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Research article

Design of forks and lifting system of a 10-ton forklift truck by FEM simulation

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Abstract

A forklift is a powered industrial truck used to lift and move materials over short distances. Forklifts have become an indispensable piece of equipment in manufacturing and warehousing. On the other hand, these forklift trucks such as every industrial equipment, need maintenance and repair. The lifting system including forks, chain, and hydraulic actuator, is the key point in forklift trucks and should be designed properly and flawlessly. Accordingly, in the present study, the lifting system of 10-ton forklift trucks is designed. It is worth mentioning that the forklift truck was an 8-ton truck before, and due to the incapability of its lifting system, it was redesigned in this project. Two materials (St32 and St52) are designated for the forks. Then, the forks are designed in CAD software, and the FEM analysis is performed to designate the dimensions and material of the forks and finally, through FEM software (ANSYS). To validate the FEM results, the analytical method will be applied as well. In addition, other components such as the chain and hydraulic actuator are designed and selected according to analytical calculations. In the end, the designed forks are manufactured and mounted to the forklift, and their function is tested. By comparing the obtained results, the St52 alloy with a safety factor equal to 1 shows better mechanical behavior than St37 with a safety factor equal to 0.8. Therefore, the St37 alloy is not proper for this purpose, moreover, the strength of the St52 alloy should be increased by heat treatment or other methods.

Keywords: Machine part design, Forklift truck, Mechanics of materials, Ansys simulation.

1- Introduction

A forklift (also called an industrial truck, lift truck, fork truck, fork hoist, and forklift truck) is a powered industrial truck used to lift and move materials over short distances. Forklifts have become an indispensable piece of equipment in manufacturing and warehousing. The lifting system (Fig. 1) including forks, chains, and hydraulic actuator, is the key point in forklift trucks.

Some literature related to the design and FEM analysis of forklift trucks and other lifting mechanisms is reviewed as follows:

Wang et al. focused on the innovative design of a new lifting mechanism for forklift trucks. Firstly, they proposed a spatial multi-link lift-guidance mechanism. And then, under the constraints of this mechanism, the mobility of the fork and fork frame was investigated in theory [1]. Choi et al. applied the light bulb shadow test, a manikin vision assessment test, and an individual test to a forklift truck to identify forklift truck design factors influencing visibility [2]. Cohen et al. used a behavior (work) sampling approach to both develop and evaluate the effectiveness of an occupational safety training program for industrial lift truck operators. Two studies, each using different experimental designs and performed at two separate warehouses, were conducted, resulting in a total of 96 operators trained [3]. Nowadays, FEM solution is widely applied to design mechanical equipment [4-7]. Bozkurt et al. performed static analyses of structural parts of a diesel forklift using the Finite Element Method (FEM), and possible modifications based on the original geometry of parts were utilized with respect to stress distributions at critical regions to improve the reliability of the forklift design [8]. Ma et al. adopted the finite element method to improve design accuracy and shorten its cycle, in the process of crane designing. The integrated finite element analysis model was established for the whole column jib crane using finite element analysis software ANSYS [9]. Prajapati focused on floor-mounted jib cranes, in which the trolley hoist moves along the length of the boom and the boom spins, allowing the lifted load to be moved skillfully in a relatively circular area. He investigated the deformation patterns in the jib crane with different designs and the work was carried out by designing reinforcement to overcome those stresses in the component [10]. Li et al. established the mathematical model for multi-objective optimal design of superstructure which superstructure was served as a whole. Reduction of the maximum of the luffing resistance moment and unbalanced torque, as well as decrease of the fluctuations of hanging point vertical displacement, were taken as the objective functions, and the coordinate of the hinge point position, structure length, and counterweight were regarded as the design variables [11]. To Manufacture the forks, forming and machining methods should be applied [12-15]. Candas et al. designed a crane by an engineering work group, which was examined in terms of static structural test analysis before being put into use according to the API Spec II [16]. Haniszewski et al. presented an approach to numerical modeling of an I-beam crane, using the finite element method particularly the most loaded elements at different speeds [17]. Solazzi et al. reported results related to the implementation of innovative materials such as composite materials to a lifting apparatus and in particular a classic jib crane with a capacity of 500 kg [18]. Sirojuddin et al. aimed to optimize the design of several variations of the crane structure of load lifters that meet the criteria of optimizing safety factors [19]. Miralbés et al. presented a new methodology of calculation by means of the FEM applied to crane jibs. Their analysis has been carried out in terms of strength and stiffness, for any type of crane jib: telescopic crane, lattice crane, and closed beam crane [20]. Bollimpelli et al. presented a static, modal, and harmonic analysis of a column-mounted jib crane using ANSYS software. They modeled a column-mounted jib crane of 1.5 Ton capacity using CATIA which was imported into ANSYS where calculations were performed [21]. There are several other surveys have been conducted on this issue some of which are introduced in [22-35]

In the present study, the lifting system of 10-ton forklift trucks is designed. It is worth mentioning that the forklift truck was an 8-ton truck before, and due to the incapability of its lifting system to lift the cargo of the factory where it is applied, its lifting system was redesigned and remanufactured in this project. This system includes forks, hydraulic actuators, chains, and links. Two materials (St32 and St52) are designated for the forks. Then, the forks are designed in CAD software (SolidWorks) and the FEM analysis is performed to designate the properness of the dimensions and material of the forks. Moreover, to validate the FEM results, the analytical method will be applied. Finally, the manufactured forks according to the FEM results are tested experimentally.

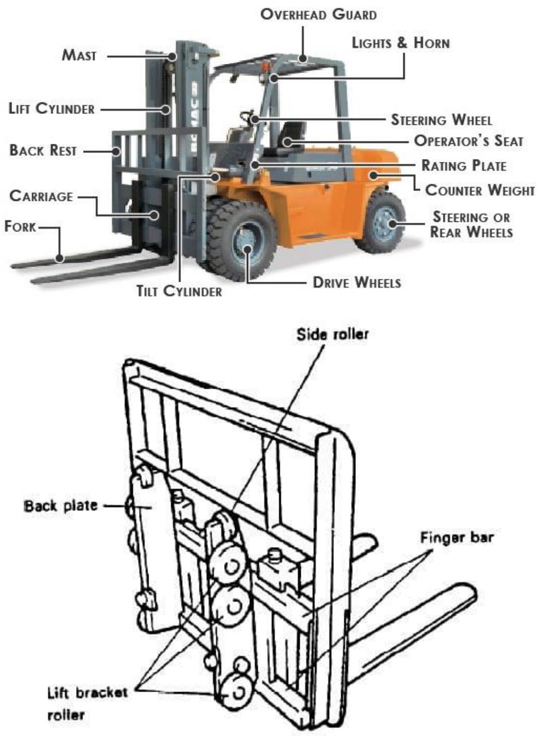

Fig. 1 Forking system of a forklift truck

2- Materials and Methods

In this study, the simulations are performed in ANSYS software version 2022. The initial model is designed via SolidWorks software. The model contains forks, links, chains, and other parts are modeled in SolidWorks according to Fig. 2.

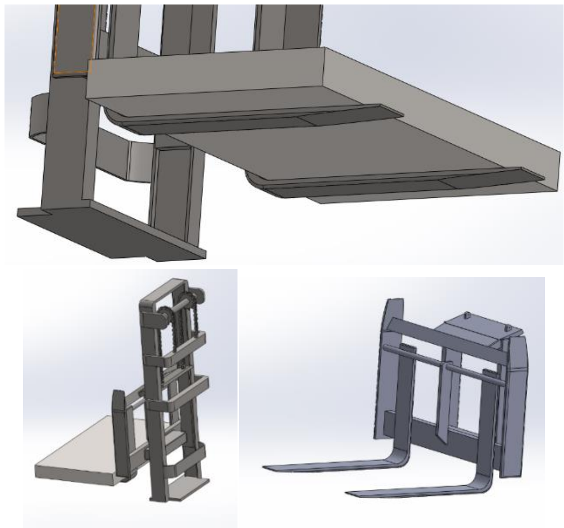

Fig. 2 Initial model of lifting system

In this project, two alloys are designated for the fork's material: St37 and St52. The chemical composition and the mechanical properties of these alloys are demonstrated in Table 1 and Table 2 respectively.

Table 1: Chemical composition St37 and St52

Steel grade	%C	%Si	%Mn	%P	%S	%N
ST37-2	0.20	0.15	0.35	0.05	0.050	0.01
ST52	0.23	<0.6	<1.60	0.05	0.045	0.01

Table 2: Mechanical property of St37 and St52

Steel grade	Tensile strength, [MPa]	Yield strength [MPa]	Elongation %
ST37-2	360 - 460	235	25
ST52	510 - 630	365	21

To investigate this project in ANSYS, three modules can be used: rigid dynamic, static structural, and transient structural. In the present study, the third module - transient structural- has been applied. The transient structural module is proper for problems with high deflection as well as high velocity. This module also has a higher analysis rate.

In the next step, the connections among parts in the Connection module are defined. For this purpose, the connection between the cubic load and the forks is defined and the coefficient of friction is presumed 0.1.

The Meshing is defined in the Mesh module. According to Fig. 3, meshing is defined for the forks and other related parts. Here, due to the significance of the forks, these parts have fine mesh sizes; despite the other parts such as links which have larger mesh sizes. If the mesh size of the whole of the mechanism is identical, the run time increases dramatically. The mesh size is 100mm and it is a 2D (surface mesh) type. By increasing the number of mesh elements, the results of the simulations converge. Figure 4 shows the mesh convergence diagram for maximum stress in the part. According to Figure 4, after 40000 elements, the stress converges to 362MPa. In addition, the mesh control is applied to investigate the convergence of the results.

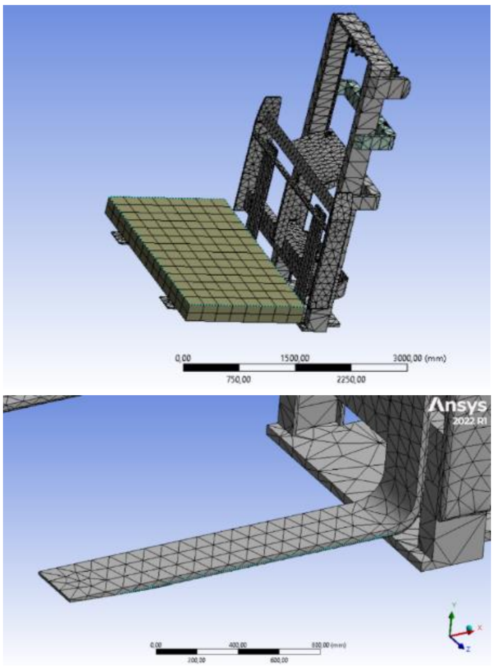

Fig. 3 Meshed part

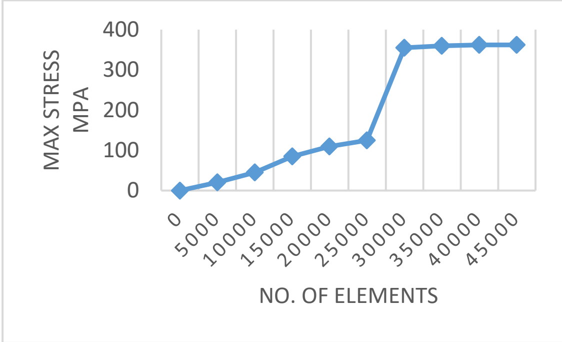

Fig. 4 Mesh converges

The next step is to run the mechanism for forks and other parts to lift the load. For this purpose, the forks move vertically and they are guided to the back mast (rails). To run the mechanism, two boundary conditions should be defined; first, the weight of the load which is vertical and downward. The second boundary condition is imposing the vertical displacement on the forks which move 500mm in a second (according to the manufacturer's catalogue).

3-Results & Discussions

The maximum stress has been calculated by ANSYS according to Fig. 5 As it is obvious, the maximum Von Mises stress is obtained at 362MPa, therefore, St37 alloy is not proper for this purpose. The safety factor for St52 alloy is approximately equal to 1 which is not acceptable.

As Fig. 5 shows, the maximum stress occurs on the knee of the forks. In other words, the knees are the weakest point of the lifting system and should be fortified.

It is worth mentioning that there are many procedures by which the safety factor can increase are available including:

- Applying alloys with higher strength
- Improvement of the fork's design, i.e., using rib and stiffer
- Enhancement of material strength by heat treatment methods

In addition, Fig. 6 and Fig. 7 show normal and shear stress in the forks.

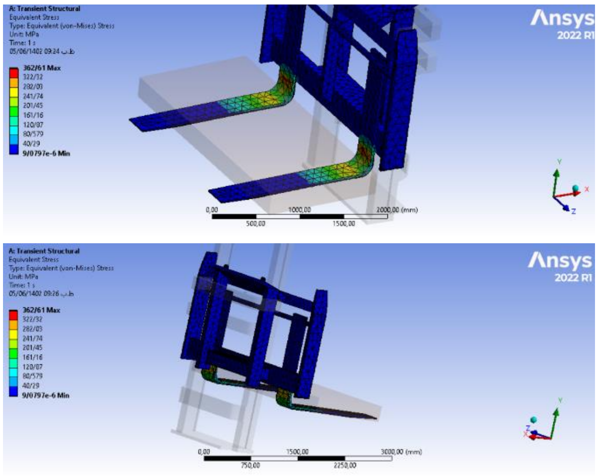

Fig. 5 Von-Mises stress

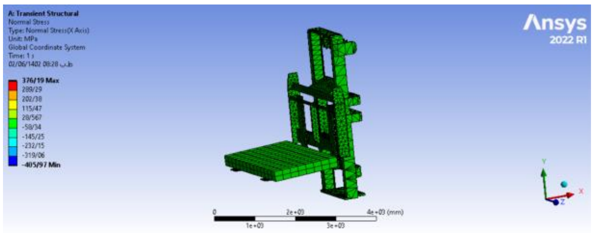

Fig. 6 Normal stress

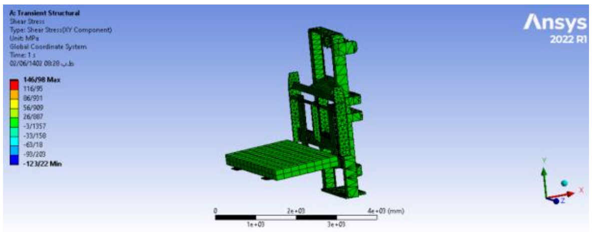

Fig. 7 Shear stress

Fig. 8 demonstrates the strain of the forks. According to Fig. 8, the maximum strain occurred in the knee section of the forks and it is approximately equal to 0.002mm/mm (for St52).

Finally, Fig. 9 shows the displacement (elongation) that occurred in the forks. As it is clear, the maximum elongation occurs in the knee section and equals 500µm (for St52).

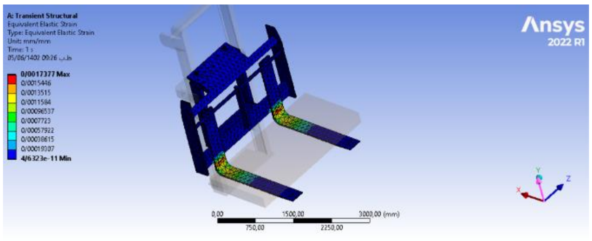

Fig. 8 Strain

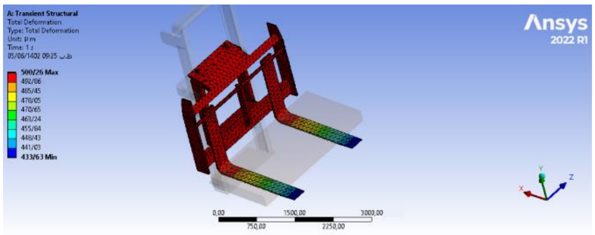

Fig. 9 Elongation

Analytical solution for forks:

The load imposed on the forks is presumed statically and acts as a load vector on the geometric center of the forks according to Fig. 10.

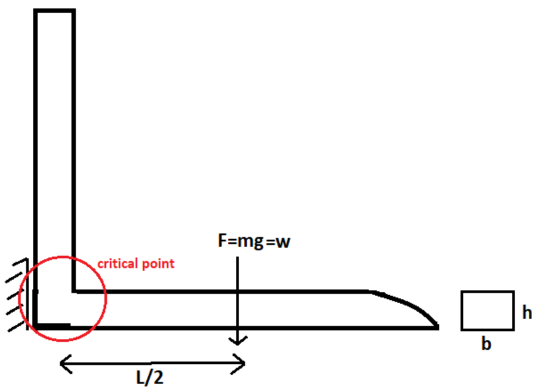

Fig. 10 Free diagram of fork

The required equations for the calculation of stress in the knee of the fork are as follows:

$$M = F \times \frac{L}{2}$$

$$\sigma = \frac{Mc}{I}$$

$$I = \frac{bh^3}{12}$$

$$c = \frac{h}{2}$$

If m=10/2 tons (because of two forks), L= 1m, b=10cm, and h=5cm then the maximum stress in the knee section of the forks is obtained σ=335 MPa. The stress obtained through the analytical method is 6% lower than that obtained through FEM analysis which is acceptable.

Designing of hydraulic cylinder and leaf chain:

The hydraulic jack should lift the 10-ton load. The hydraulic pump used in the forklift truck is piston-type which provides 25MPa pressure. Therefore, the size of the hydraulic cylinder can be calculated from the following equation:

$$(D^2 - d^2)\frac{\pi}{4} = \frac{P}{F}$$

In which, P=25 MPa and F=100kN.

The lifting system is demonstrated in Fig. 11. The hydraulic cylinder has been chosen from a well-known Chinese manufacturer “AiSoar”[1]. The selected hydraulic cylinder and its specifications are shown in Fig. 12. The effective area ($(D^2-d^2) \times \pi/4$) of the selected hydraulic cylinder is 2.24 in^2 (1445mm^2).

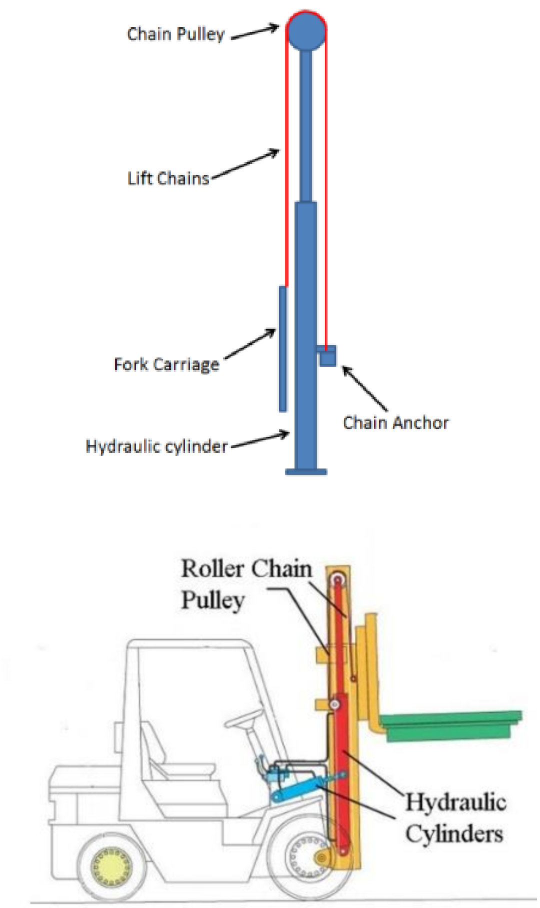

Fig. 11 Lifting system

Capacity (Tons)	10
Stroke (in)	6.14
Oil Capacity (in^3)	13.79
Cylinder Effective Area (in^2)	2.24
Minimum Height (in)	9.72
Maximum Heights (in)	15.86
Outside Diameter (in)	2.24
Weight (lbs)	11.000000

Fig. 12 Applied hydraulic cylinder and its specifications

[1] https://www.aisoarhydraulics.com/

The leaf chain of the forking truck is responsible for transferring the force from the hydraulic cylinder to the forks (Fig. 13). Two leaf chains are applied Simultaneously to lift a 10-ton load, therefore, each chain carries a 5-ton load. The leaf chain has been selected from a famous Chinese manufacturer “Maxizm Machinery (Qingdao)” and its specifications are shown in Fig. 14.

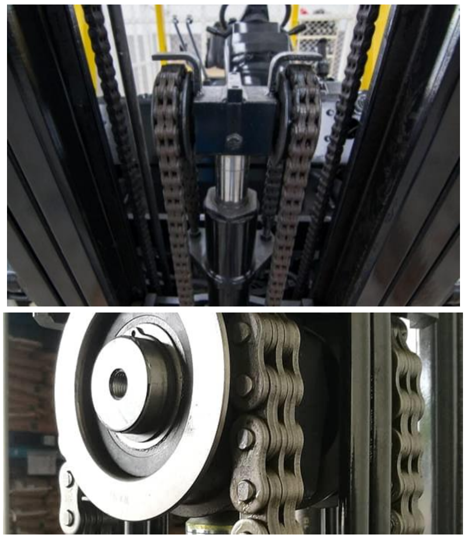

Fig. 13 Leaf chain in a forklift truck

Model	CPCD100	unit
Power Unit	Diesel	
Rated Capacity	5000	kg
Load Center	600	mm
Mast height,extended(with backrest)	4415	mm
Standard Lift Height	3000	mm
Overhead guard height	2560	mm
Overall length(without forks)	4210	mm
Truck body width	2165	mm

Fig. 14 Applied leaf chain and its specifications

Manufacturing of forks:

The forks were manufactured with St52 alloy and then, they were heat treated to increase their strength and finally, they were mounted to the forklift according to Fig. 15, The function of the forks in lifting loads was acceptable and no signs of damage were observed throughout them. This verifies the results of FEM simulations. The manufactured forks were heat-treated to enhance their strength and hardness.

Fig. 15 Manufactured forks

4- Conclusion

In the present study, the lifting system of 10-ton forklift trucks was designed and manufactured. Two materials (St32 and St52) were designated for the forks. Then, the forks were designed and the FEM analysis was performed to designate the dimensions and materials of the forks. To validate the FEM results, the analytical method was applied as well. The following conclusions can be drawn from the present work:

- The maximum Von Mises stress is obtained at 362MPa, therefore, St37 alloy is not proper for this purpose. The safety factor for St52 alloy is approximately equal to 1 which indicates the requirement for heat treatment of the forks.

- The maximum stress occurs on the knee of the forks. In other words, the knees are the weakest point of the lifting system and should be fortified.
- The maximum strain occurred in the knee section of the forks and it is approximately equal to 0.002mm/mm (for St52).
- The maximum elongation occurs in the knee section and is equal to 500µm (for St52).
- The hydraulic cylinder was selected from a Chinese manufacturer and the effective area ((D2-d2) × π/4) of the selected hydraulic cylinder was obtained at 2.24 in2 (1445mm2).

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