SHAPE OPTIMIZATION OF AN OVERDESINGED CHAIN LINK BY USING DESING OF EXPERIMENT AND GRAPICAL OPTIMIZATION

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Abstract - Chains are one of the most important structural and carrier element in the industry. Chains often used in lines which is carrying heavy components. Therefore, they are exposed to heavy. Thus, in general chains ,which are carry heavy loads, and their geometries are quite large. In general designers prefer high safety factors for these components so the chain mass is increase unnecessarily. In this study a chain link which works under the tensile loads was investigated according to stress, mass and geometrical properties. The first design of the chain link was determined overdesign. Thus an optimization study was done. Two different geometrical dimensions of the chain were selected design variables. By using design of experiment and response surface method, shape optimization process was done. Also the shape optimization was performed by using graphical optimization method. Both methods gave the same result. As a result of the study the chain mass was decreased nearly %50.

I. INTRODUCTION

Optimization can be defined as, to make the things in a best way or finding the best way from other available alternatives. Modern optimization techniques are frequently used in many areas in the industry nowadays. Especially shape optimization is very appropriate for design engineering. In the shape optimization process, the precise dimension of the products which is provide the desired strength, mass and function are defined. Thus, shape optimization is very significant tool for the design engineers.

Design of experiment study is an another important tool for design engineering. With the development of computer-aided design and finite element method this approach could be easily applied on the new products. By using this method, the effect of design variable on the product quality can be easily determined and the important and unnecessary design parameters can be defined and products with optimum dimension can be design. Thus in the literature, many researchers interested in shape optimization and design of experiment study.

In the literature many researchers were interested in shape optimization, Kaya et al. [1] investigated a failed clutch fork which is used in passenger vehicle. In that study, a clutch fork is analyzed statically an then a fatigue analysis is done. The fatigue analysis results shows that the fork is damaged before its design life. To eliminate this disadvantage of clutch for, topology and shape optimization techniques used respectively. In the first stage by using topology optimization the fork dimensions were determined roughly and the exact dimension were defined by using design of experiment study and shape optimization, as a result of the study the mass of clutch fork is decreased and the fatigue durability of the fork is increased considerably.

A similar study were performed by Dogan et al. [2]. The authors examined tractor clutch PTO finger by using both topology, shape optimization techniques and design of experiment method. In conclusion, the researchers accomplish more than % 50 fatigue durability and % 25 mass reduction.

Khamneh et al. [3] were investigated to estimate the spring-back for creep age forming. In this paper, a design of experiment study was done. Time and temperature were selected as a design variables. Their effect on the spring-back for creep age forming were investigated experimentally. The study shows that temperature was the most effective parameter on the spring-back for creep age forming. At the end of the design of experiment study, the optimum temperature and time values are determined to obtain best mechanical properties of 7075 Alcald alloy.

Luo et al. [4] optimized scaffolds for bio-root regeneration by using shape and size optimization methods. The scaffolds design by using Pro/Engineer and analyzed by using ANSYS Workbench. Height and upper diameter of the scaffold were determined the design variables. By using these variables the optimization procedure were done and optimum scaffold diameters were determined.

In this study an overdesign chain link is investigated in terms of stress and mass prosperities. The chain link is analyzed by using FEM. Based on FEM results the chain link is redesign and two design variables is defined as design parameters. By changing these parameters with different levels, design of experiment study is completed. Two different model is created for the shape optimization and the shape optimization is done in a different way. As a result of the study, the overdesign chain link mass is reduced nearly % 50.

II. FE MODEL OF CHAIN LINK

In this study, an overdesign chain link, which is exposed to tensile forces, was investigated in static conditions. To perform finite element analysis, firstly the chain model was created. The model was created by using Solidworks CAD software package. The chain link geometrical dimensions were determined with the help of real chain. The chain length and height were defined 200 and 55 mm. The real and CAD model chain link view are given in Figure 1.

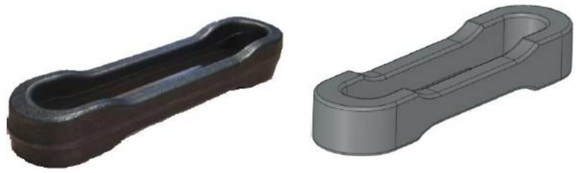

Figure 1. The Real and Solid model of the Chain Link

After the creation of the CAD model, the model was exported ANSYS software to carry out finite element analysis. In real condition the chain link is exposed to, static tensile loading. Thus, the static structural module was selected in ANSYS Workbench. In the Workbench the general static structural procedure is consist of five stages. The first stage of the finite element analysis is defining the material. The chain material is S235 whose mechanical properties is defined below Table 1. The material properties was created in ANSYS by using engineering data.

Material	**S 235**
Modulus of Elasticity	**210 GPa**
Yield Strength	**235 MPa**
Tensile Strength	**370 Mpa**

Table 1.Mechanical properties of Chain Link

The second phase of the finite element procedure is the creation of the finite element geometry. The chain geometry model was imported in STEP file format to ANSYS which was created in Solidworks. Then the procedure was continued with model section. In this section the model was divided into meshes. In this study the model was divided into approximately 35000 hexahedral finite element meshes also the model was consisted of 130000 nodes. The element size of the meshes were selected 2 mm. For the boundary conditions, the static 10000 N was applied on the tensile direction of the chain link. The load value was defined according to chain catalogue. The finite element mesh model and the boundary conditions are shown in Figure 2.

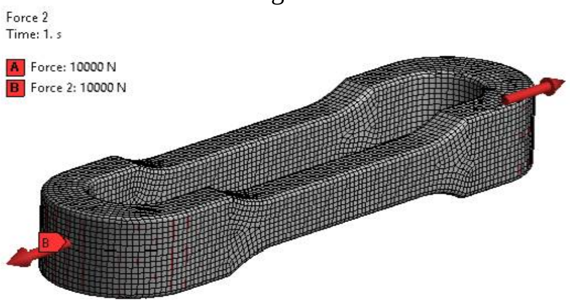

Figure 2. Mesh Model and Boundary Conditions of the Chain Link

The fourth phase of the study is running of the finite element model. In the static structural analysis the fundamental finite element equation which is given below is solved.

$$[K][u] = [F]$$

Where;

K : The stiffness matrix.
u : The displacement vector
F : The vector of applied loads

The equation was solved for all nodes by using ANSYS direct solver. For the calculation of the stress which was occurred on the model the Hooke's law was used in the static structural analysis. The Hooke's law can be defined as;

$$[\sigma] = [E][\varepsilon]$$

Where;

σ : Stress
E : Modulus of elasticity of material
ε : Strains

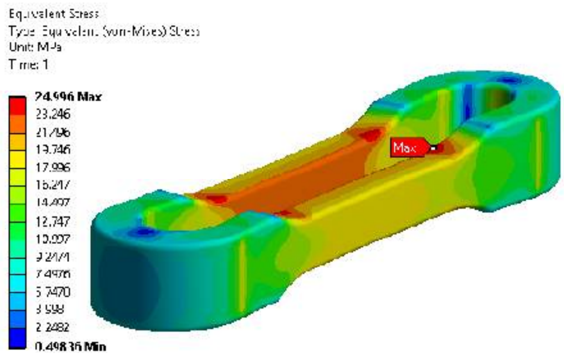

Figure 3. FEA Result of the Chain Link

The last step of the finite element anaysis is post processing. In this stage the stress and displacement values which were occurd on the model is given. In Figure 3. the finite element stress distrubution of the chain link was given. The maximum streses were occrued in the top radius region of the chain. The value of the stress is 25 MPa.

In the decision phase whater the chain is acceptable or not. The stress is given from the finite element analysis shold be compared with the material yield strength. If the stess are bigger than the yield strength the model is not acceptable. When these two values are compared the safetly factor of the chain could be easily calculated.

The safetly factor of the chain link was also calculated in ANSYS. In Figure 4. the safetly factor disturubiton of the chain link was given. The avarage safetly factor of the chain link was defined 10.

The safetly factor value 10 is too much for the static systems. Thus; it could be said that this chain link is overdesign and the mass of the chain too much. Thus, by using optimization methods the chain link should be optimized.

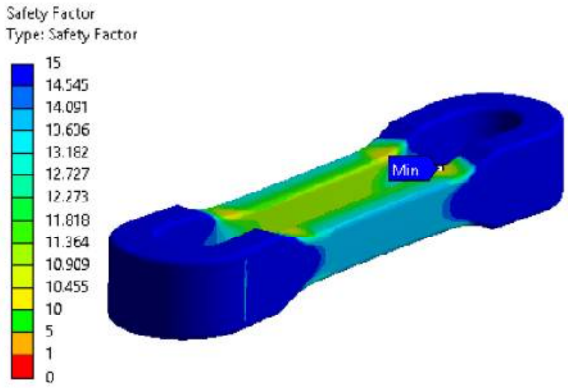

Figure 4. Safety Factor of the Chain Link

III. RESPONSE SURFACE METHOD AND SHAPE OPTIMIZATION OF THE CHAIN LINK

3.1 Shape Optimization With Response Surface Method

Shape optimization is a processes that is used to determine the optimum dimensions of the mechanical components. To perform shape optimization a concept design and design variables should be defined first. Then the design variables effect on the maximum stress, mass, maximum displacement, fatigue life etc. should be determined and this effect should be defined as a mathematical equations. Then the optimization problem solved by any optimization method.

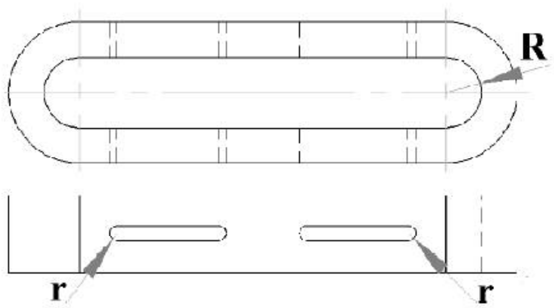

Figure 5. Shape Optimization Design Variables

In this study, the concept design was defined as, Figure 5 and two concept design variables which were chain inner radius (R) and hole radius (r) were defined. The design variables defined to reach minimum mass.

The design variables effect on the maximum stress and mass were investigated parametricly. The new model was created in ANSYS and two design variables were defined as a parameter in ANSYS. The chain inner radius (R) changed from 14-22 mm, beacuse of the pin diameter was not possible to define chain inner radius up to 22 mm. Also the hole radius was changed from 3-7 considering the stress concentration factor. The full factorial desing of experiment table is given below.

Experiment Number	Chain Inner Radius (R)	Hole Radius (r)	Max.Eq Stress (MPa)	Mass (g)
1	14	3	26.2	1263
2	16	3	32.6	1100
3	18	3	51.9	933
4	20	3	91.7	757
5	22	3	179.2	577
6	14	5	29.6	1173
7	16	5	36.7	1023
8	18	5	52.8	867
9	20	5	92.9	705
10	22	5	182.7	538
11	14	7	34.3	1070
12	16	7	42.3	935
13	18	7	55.6	794
14	20	7	94.9	646
15	22	7	186.9	494

Table 2.Full Factorial Design Table

To perform shape optimization the effect of dimensions on the mass and stress should be define as a equation form. For this aim different equations, which were best fit the design of experiment table, were created.

For the maximum Von-Mises Stress and total mass, model1 and model2 which are given below selected respectively.

$$\textbf{Model 1}= a_1R^3r^2 + a_2R^3r + a_3R^3 + a_4R^2r^2 + a_5R^2r + a_6R^2 + a_7Rr^2 + a_8Rr + a_9R + a_{10}r^2 + a_{11}r + a_{12}$$

$$\textbf{Model 2}= a_1R^2r^2 + a_2R^2r + a_3R^2 + a_4Rr^2 + a_5Rr + a_6R + a_7r^2 + a_8r + a_9$$

The unknown coefficients of the equation were defined by using MATLAB surface fitting tool. As a result of the surface fitting operation. The stress and mass equations which are defined as;

<u>Maximum Von-Mises Stress;</u>

$$f(h,t)_{Stress} = -1.456\ 10^{-3}\ R^3r^2 + 0.022568\ R^3r + 0.3094\ R^3 + 0.06552\ R^2r^2 - 1.01556\ R^2r - 13.923\ R^2 - 0.9948\ Rr^2 + 15.4194\ Rr + 211.395\ R + 4.98\ r^2 - 77.19\ r - 1058.25$$

<u>Total Mass;</u>

$$f(h,t)_{Mass} = -7.5\ 10^{-4}\ R^2r^2 + 0.03675\ R^2r - 0.85275\ R^2 - 0.059\ Rr^2 + 2.891\ Rr - 67.083\ R + 2.238\ r^2 - 109.662\ r + 2544.606$$

The coefficient of determination of these equations were calculated r^2=0.991. This means that the models were so close to design of experiment study. Therefore, these equations could be use in the shape optimization algorithms.
By using these equations, the responses of maximum Von-Mises stress and total mass are given Figure 6-7. It is clearly seen that chain inner radius is much more effective than the hole radius in terms of stress and mass values of the chain.

Now the optimization problem could be defined. As a constrains of the optimization problem, the maximum Von-Mises stress is defined. Because, the safety factor cannot be under 2.5 thus, the maximum Von-Mises stress cannot be more than 100 MPa. Also the geometrical constraints are selected as a constraints functions. Finally the objective function is defined minimum mass.

The optimization problem can be defined as;

- ✓ Objective function is:
  Minimum $[f(R,r)_{Mass}]$

- ✓ The constraints functions are;
  Constraint 1 - $f(R,r)_{Stress} \leq 100$ MPa
  Constraint 2 - $14 \leq R \leq 22$
  Constraint 3 - $3 \leq r \leq 7$

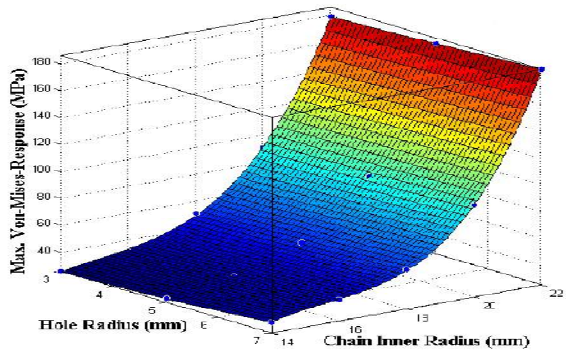

Figure 6. Response Surface for Maximum Von-Mises Stress

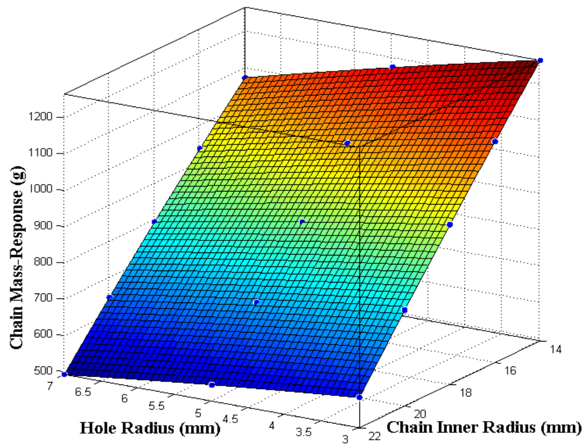

Figure 7. Response Surface for Chain Link Mass

After determination of the optimization problem in MATLAB, the problem was solved by using MATLAB fmincon function. As a result of the study the optimum chain dimensions were defined as in Table 3.

Mass (g)	**631.899**
Max Von-Mises Stress (MPa)	**100**
Height (h) (mm)	**20.0945**
Thickness (t) (mm)	**7**

Table 3.Result of the Shape Optimization

3.2 Shape Optimization With Graphical Optimization Technique

Optimization functions which are consisted of two variables can be also solved with graphical optimization method. In this method, firstly all constraint functions are defined and the feasible region is determined. The equivalent curves (contours) of the objective function are drawn and the optimum values are read from the graph [5]

In this study, the optimization problem was also solved with graphical optimization. The red lines defined the geometrical constraint functions which are $14 \leq R \leq 22$ and $3 \leq r \leq 7$ and the blue line is symbolize the stress constraint f(R,r)Stress $\leq$ 100 MPa. Thus the feasible region of the optimization problem is defined.

The equivalent curves of the objective function was define with the black curve for different levels of the mass which are 500, 632, and 700. The optimum point was determined in the feasible region where the intersection point of the objective function and the constraints functions. Hence the hole radius and chain inner radius determined 7 and 20.095 mm. In this conditions the maximum Von-Mises stress which was occurred on the chain was define 100.017 MPa (Figure 8).

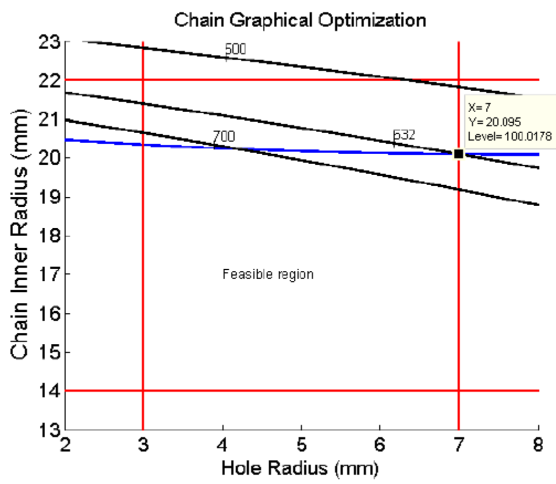

Figure 8. Graphical Optimization

Both MATLAB fimincon function solver and graphical optimization results matched well. However, the chain link which has optimum dimensions has not validated yet. Thus in the section 3.3 the validation process of the chain link is identified.

3.3 The Verification of New Design

After the determination of the optimum dimensions of the chain link a verification was needed. Thus, with some minor revisions, the chain link which has the optimum dimensions modeled again (Figure 9).

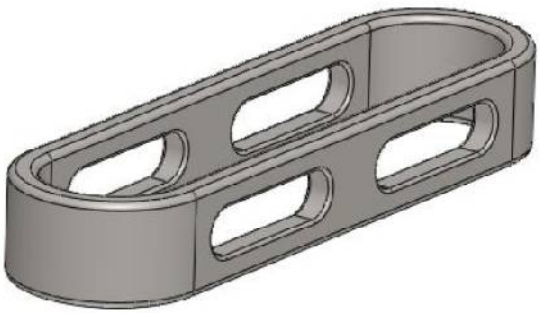

Figure 9. New Design of Chain Link After Shape Optimization

The optimized new geometry imported ANSYS for the verification analysis. In this analysis, mesh type, size were selected same with the first analysis. Also all boundary conditions were taken same. As a result of the validation analysis, the maximum Von-Mises stress was given 97.421 MPa. This value was calculated 100 MPa by using both solving optimization problem with fmincon and graphical method.

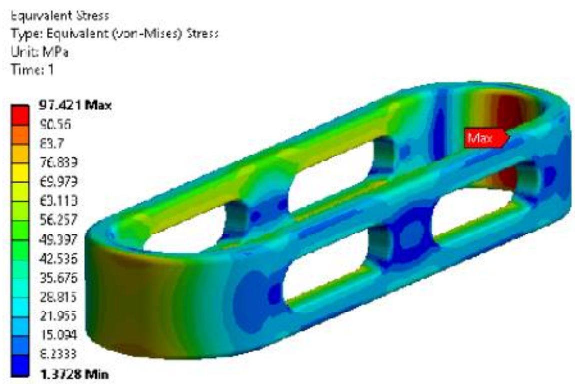

Figure 10. Von-Mises Stress Distribution of Novel Design Chain Link

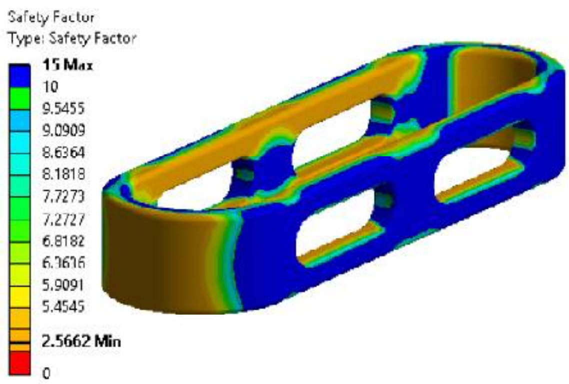

Figure 11. Safety Factor of the Optimized Chain Link

In the last phase of the study the safety factor was investigated. The safety factor of the chain link was determined minimum 2.56. The safety factor distribution of the chain link was given (Figure 11). This safety factor is enough and guarantees strength of the chain.

The results of the study were presented in Table 4. The overdesign chain link was optimized and the mass of the chain link was decreased nearly %50. The maximum stress values were increased normally but the incensement of the stress values were in the safety region.

	Over Designed Chain Link	Optimized Chain Link	Result
Max Von-Mises Stress (MPa)	**25**	**97**	**Acceptable**
Mass (g)	**1172**	**632**	**Decreased 46 %**
Average Safety Factor	**10**	**2.6**	**Acceptable**

Table 4.Comparison of First and Last Chain Link

CONCLUSION

In this study an overdesign chain link was investigated. Firstly the chain link was analyzed in ANSYS static structural module. It was seen that the maximum Von-Mises stress valeus were too low and the mass of chain link was too much. To optimize this chain link, two design variables which were chain inner radius and hole radius were selected. A full factorial experiment table was created by using these variables. Equations which were used to find design of experiment table values, were created in MATLAB. Two different optimization methods were applied on this chain link and shape optimization procedure was performed. As a result of the both MATLAB fmincon function and graphical optimization method, the precise dimensions of the chain link was determined. To verify these dimensions, the finite element analysis procedure was repeated and the last design was validated. At the end of the study the mass of the chain link was decreased nearly 50 % and the safety factor of chain link was taken to an acceptable limit.

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