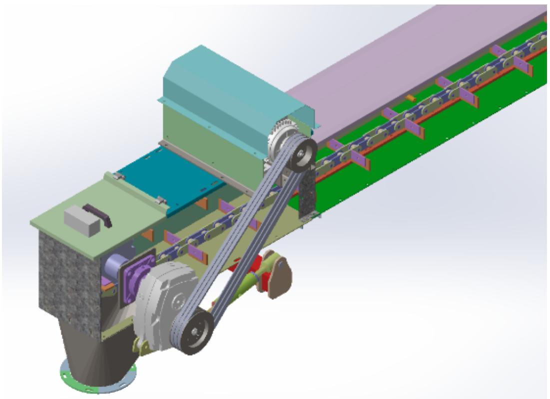

Figure 1. Conveyor model

The conveyor shown in Figure 1 shows a sample of a scraper conveyor that has the capability of conveying 80 tons of wheat grain per hour that is produced by Cukurova Silo Company. The system has chains connected by pins and scrapers welded to chains by a support. All of those components are connected to a motor which gives motion to the system for conveying the bulk grain via sprockets. The chain drive system, which consists of one or more chains and at least two sprocket wheels, is the most crucial component of a scraper conveyor. In this case, the chains are wrapped around the sprocket wheels to form a closed loop. The effectiveness of the chain drive mechanism can directly impact how dependable the scraper conveyor is.

In the working environment, chain breakage and jamming are frequent issues with chain drive systems, and there are several causes of these issues like the laying length and contact problems which produce high resistance. With increasing contact problems and laying length the motor power requirement increases, for this reason, multi study was done to make topology on the chain structure and design to improve it and to make optimum design [1-4].

2. Materials and methods

While conveying the bulk grains, friction force and hence mass of the system are important criteria to determine the power requirement and determination of tensile stress on the chain links. Decreasing the amount of friction force or the weight of the chain system decreases the power demand. While reducing the weight of the system it is also important not to sacrifice the safety of the system. For this purpose, topology optimization is applied to the components. Topology optimization is the numerical technique used to obtain the optimal layout of structural components by determining the areas of the parts that can be removed to maximize stiffness while reducing weight and keeping maximum stress below a certain value [1].

In this way, the application of topology optimization to the chain system reduces the total weight of the system without sacrificing from safety factor significantly. For the topology optimization, Ansys Mechanical software was used. To be able to do topology optimization on chain links it is necessary to determine the stresses on chain links. For that reason, the forces that affect the tension of chain link were investigated.

2.1 Determination of chain tension force

Determination of chain tension force is vital for the application of topology optimization. For the chain components, the stress is created by the friction forces and the sagging section

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of the chain system. It may differ in some cases in which additional systems were added for design purposes. Friction forces are related to the resistance force between the bulk material and solid surfaces that have touch with it. On the other hand, chain tension forces are the total forces imposed on the drive power as a result of the load, gravity acting on an inclined portion, and the weight of the chain and attachments. The lack of tension force produces sag. The unsupported loose side of the chain creates extra tension force, and it must be added to the total tension forces of the chain. This phenomenon called as Catenary effect 2].

2.1.1 Friction between chain system and trough

The chain is sliding on a trough while conveying the bulk grain. As a result of this motion friction force is seen in between chain and trough. The weight of the chain system and the friction coefficient in between them are important to calculate friction force.

$$F_c = \mathcal{L}_{cs} \times q_c \times g \times (\mu_c \times \cos\alpha) \tag{1}$$

F_c: Friction force between chain and conveyor (N).
$\mathcal{L}_{cs}$: The length of the conveying section where the chain is in contact with (m).
q_c: The meter weight of the chain and scraper (N).
g : Gravitational constant (m/s^2).
μ_c: The estimated friction coefficient between the chain and trough.
$\cos\alpha$: The angle of inclination(degree) [3].

2.1.2 Friction between bulk and trough

Bulk and trough friction is another important criterion for the calculation of chain tension forces. Figures 2 and 3, show the design of the conveyor and the main dimensions of the trough represented with order by dimension unit of millimeters.

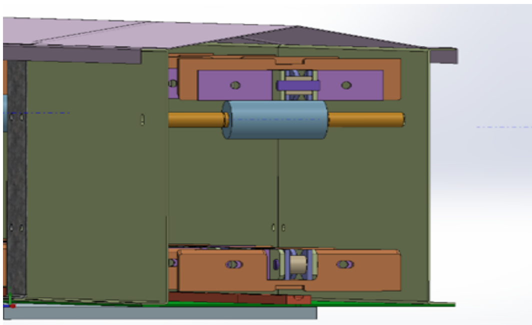
Figure 2. Model of trough

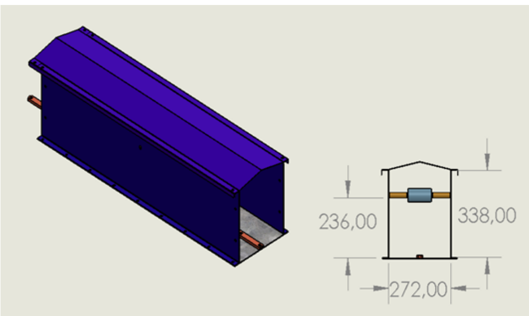

Figure 3. Dimensions of trough

While conveying the bulk materials, friction is seen between the trough base, trough side walls, and bulk material as seen in Figure 4, this friction is related to contact area, density of bulk material, and coefficient of friction between bulk material and trough material. On the other hand bottom wall and side wall pressure distributions are seen in Figure 5, for the lateral pressure distribution of the bulk grain, it is assumed that the pressure increases linearly [7].

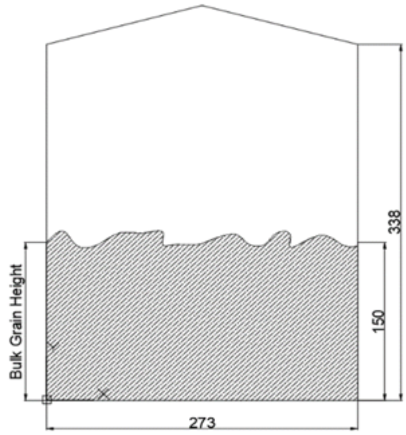

Figure 4. Dimensions of bulk

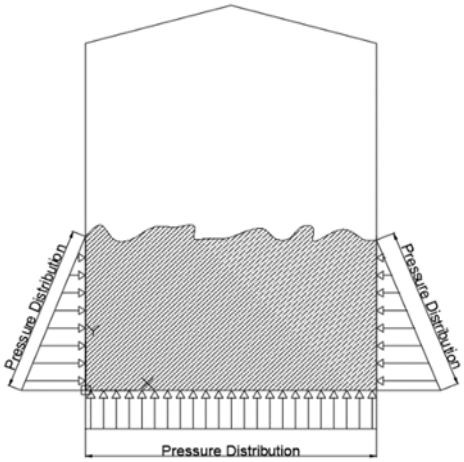

Figure 5. Pressure distribution of bulk grain

At the direction of the z-axis, the surface friction can be calculated as:

$$F_{fb} = \rho_b g h A_{base} \mu_\omega + \frac{\rho_b g h}{2} k A_{si\,de} \mu_\omega \times 2 \tag{2}$$

Where**;**
F_{fb}: Total bulk friction force (N).
ρ_b : Bulk density (kg/m^3).
g : Gravitational constant (m/s^2).
h : Height of the bulk material in trough (m).
A_{base} : Base area of the trough that bulk conveys on (m^2).
μ_ω : Wall friction coefficient between bulk material and trough.
$A_{si\,de}$: The side area of the trough where bulk is in contact while conveyed (m^2).
k : The ratio of lateral pressure to vertical pressure.

$$k = \frac{1-\sin\phi}{1+\sin\phi} \text{ [4]} \tag{3}$$

The value of k can be found for wheat when ϕ (internal friction angle) is found. ϕ Value for wheat is between 26°-32° [5].

2.1.3 Catenary effect

The catenary effect in this system is created by the sagging section of the chain. It is assumed that the upper side of the chain is unsupported. A model is shown in Figure 6. The sagged section is on the upper side of the conveyor.

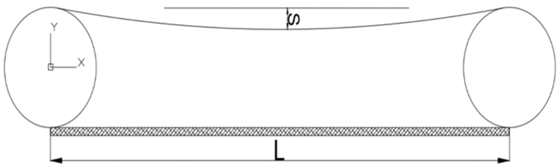

Figure 6. Chain configuration

$$T_s = q_c\sqrt{\left(\frac{L^2}{96s}\right)^2 + \left(\frac{L}{24}\right)^2} \quad (4)$$

Where,
T_s : Force from chain sag (lb).
L : The distance in between the center of sprockets (ft).
q_c : The meter weight of the chain and scraper (lb/ft).
s : The sag distance (in) [2].

Finally, Total tension forces are the total friction forces between the chain system and the trough F_c; friction force in between bulk material and trough F_{fb} and catenary force T_s.

$$F_{TOTAL} = F_c + F_{fb} + T_s \quad (5)$$

2.2 Finite element analysis (FEA)

In mechanical structural Analysis, FEA enables engineers to assess the structural integrity of conveyor components such as frames, supports, rollers, and belts. By dividing the structure into smaller finite elements and applying mathematical models, FEA calculates the stress distribution, deformation, and displacement in these components. This analysis helps ensure that the conveyor system can withstand applied loads without experiencing excessive stresses or deformations [6]. FEA allows engineers to calculate and analyse the forces, moments, and pressures acting on a system such as conveyors. This includes static loads due to the weight of conveyed materials, as well as dynamic loads caused by material handling, impact loads, and gravitational forces. Understanding these loads is crucial for designing conveyor systems that can handle the applied forces while maintaining stable and efficient operation [7].

Many studies reported on conveyor analysis, Jiang et al [8] made an assertion a chain drive system finite element model carried out contact simulations. Obtained von Mises stress and contact pressure curves for several risky regions on the horizontal ring, vertical ring, and sprocket wheel. Compared analysis of the difference between the von Mises stress and the contact pressure of the rings and sprocket wheel. Another study discussed the casual analysis and solution of the teeth failure in sprocket drivers in a clinker scraper conveyor of a cement plant. The assessment includes an analysis of the sprocket material and calculations of the stress fields in the teeth surface. The results show the failure is the result of using a sprocket material with high-abrasive resistance but with yield strength lower than required for operating conditions [9]. Yu et al used the finite element to analyse the 1350 scraper conveyor is carried out of the nonlinear finite element method, and during the tension and compression processes, the concave and convex ends of the groove experience plastic deformation. By extending the length of the dumbbell rod concave end section and the diameter of the bell mouth via analysis and comparison, an optimization approach is given to decrease the stress value during the tension and compression process, therefore enhancing the dependability of the scraper conveyor [10].

In this study, a model chain was meshed by using Ansys Mechanical. Ansys Mechanical represents interval values to classify the mesh quality and it is shown in Table 1

Table 1. Mesh quality intervals

	Excellent	Good	Acceptable	Bad
Skewness	0-0.25	0.25-0.80	0.8-0.94	0.98-1
Aspect Ratio	1	1-5	5-10	20
Orthogonal Quality	1-0.95	0.95-0,2	0.20-0.15	0-0.001

2.3 Topology optimization

Topology optimization is an improved method that enables the determination of the ideal material distribution in light of restrictions, performance, and load circumstances[11]. A comprehensive evaluation of topology optimization for additive manufacturing was put out by Zhu et al [12]. Methods of optimization play a big part in structural design. They make it possible to decide on a sensible material distribution while taking into account a variety of functional constraints. In general, consideration is given to the geometric parameters, the topological parameters, and the transverse dimensions of the force elements.

The three primary categories into which structural optimization problems may be divided are:

- The goal of sizing optimization is to determine the ideal values for the various dimensions to achieve the optimum balance between weight and resistance.
- Shape optimization aims to improve a structure's performance by modifying its boundaries.
- Topological optimization: Unlike earlier optimizations, this one is far more flexible since it doesn't take into account any assumptions about the structure's borders or the size and form of its cross sections [13].

Topology optimization of a conveyor chain using ANSYS involves optimizing the material distribution within the chain structure to achieve desired performance objectives. ANSYS provides tools and capabilities for performing topology optimization, allowing engineers to explore innovative design configurations and achieve efficient and high-performing conveyor chain designs. Qie et al made two different topologies related to the scraper conveyor. First topology optimization is applied to the design of the middle pan, which can provide a valuable conceptual design scheme for the selection of the middle pan pattern. The second is applied to the design of the baffle on the scraper conveyer [14, 15]. The topology optimization for Zahang et al was carried out in the scarper After optimization, the scraper's maximum stress value drops to a value that is 26% lower than it was before, the deformation is significantly decreased, and the scraper's overall safety factor rises by roughly 15%. After development, the scraper can adapt to a variety of harsh working circumstances in addition to the original working state, providing regular and effective transportation at work [16]. Martinz et al found that Polymeric materials have a great potential to reduce idlers' weight due to their low density. However, polymers have lower Youngs's modulus when compared to metals, making a hybrid design (metal + polymer) a very suitable option for the idler, the topology optimization results It was showed that a great amount of mass in the polymeric roller is necessary, but the shaft can be as light as possible [17]. In this study, the development aimed to minimize the mass of the chain as much as possible to reduce the loads on the motor, and also to utilize removed parts in recycling processes.

3. Results and discussion

3.1 Results of chain tension force

The study was done using 80 ton/hr conveyor that is produced by Cukurova Silo Company, friction force in between the chain and trough is found by using formula (1). $\mathcal{L}_{cs}$ is 15 meters, q_c was found to be 7 kg/m, In the 1-meter distance there are 14 couples of chains and 3 scrapers in one meter of the conveyor, Total mass equals 7 kg/m, Weight is found to be 68.67 N/m, μ_c is the friction coefficient between galvanized steel trough and steel chain is 0.5 [18], and $cos\,\alpha$ is 1 as the angle of α is 0 degrees as the conveyor is horizontal. (There is no inclination.). Depending on these parameters F_c ≅515N.

Friction force in between grain bulk and trough is found by using the formula (2). ρ_b is taken as $830kg\,/\,m^3$,g is the gravitational constant $9.81m\,/\,s^2$,h is the height of bulk grain in the system 0.15 meters, A_{base} is the base area and $5m^2$, μ_ω is 0.46 [5], k is 0.39, and $A_{si\,de}$ is $2.21m^2$.
Depending on these parameters F_{fb} ≅3293N.

The catenary Effect was calculated to be T_s=31.7 lb = 141N, using equation (4), using the distance in between the center of sprockets as 49.2 ft, the sag distance as 3.937 in, and the meter weight of chain and scraper as 4.705 lb/ft

The total force is found by using the formula (5):
F_{TOTAL} =3293 N+141 N+515 N=3949 ≅ 3950 N

3.2 Determination of stress by using Ansys mechanical on chain link

The results of von Mises stresses and safety factors of the chain link before the topology optimization application and after the topology optimization application are shown in this section. For analysis and topology optimization of the chain model was created in ANSYS Mechanical. One of the assembled chains shown in Figure 7.

Table 2. Mesh Quality of the Model

	Min	Max	Average	Quality
Skewness	1,31e-010	0,49218	3,71e-002	Good
Aspect Ratio	1	2,7615	1,0826	Good
Orthogonal Quality	0,7828	1	0,98856	Very good

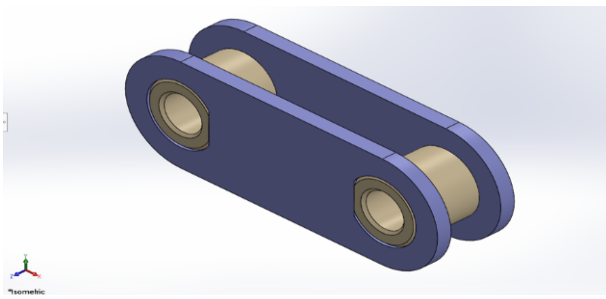

Figure 7. Assembled chain

Tension force is applied to only one of the chain links as the assembled chain includes two identical chain links. The meshed model of one side of the chain link is shown in Figure 8 and the quality is shown in Table 2.

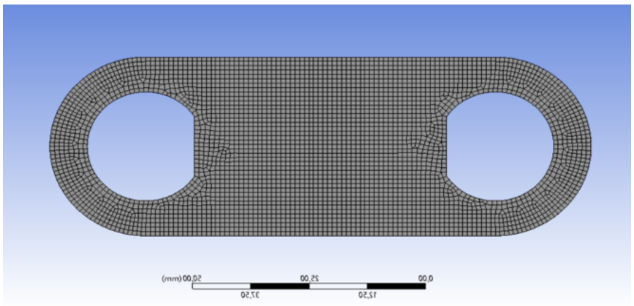

Figure 8. Meshed model of chain link

Force was applied as tension forces for both directions, as it is represented in Figure 9.

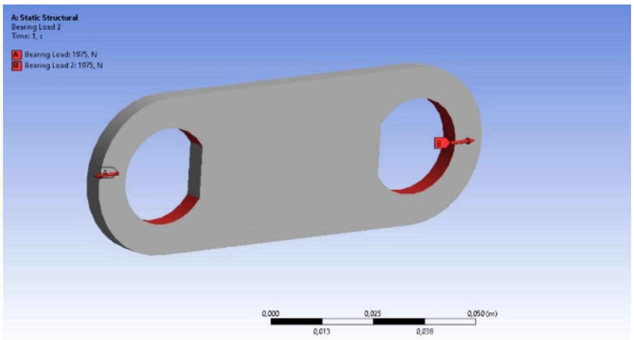

Figure 9. FEA setup

After applying the force, Figure 10 and Figure 11 shows Von Mises Stresses and the Safety Factor of the chain link before topology optimization.

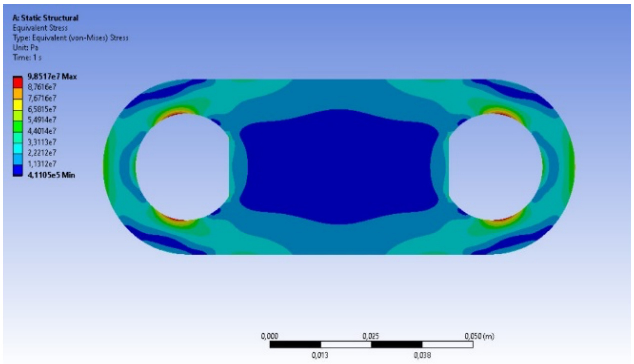

Figure 10. Von mises stresses of chain link

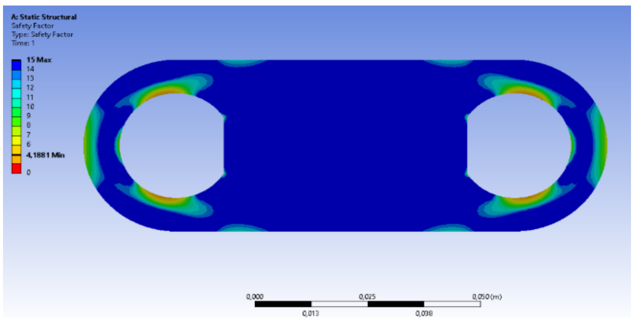

Figure 11. Safety factor of chain link

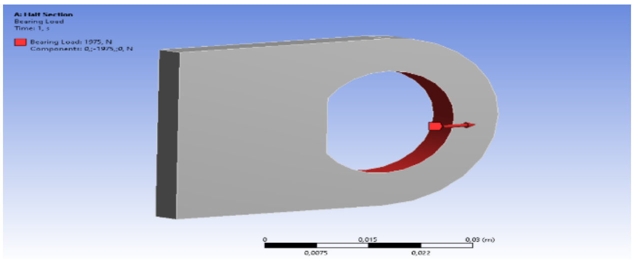

Figure 12. Half chain link FEA setup

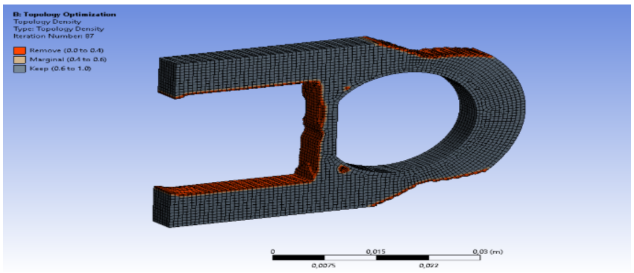

Figure 13. Optimized region of half chain link

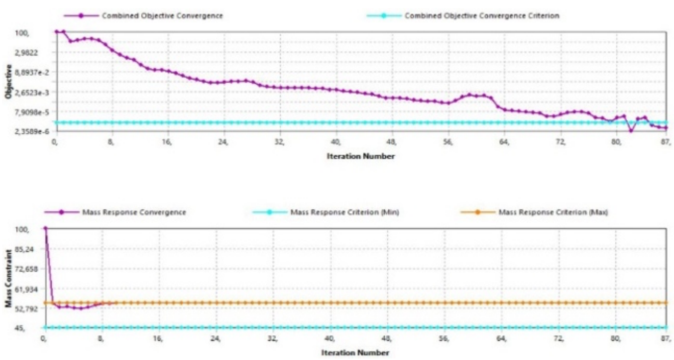

Figure 14. Solution information related to iteration number concerning mass and objective

3.3 Topology Optimization of the Chain.

For topology optimization, the whole chain link was divided into two half-sections as stress distribution is the same for both sides of the chain link. Half section of the chain link was fixed from mid-surface as seen in Figure 12 and result in Figure 13. After topology optimization is applied the new design was generated by considering the production of the part.

Topology optimization was completed at the 87th iteration when convergence criteria were set up at 0.00001 and the minimum normalized density was set as 0.0001.

Taking into account the required manufacturing processes for this new component, the decision to utilize a pressing machine for removing the middle part was made based on the optimization results. The selection of this method aims to streamline the production process while ensuring ease of removal. Consequently, the optimal removal mass ratios, falling between 45 and 55 percent, were chosen to minimize mass while optimizing production efficiency.

Table 3. Difference between optimized and original shape

Properties	Original Shape	Optimized Shape	Change (%)	Properties
Safety Factor	4.773	4.004	16	Safety Factor
Weight(gram)	135	96	28.89	Weight(gram)

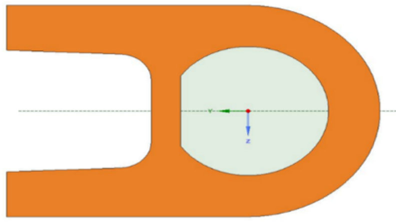

Figure 15. Redesigned optimized half chain link

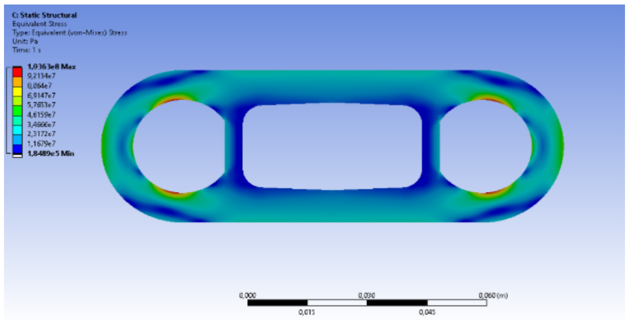

Figure 16. Von mises stresses of optimized chain link

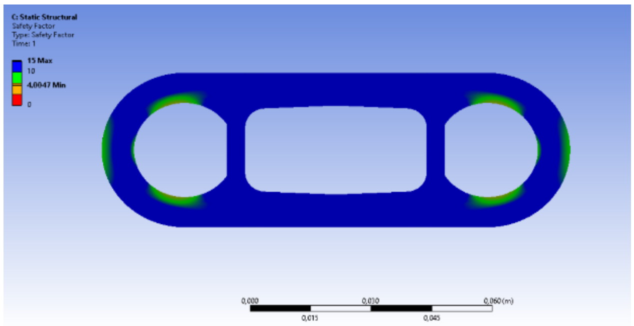

Figure 17. Safety factor of optimized chain link

Finally redesigned part of the half section for production and completed the chain link is shown in Figure 15.

4. Conclusions

In this study, an example of topology optimization is shown for the conveyor chains used in Cukurova Silo for conveying wheat at a ratio of 80 tons per hour. In order to increase the efficiency of the system by reducing the weight of the components without sacrificing the safety factor a lot was the main aim. For the production of the chains, 4140 steel was used and finite element analysis was done in Ansys Mechanical. Von Mises stresses and safety factor values were found. Topology optimization was applied and the region where von Mises stresses are lowest was removed. Considering the production of chains, the shape of the chain was redesigned and analyzed by applying the same force at the same region. Results showed that the safety factor decreased with a ratio of 16% while weight decreased by %28.89. However, this change in safety factor is still acceptable for the chain link. So, the weight is reduced significantly while the safety factor is preserved. In this way, the system efficiency is increased and excessive material can be recycled.

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Author contributions

Hamit Türkmen: Investigation, supervision, project administration, methodology, writing - review & editing

Melih Gazi Kirpik: Software, formal analysis; methodology, writing - review & editing, resources

Tuğrul Sapmaz: Visualization, conceptualization, roles/writing - original draft

Fethiye Yalçin: Funding acquisition, resources, data curation.

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