2006-55: A HYDRAULIC WOOD-PALLET MACHINE

Cheng Lin, Old Dominion University

A HYDRAULIC WOOD-PALLET MACHINE

Abstract
This paper presents a design and test of a wood-pallet machine. The project was supervised under the Technology Application Center (TAC) at Old Dominion University.
A hydraulic-power machine was designed to press six metal plates simultaneously onto six end surfaces of a wood pallet, which is used to stack items during movement or storage. Operation of the machine significantly reduces the manual hammering time from four minutes to forty five seconds. Students were guided to design the mechanical components and hydraulic power system. Animation software using Automation Studio and Autodesk Inventor simulated the system during the design stage before the machine was fabricated. Main design equations are also given in this paper.

1. Introduction

The course of Automation and Controls offered in the Mechanical Engineering Technology Program of the Department of Engineering Technology at Old Dominion University has the following objectives:[1]

(1) Pneumatic components and pneumatic circuit designs.
(2) Feedback from electrical sensors and related ladder diagrams.
(3) Introduction to Programmable Logical Controllers (PLC)[2,3] and programs.
(4) Integration of pneumatic, electrical, and/or hydraulic components with PLC programs.

To let students have hands-on applications in this course, a two-hour/week lab is also offered to train the students to integrate mechanical, pneumatic, and electrical components with ladder diagrams or PLC programs. The lab basically includes three main sessions: (1) four weeks of pneumatic applications, (2) four weeks of pneumatic components, electrical sensors, and ladder diagrams, and (3) five weeks of PLC programming.[2,3] The lab, however, does not include hydraulic system design. Although the design logic between pneumatic and hydraulic systems is very similar, to have TAC (Technology Application Center) projects in the area of hydraulic system certainly helps students gain industrial experiences before they graduate from the department. In this paper, a faculty student project with design and fabrication of a hydraulic wood-pallet machine using hydraulic power is used to fulfill this purpose.
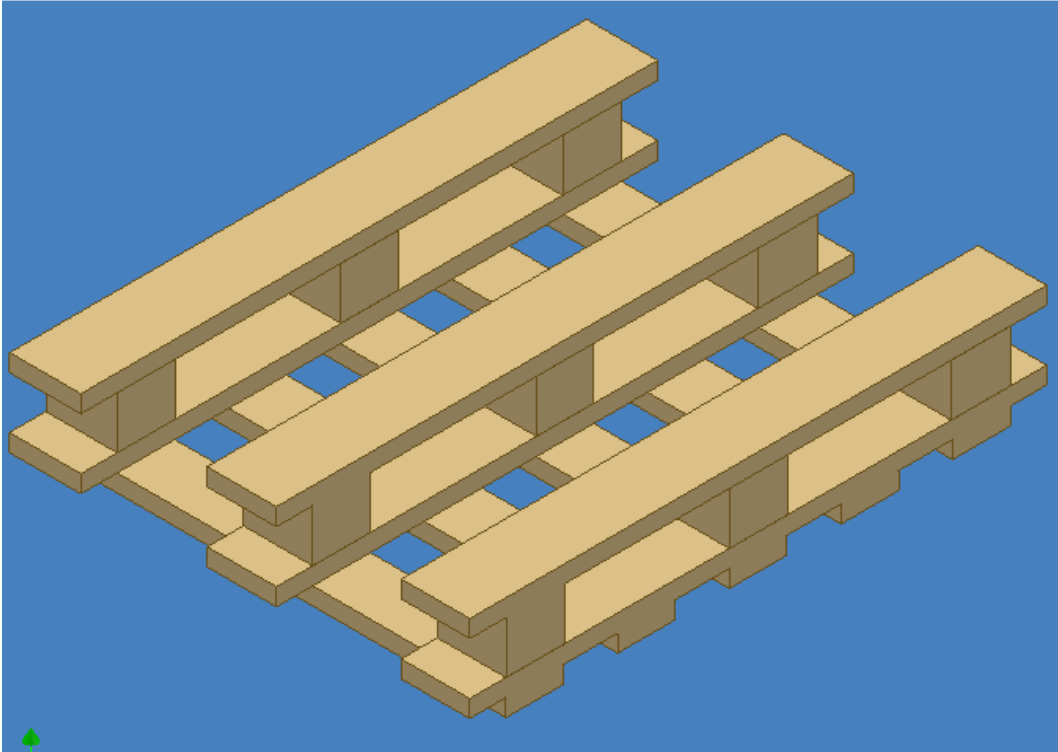
Figure 1: Wood Pallet.

As given in Figure 1, wood pallets are used to stack items during moving or storage. They are made of wood plates jointed by nails. To strengthen a wood pallet from been damaged due to collisions during the transportation processes, a metal plate with nails on one side, as given in Figure 2, has been nailed onto a side surface of the wood pallet. In this application, six nail plates in total are needed for each wood pallet. Figure 3 shows the nail-plates fitted onto a wood pallet. Originally the operation was done by a manual hammering operation, which required time and labor. In addition, the hammering operation also generated noise. To solve these problems, a machine using hydraulic power was designed to press the six nail plates onto the six side surfaces simultaneously.
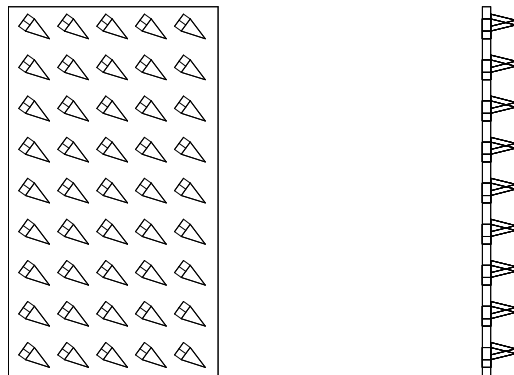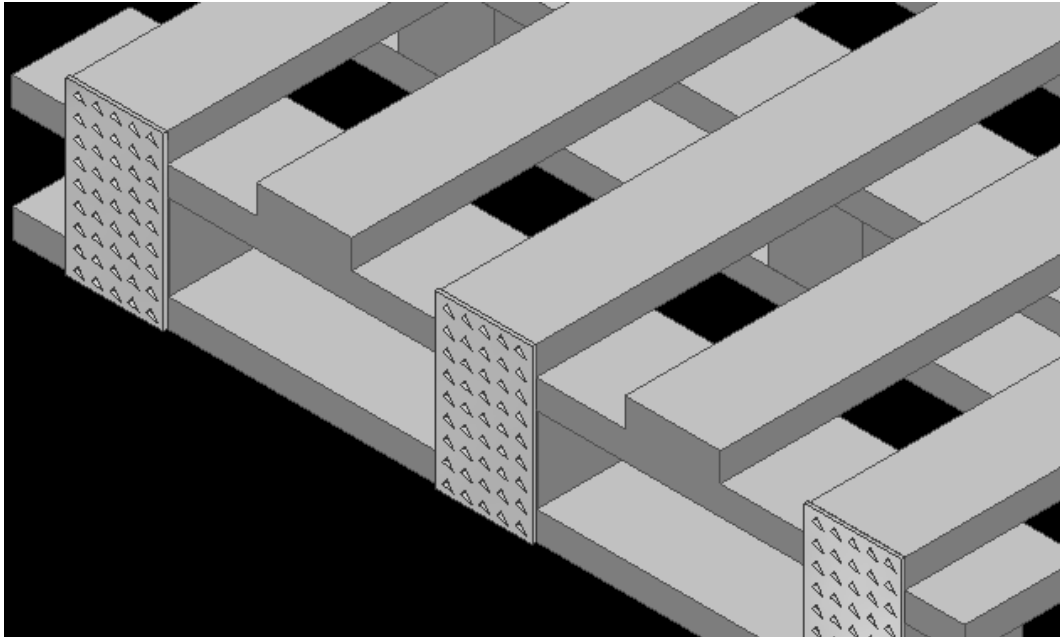

Figure 2: Nail plate.

Figure 3: Nail plates fitted onto a wood pallet.

2. Students Roles

In this project, students were divided into two groups: (1) mechanical design and (2) hydraulic circuit design. Design tasks in each group are described in the following sessions. In mechanical design, students were asked to seek the force required to press the nails onto the pallet surfaces, design the press-operation mechanism, and place dimensions on the design drawings. In hydraulic circuit design, students were asked to control the operation cycle time, to determine the diameter dimension for hydraulic cylinders, and to perform hydraulic circuit design.

3. Nailing Force

A material testing machine[4], as given in Figure 4, was used to test the force required to press a plate onto a wood pallet surface. With several tests performed, results showed that the machine needed approximately 6000 lb to press one nail plate onto a surface. To account for varying properties in the wood material, the design used 10,000 lb of compression force in the calculation.
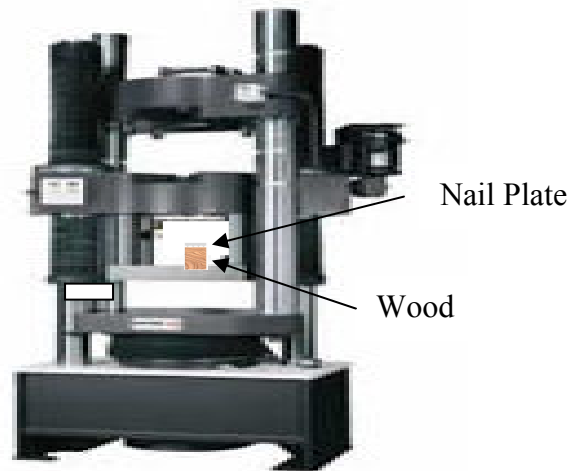
Figure 4: Compression test of the nail plate to wood pallet**.**

4. Diameter of the Hydraulic Cylinder
The diameter of the hydraulic cylinder can be calculated by using the following equation[5]:

$$F = P* (p/4)*d^2 \tag{1}$$

where F is the compression force, in this case $F = 10,000\ lb$; P is the hydraulic pressure and in this case, $P=1500\ psi$. By substituting these values into Equation (1), the diameter of the hydraulic cylinder d is found to be approximately 3 inches.

5. Hydraulic Force Mechanism
To save the working space of the whole system, the hydraulic components were placed under a 6'x5'x4'working table. The press-operation mechanism is shown in Figure 5. With this simple linkage design, the hydraulic force can be transmitted from a hydraulic cylinder to a compression head, which is located on the top surface of the working table. When the double-acting hydraulic cylinder is moving forward, a compression force is exerted on the top of the working table to press a metallic plate onto a wood pallet surface. When the cylinder retracts, a clear space is created to remove the wood pallet.
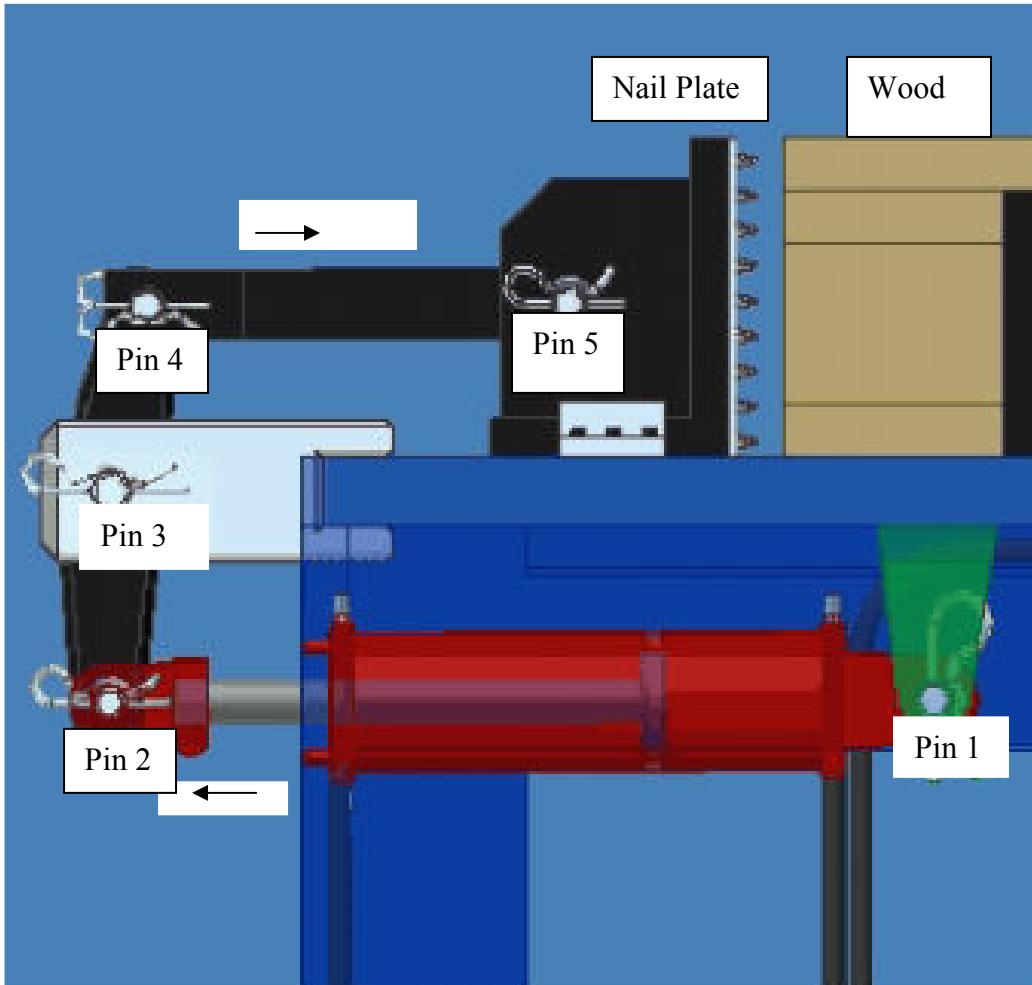
Figure 5: Nailing Mechanism.

7. Pin Diameter
Diametric size of the five pins in Figure 5 can be found from the following equation:[5]

$$F = S_{sw}*(pd^2/4) \qquad (2)$$

where F is the force from the hydraulic cylinder, in this case $F = 10,000\ lb$; S_{sw} is the allowable shearing stress; d is the pin diameter; Using maximum shear stress theory, S_{sw} can be found from the following equation[5,6]:

$$S_{sw} = S_{ys}/(2*Fs) \qquad (3)$$

where S_{ys} represents the yield strength of the pin, in this case, $S_{ys} = 100,000$ psi was selected; Fs is the factor of safety and is set to be 2. Therefore, from Equation (3), $S_{sw} = 25,000\ psi$. When substituting these values into Equation (2), the pin diameter can be found as 0.71 inches. For convenience, $d = 0.75$ inches.

8. Dimensions of the Vertical Link in Figure 5

As given from Fig. 5, the vertical link is the link from Pin 2 to Pin 4. It experiences a bending stress generated by the hydraulic force. The following equation is used:[5,6]

$$\sigma_b = K \frac{MC}{I} \tag{4}$$

where σ_b is the bending stress; K is stress concentration factor; M is the bending moment; C is the distance from the neutral axis of the link section to its outer surface; I is the moment of inertia for the link section.

When using the maximum normal stress theory in this design, σ_b can be determined from the following equation:[5,6]

$$\sigma_b = \frac{S_{ys}}{F_s} \tag{5}$$

where S_{ys} is tensile yield strength of the material and F_s is the factor of safety. In this application, an AISI 1040 steel with 90,000 psi in tensile strength was selected. Assuming $F_s = 1.5$, the allowable working bending stress σ_b is found as 60,000 psi. Also from stress-concentration-factor tables, K can be found as 1.8[5,6].

From the design space available, the center distance between Pin 2 and Pin 3 in Figure 5 was set to be 7.5 in. Therefore, the bending moment M is equal to[5,6]

$$M = 7.5 \text{ x } 10,000 = 75,000 \text{ lb-in} \tag{6}$$

I can be found from the following equation:[5,6]

$$I = \frac{1}{12} bh^3 \tag{7}$$

where b is the thickness of the plate, in this case $b = 2.0$ in and h is the width of the link. Both b and h are shown in the parentheses of Figure 6. C in Equation (4) is one half of the width of the link, therefore $C = (1/2)* h$. By substituting these values into Equation (4), the link width h can be found as *2.6 in*. The design drawing is then given in Figure 6. Figure 7 shows this six press-operation mechanisms when mounted on the working table.
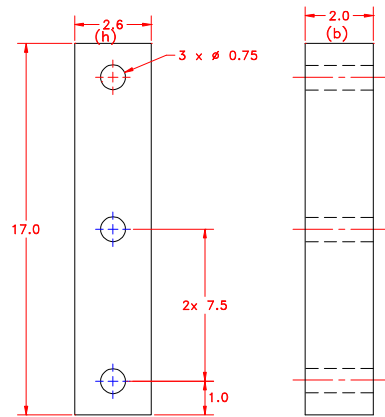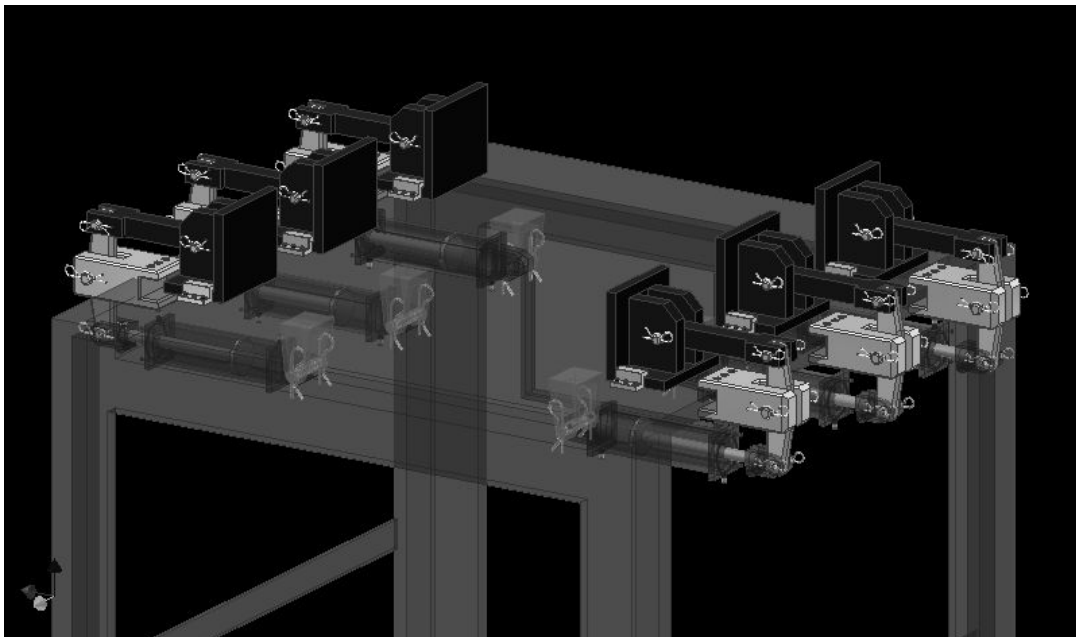
Figure 6: Design drawing of the link.

Figure 7: Six hydraulic nailing mechanisms.

9. Flexible Locking Mechanism

A locking mechanism was designed to lock the wood pallet on the top surface of the working table during the nailing process. Because the wood pallets are manually made, the distance between two inner surfaces used to locate the pallets varies by as much as one quarter of an inch. The problem is shown as "Varying Distance" in Figure 8. To protect the pallet from being bent or damaged by the compression force during the nailing process, a flexible locking mechanism was applied to resolve this problem. As also shown in Figure 8, it was designed with a fixed end on one side and a movable end on the other side to compensate for the problem of varying distances. Figure 9 shows the principle of the

locking operation. Since the direction of the movable end is different from that of the hydraulic compression force, the locating surface on the movable end will stay at the locking position during the press-operation process.
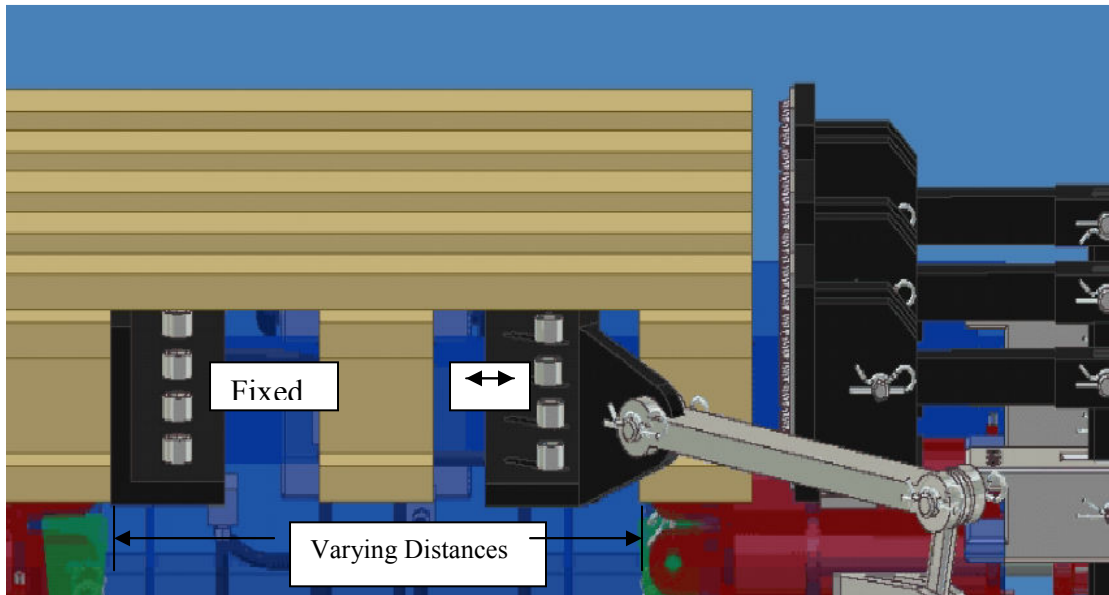

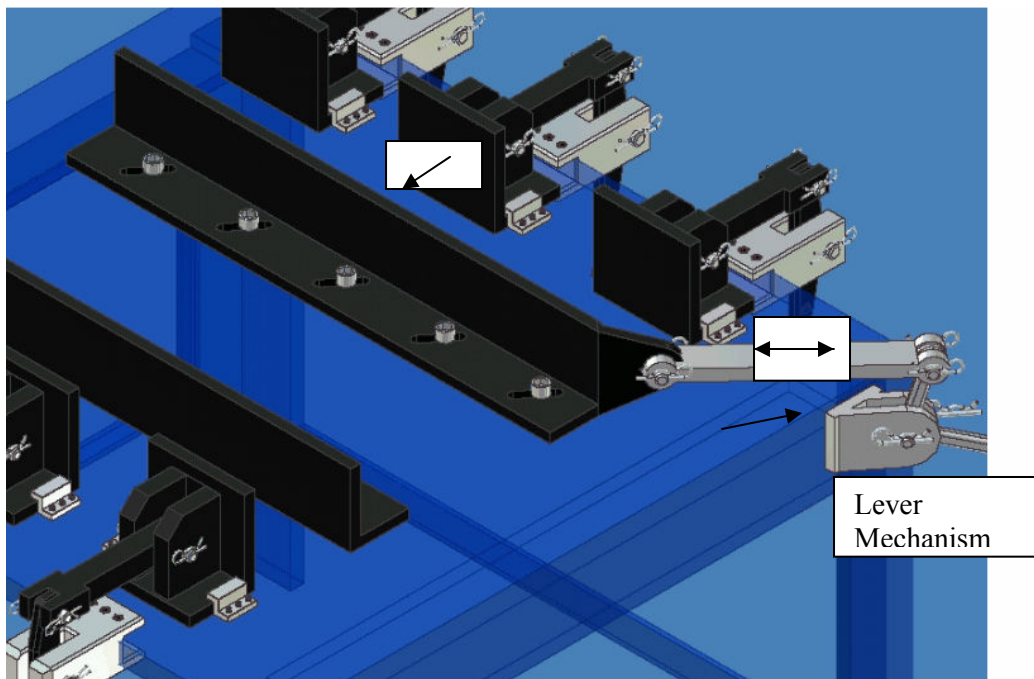**Figure 8**: Locking mechanism for varying inner distances of the wood pallet.

Figure 9: The automatic anti-reverse lever mechanism.

10. Compression Head

The compression head is equipped with a permanent magnetic plate. The magnet is used to hold the nail plate, as shown in Figure 10. Each compression-head face has an additional space in order to allow the nail plate to be exactly aligned with its target to accommodate the size variations of the wood pallets.
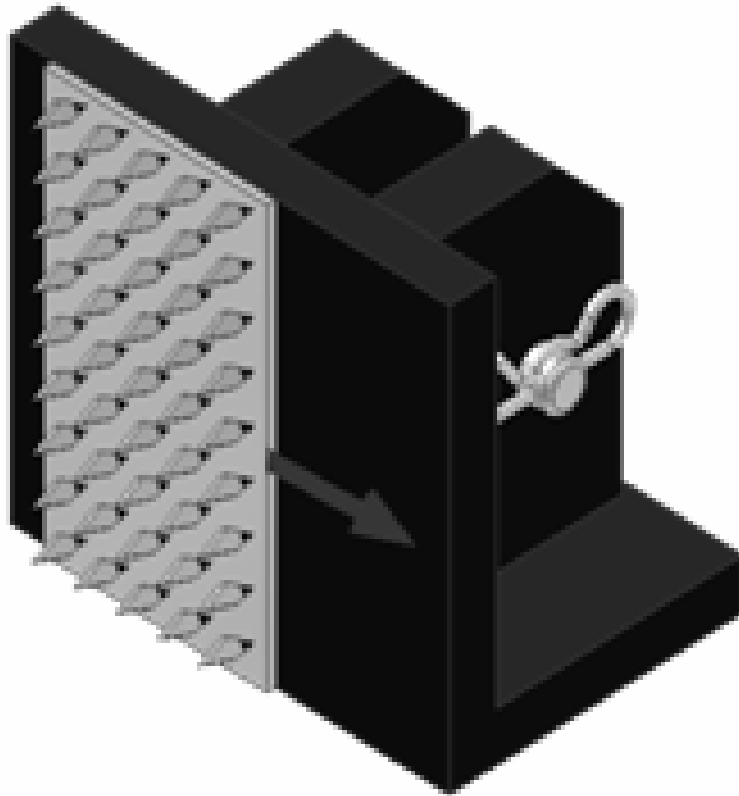

Figure 10: Adjusting the nail plate on the compression head face.

12. Hydraulic System Design

Students were asked to use the simulation software of Automation Studio[7] for the hydraulic circuit design, as shown in Figure 11. Operation steps of the circuit are listed as following:

(1) A Normally Open (N.O.) Push Button PB 1 is pressed to activate SOL 1.
(2) When SOL 1 is activated, it will activate the right position of the 4/2 directional control valve. The hydraulic fluid will push the double-acting cylinder in the forward direction to perform the press operation.
(3) A Normally Close (N.C.) Push Button PB 2 can be pressed at any time to deactivate SOL 1 and to move the cylinder back to its retracted position.

(4) When overloaded, the pressure relief valve will be opened and the fluid will be drained directly to the reservoir.
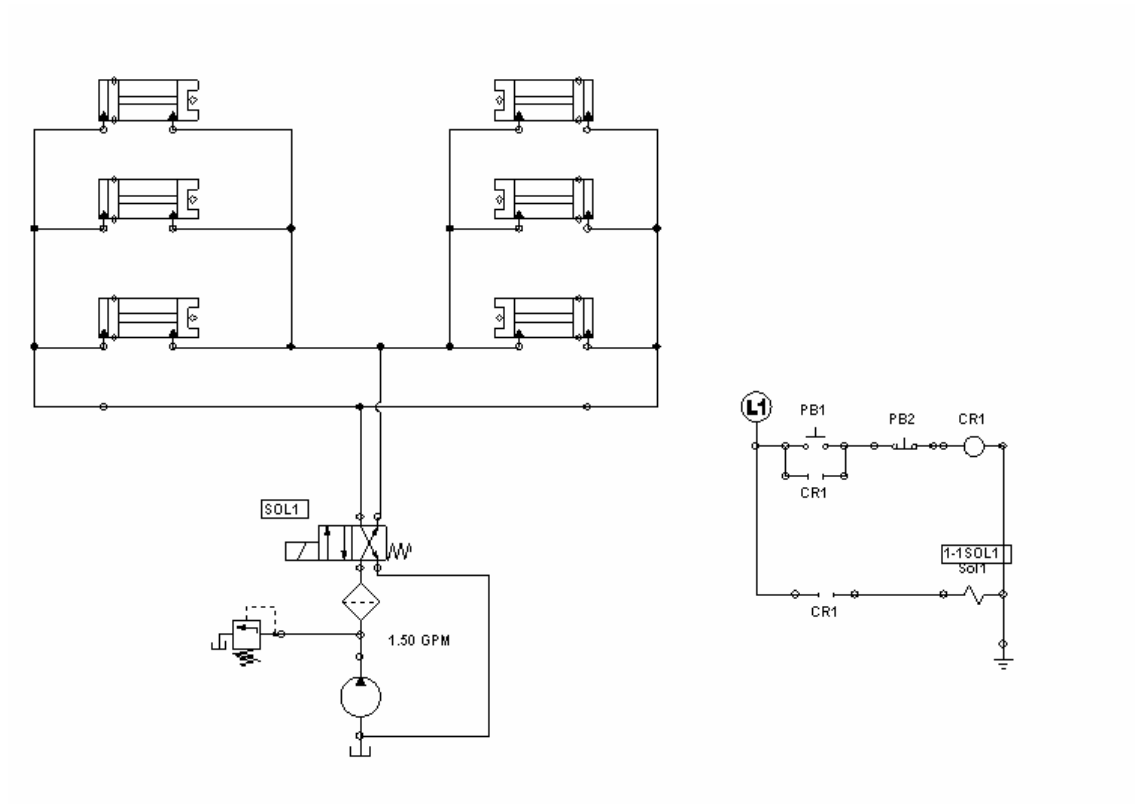

Figure 11: Hydraulic circuit.

13. Flow Rate of the Hydraulic Pump

Flow rate of the hydraulic pump in Figure 11 can be expressed in gallons per minute (GPM). The following equation is used:[8]

$$GPM = \frac{V}{t*231} \tag{8}$$

where V is the total volume of the hydraulic cylinder in cubic inches; t is the operation cycle time in minutes, in this case t is set to be 0.5 minutes; one gallon equals *231* cubic inches. Since the diameter of the cylinder is found to be 3 inches from Equation (1), V can be found using the following equation:

$$V = n*Str*\frac{\pi*d^2}{4} \tag{9}$$

where n is the number of cylinders, in this case $n=6$; d is the diameter of the piston and is equal to 3 inches; *Str* is the stroke or total displacement of each hydraulic cylinder, in this

case *Str= 4* inches. By substituting these values into Equations (9) and (8), the GPM can be found as 1.47. Therefore, a 1.5 GPM hydraulic pump with fixed displacement was chosen in this project.

14. Tests to validate design theory and operations

Before the machine was delivered to the company, numerous nailing tests were performed to validate the design theory. Result shows that there was no any damage on the mechanical components. In addition, the whole operation can be accomplished in approximate forty-five seconds. The hydraulic operation is very quiet and smooth without generating any noise. Figures 12 to 15 show the operational steps of the system. In Figure 12, and six nail plates are placed on six magnetic compression heads and the wood pallet is locked in the position on the table. Figure 13 shows the compression heads pushing six nail plates onto the wood pallet surfaces. After the press operation, Figure 14 shows the retracted position of the hydraulic heads;. Figure 15 shows the wood pallet is lifted up from the machine when the operation is completed.
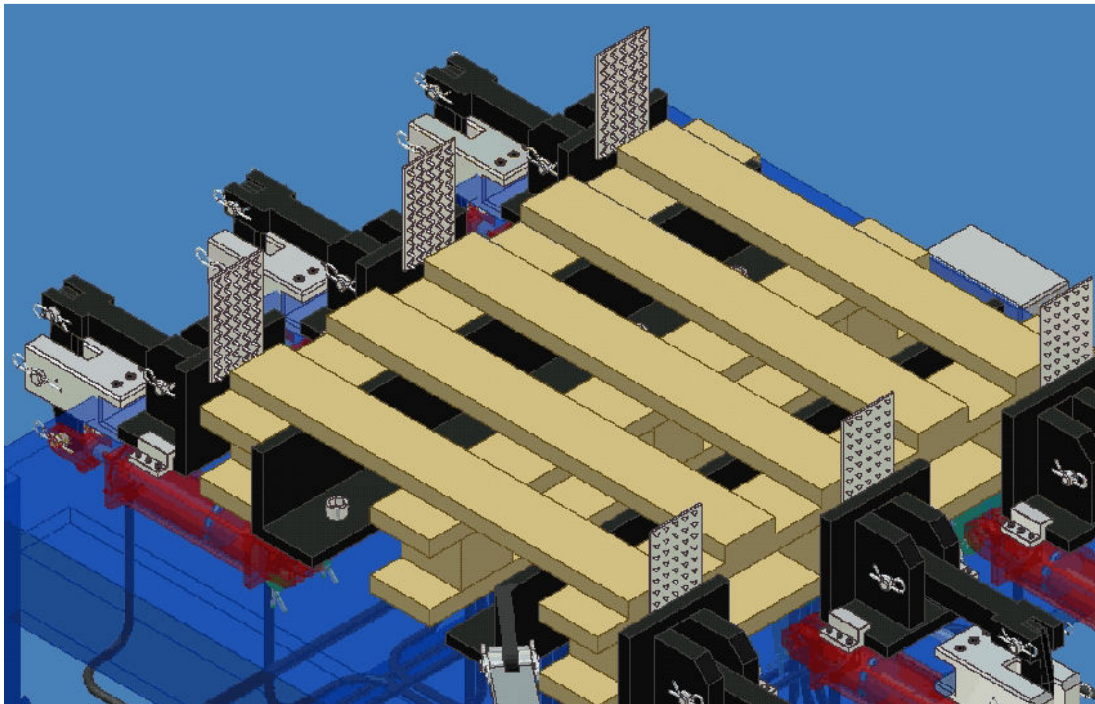

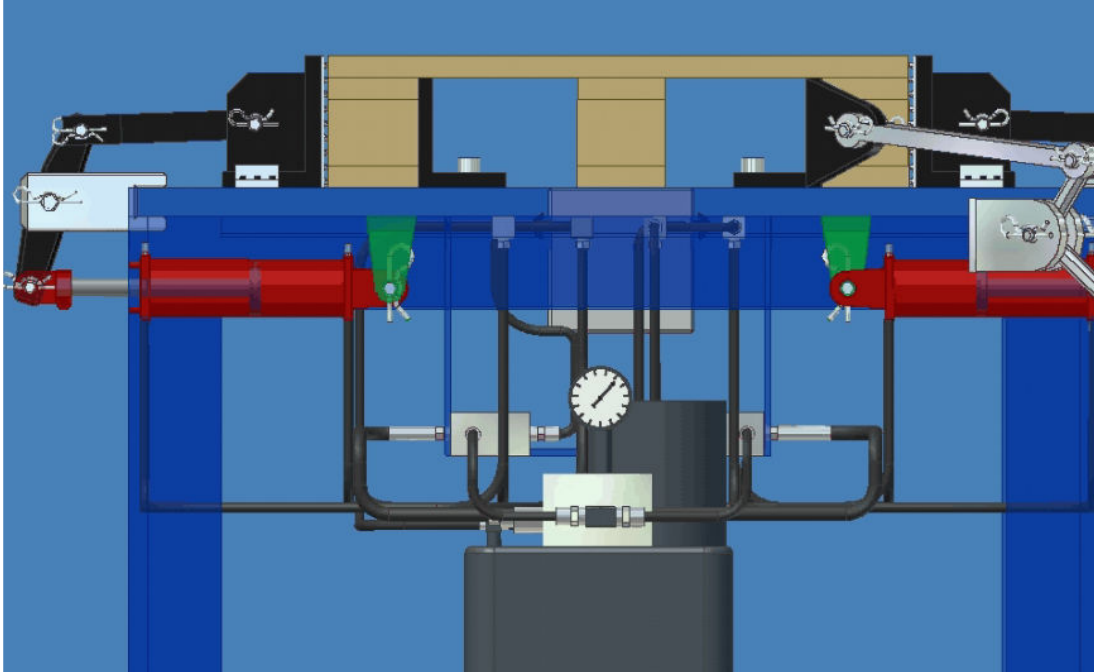**Figure 12:** Nail plates are placed on the magnetic hydraulic heads.

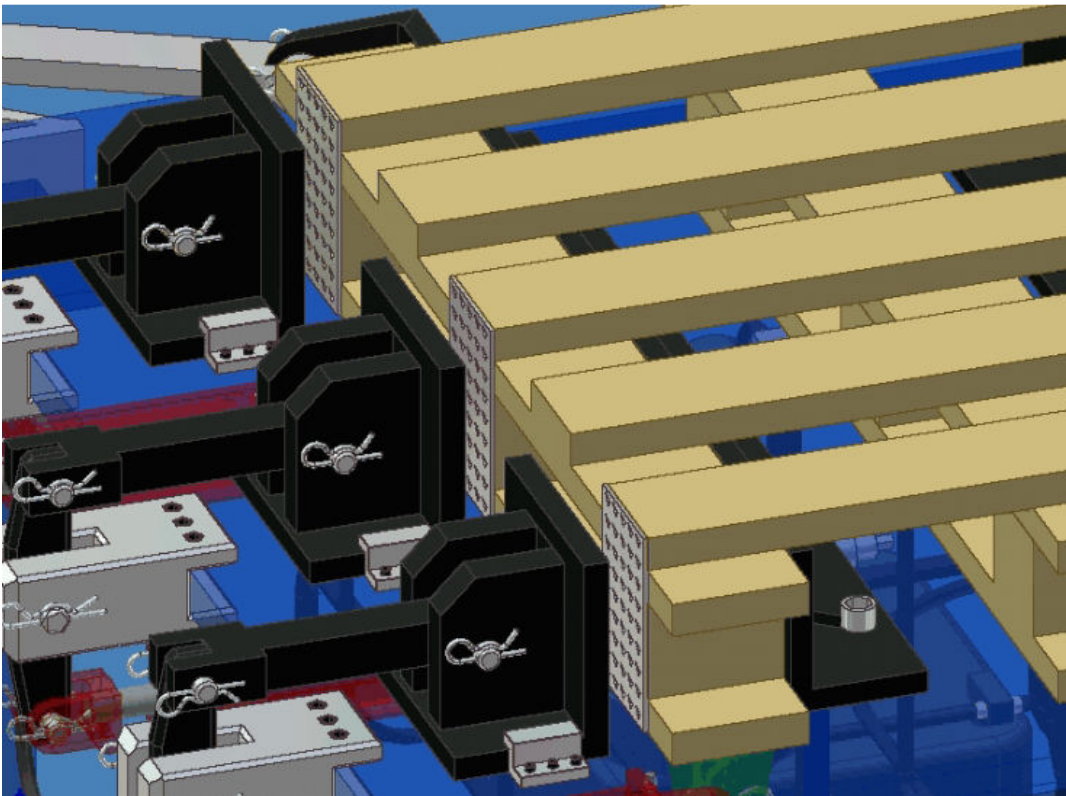**Figure 13:** The nail plates are pushed onto the wood pallet.

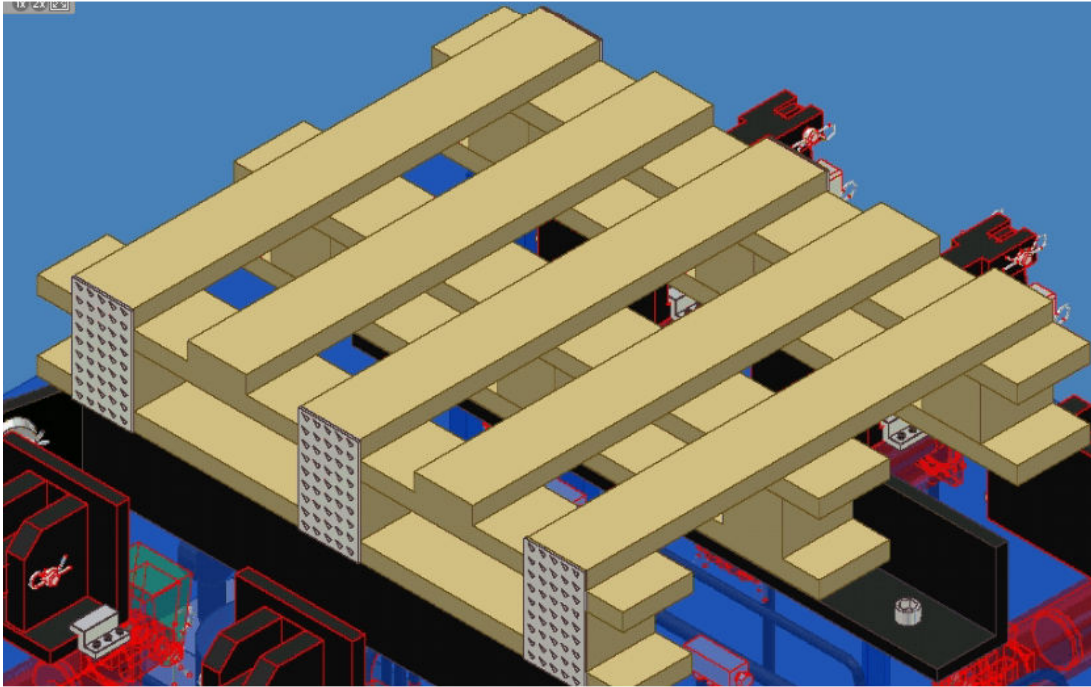**Figure 14:** The hydraulic heads are in retracted position.

Figure 15: Wood pallet is removed after the whole cycle completes.

15. Students' Learning Experiences from the Project

In addition to the hydraulic circuit design, students gained two main experiences from this project:

(1) Design of the locking mechanism to lock the wood pallets, which were made with variable inner distances for locating position.
(2) Use of stress concentration factor in the machine design.

The locking mechanism was originally designed by only using two fixed steel plates to loosely locate a wood pallet during the first operation. However, due to the varying distances between the inner surfaces, pallets could not be tightly locked and several wood pallets were bent and damaged during the operation. Therefore, one side of the locking mechanism was modified to become movable. The flexible locking mechanism protected the wood pallets and improved the nailing operation. From this lesson, students learned about the increasing design cost for the operation when a critical tolerance in the parts is not well controlled. Also, because students forgot to use the Stress Concentration Factor K in Equation (4) during the first design, the link failed during the first test. After noting the ¾"-diameter holes in the link, K was included in the design equation and the problem was resolved.

16. Summary

The project basically accomplished two goals: (1) it satisfied an industrial need and (2) it provided design experience for students. The automation process of the nailing operation greatly increases the productivity and also reduces the hammering noises made by manual operation. Students also learned how to use the design equations and animation software for mechanical components and hydraulic systems. In addition, they learned how to

modify the mechanism design to meet size variations when locking down the wood pallets. The machine was tested numerous times before it was delivered to the users. Result shows that the machine is very reliable and meets the original expectation.

References:

1. C.Y. Lin & G.R. Crossman, "*Automation Laboratory Development with Design Implementation Scheme and Simulation Software*", Proceedings of 2004 ASEE Annual Conference.
2. F.D. Petruzella, "*Programmable Logic Controllers*", McGraw-Hill Companies, 2003.
3. Allen-Bradley Controllers, http://www.ab.com/plclogic/.
4. Universal Material Testing Machines, http://www.instron.us/wa/products/universal_material/default.aspx
5. C.E. Wilson, "*Computer Integrated Machine Design*", Prentice Hall, 1997.
6. R.L. Mott, "*Machine Elements in Machine Design*", Prentice Hall, 1999.
7. Automation Studio, http://www.automationstudio.com/.
8. Hydraulic System Power Requirement, http://www.allstar.fiu.edu/aero/Hydr03.htm.