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Development of a new temporary fastener for aerospace automation

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DEVELOPMENT OF A NEW TEMPORARY FASTENER FOR AEROSPACE AUTOMATION

by

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ABSTRACT

Temporary fasteners are required in aircraft assembly, especially in the assembly of wings, fuselage, and aircraft skin's substructure prior to drilling holes for permanent fasteners by automated drilling machines. The objective was to develop a temporary fastener that can be installed, clamped, loosened, and removed from one side with a short head length. Published papers, web pages and patents relating to temporary fasteners were reviewed. Then by considering the ability to meet the operation requirements and concerns, a temporary fastener was designed with the following advantages:

- a simple structure that can be easily fabricated
- a short head length to save assembly time and reduce the risk of collision between the drilling machine and the head of temporary fastener
- an inner thread driver to provide a high clamping load
- capable of single-sided one-man operation

The designed fastener was fabricated using VascoMax C300 material. Finite element analysis (FEA) was employed to simulate the working process of the fastener with different design parameters. Deformed shapes of the temporary fastener flexible fingers after heat treatment were simulated, and the simulation results were validated with physical prototypes using a reverse engineering approach. The design parameters of both the flexible fingers and the spring were analyzed, and the analytical data was validated with experimental data measured by strain gages. During the fastener working process, a load cell and a torque sensor were employed to measure clamping force and tightening torque, respectively. The measured results agree well with FEA predictions.

ACKNOWLEDGMENTS

Firstly, I would like to thank my advisor, Dr. Ming C. Leu, for his invaluable advice and guidance throughout my whole degree program. Without his immense patience, continued support and insightful advice, this research would not have been possible.

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1. INTRODUCTION

Temporary fasteners are typically used to align the aerospace parts of a multi-layer structure and apply clamping loads to these parts, which include panels, structural members, etc., in order that drilling a series of holes in these parts and riveting them together can be performed. An example of temporary fasteners used in the aerospace assembly operation is given in Figure 1.1.

Figure 1.1. Temporary fasteners that hold the skin in place for riveting [1]

Aircraft companies use thousands of temporary fasteners every day. The motivations of this study are described below.

Conventionally, slave bolts are used to secure skins as shown in Figure 1.2. Installing and removing these bolts is, however, not only time-consuming but also requires two-man operation. Additionally, the underside of a workpiece is often inaccessible.

Figure 1.2. Two-man operation [2]

Elongated and oversized holes are key quality issues within the aircraft manufacturing industry. These are often a result of drilling out temporary fasteners, used to hold aircraft skins to substructures, prior to drilling holes to install permanent fasteners with automated drilling machines. Removing and replacing these fasteners is time-consuming and may cause elongated and oversized holes.

One of the main issues of the temporary fasteners currently used in the industry is the head length, which is the length of the fastener protruding above the top surface of the workpiece when the temporary fastener is clamped. An example of head length (L) of a temporary fastener is illustrated in Figure 1.3. A temporary fastener with a longer head length increases the time of drilling holes for permanent fasteners because the drilling machine has to travel up and across the heads of these temporary fasteners to drill the neighboring holes. The drilling retraction distance (D) is also illustrated in Figure 1.3, where the drill retraction time is determined by the head length of the temporary fastener, therefore shortening the head length saves the assembly time significantly for a large number of fastening operations. Additionally, the drilling machine may more likely run into the head of the installed temporary fastener for a temporary fastener with a longer head length. The crash between the drilling bit and the head of the temporary fastener causes damage to the workpiece and may incur expensive repair.

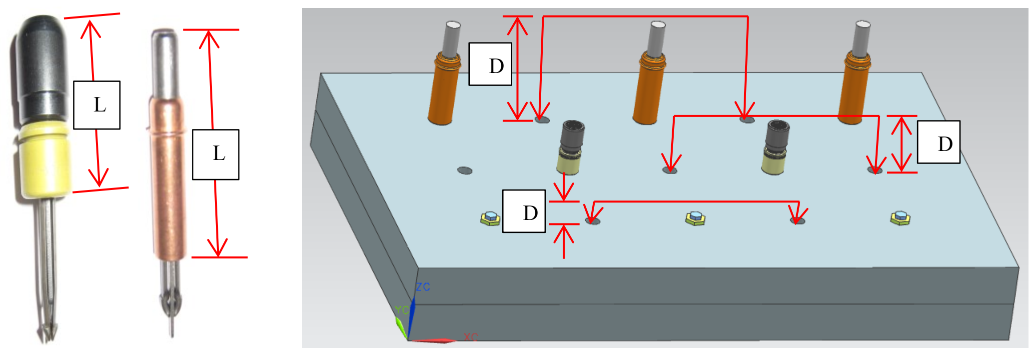


Figure 1.3. Head length (L) and drill retraction distance (D)

Properly designed temporary fasteners that can handle high clamping loads, save installation time and cost, have the ability to align parts of close tolerances, and allow single-sided one-man operation are of great interest to the aerospace manufacturing industry.

The objective of this research is to develop a temporary fastener with the following design criteria:

- One-sided operation
- Short head length
- Not damaging the hole

- Allows the clamped workpieces to have adjustable total thickness
- Provides proper clamping force
- Easy to operate
- Easy to manufacture

The organization of the thesis is as following: after a brief literature review in section 2, new design concepts brainstormed were described in section 3. In section 4 and 5, manufacturability and manufacturing process were studied, and the selected design of the temporary fastener was fabricated using VascoMax C300 material. FEA was performed to study the effects of the fastener design parameters in section 6. Experimental data was used to validate the FEA results in section 7. After the FEA results were validated, the fastener design parameters were optimized based on the FEA predicted data, and the temporary fasteners with the optimized design parameters were fabricated in section 8. Finally, the conclusion was drawn in section 9.

2. REVIEW OF LITERATURE

In the past few decades, quite a few temporary fasteners have been developed and used in the industry. US patents related to temporary fasteners were surveyed, and the temporary fasteners currently used in industry were reviewed. The existing temporary fasteners were categorized into four types.

2.1. CLASSIFICATION OF TEMPORARY FASTENERS IN U.S. PATENTS

The surveyed temporary fasteners in US patents could be categorized into four main types: top-spring type, outer-screw type, ball-end type, and inner-screw type. The four types are illustrated in Figures 2.1.

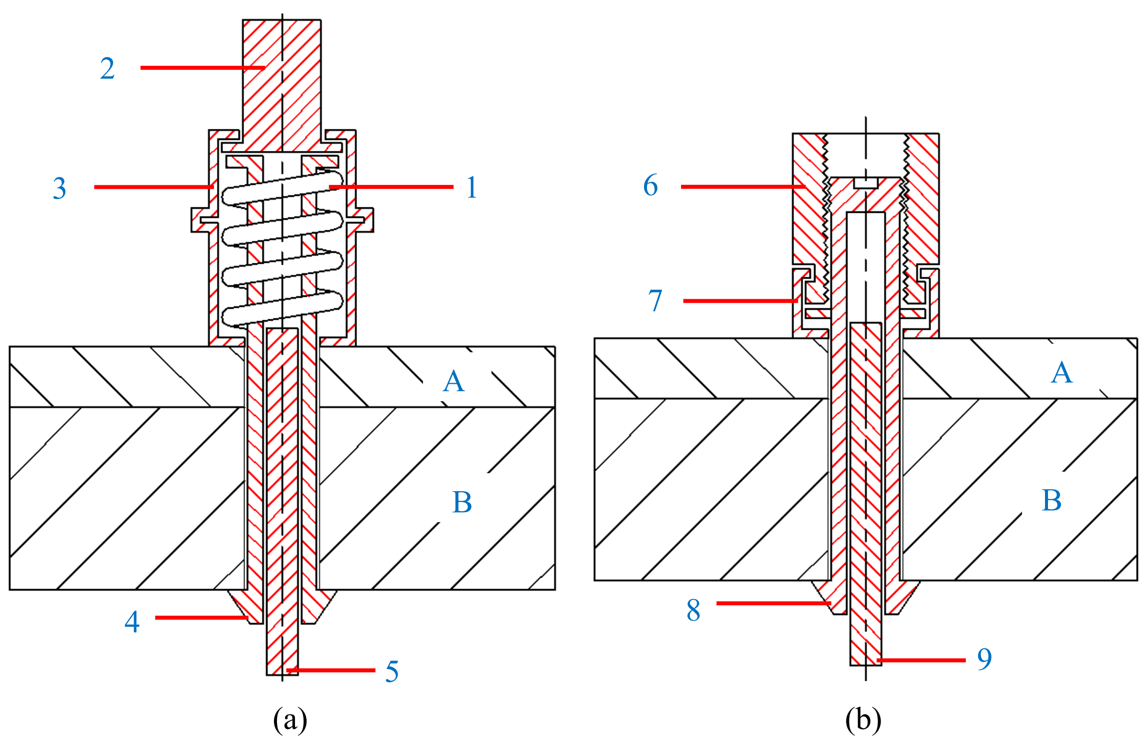


Figure 2.1. Different types of temporary fasteners: (a) top-spring type, (b) outer-screw type, (c) ball-end type, and (d) inner-screw type

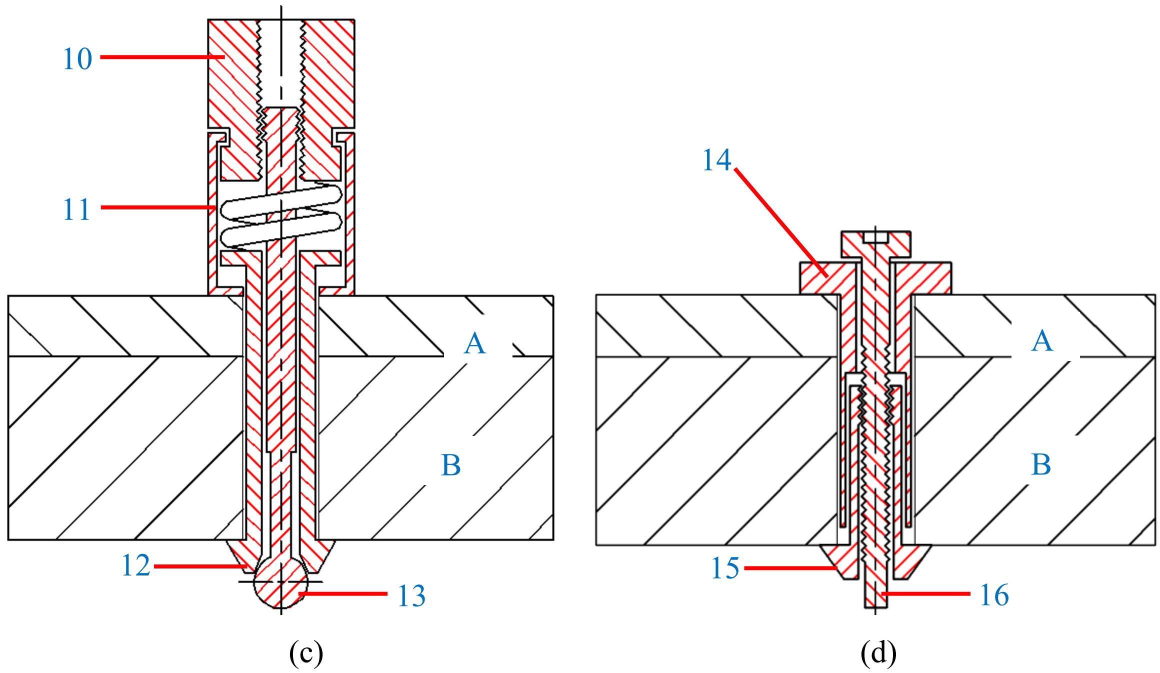


Figure 2.1. Different types of temporary fasteners: (a) top-spring type, (b) outer-screw type, (c) ball-end type, and (d) inner-screw type (cont.)

Temporary fasteners of the top-spring type have springs on their heads. A typical example of top-spring type temporary fastener is shown in Figure 2.1a. It has a top piece (2), a hollow body (3), some flexible fingers (4), and an inner support (5). A spring (1) located inside the hollow body (3) is used to drive the inner structure of the fastener and provide the clamping force. A particular plier is employed to operate this type of fastener. During operation, the hollow body (3) is held by the plier, and the force is applied to the top piece (2). Thus the spring (1) located inside the hollow body (3) is compressed, and the top piece (2) pushes the flexible fingers (4) down and slide away from the inner support (5). The flexible fingers (4) collapse without the inside support, so they could go through the hole in the workpieces. When the force applied to the top piece (2) is removed, the spring (1) will extend, and the flexible fingers will move up and expand to clamp the workpieces together. A number of patented temporary fasteners could be categorized into the top-spring type, including the following:

- C. J. Koenig, “Fastener,” U.S. Patent 2317201, 1943.
- D. H. Finkle, “Fastener,” U.S. Patent 2324687, 1943.
- R. W. Edwards, “Temporary Fastener,” U.S. Patent 2343499, 1944.
- K. C. Bugg, “Temporary Fastener,” U.S. Patent 2393587, 1946.
- P. Van Sittert, “Fastener,” U.S. Patent 2397892, 1946.
- F. E. Johnson, “Temporary Positioning and Holding Means for Aperture Members,” U.S. Patent 2398644, 1946.
- P. Van Sittert, “Fastener,” U.S. Patent 2411914, 1946.
- P. Van Sittert, “Fastener,” U.S. Patent 2430486, 1947.
- J. M. Kosterubanic, “Fastener,” U.S. Patent 2463700, 1949.
- E. Werner, “Nut and Plate Temporary,” U.S. Patent 2570618, 1951.

Temporary fasteners of the outer-screw type have the driving thread located on the outer side of the shaft that has flexible fingers. A typical example of outer-screw type temporary fastener is shown in Figure 2.1b. It has a top piece (6), a hollow body (7), some flexible fingers (8), and an inner support (9). The top piece (6) has internal threads, and the shaft connecting the flexible fingers (8) has external threads. When the hollow body (7) is held still while the top piece (6) is rotated by a fastening tool, the flexible fingers (8) will expand and slide up to clamp the workpieces together. A number of patented temporary fasteners could be categorized into the outer-screw type, including the following:

- S. B. Jones, “Clamping Device,” U.S. Patent 3883129, 1975.

- J. D. Pratt, “Wedge-type Low Profile Fastener,” U.S. Patent 4537542, 1985.
- T. E. Armstrong and G. M. Moon, “Limited Force Cartridge for Temporary Fasteners,” U.S. Patent 5240361, 1993.
- T. O. Blankenship and J. L. Morrison, “Spring Loaded Bushed Wedgelock,” U.S. Patent 5927919, 1999.
- R. G. Falk, “Temporary Fastener with Projecting Tool-guide Bushing,” U.S. Patent 6196779, 2001.
- V. T. Olson and S. T. Ulinski, “Tool Clamp and Method,” U.S. Patent 6755407, 2004.
- M. L. Anderson and W. J. Koch, “Wedge-lock Fastener and Associated Installation and Assembly Methods,” U.S. Patent 6827345, 2004.
- D. G. Starr, “Device and Method for Temporarily Fastening a Plurality of Workpieces in Response to the Introduction of Pressurized Fluid,” U.S. Patent 7048266, 2006.

Temporary fasteners of the ball-end type use a ball end to provide pressure to expand the flexible fingers and clamp workpieces together. A typical example of ball-end temporary fastener is shown in Figure 2.1c. It has a top piece (10), a hollow body (11), some flexible fingers (12), and an inner support with a ball-end (13). The top piece (10) has internal threads, and a shaft connecting the ball-end (13) has external threads. When the hollow body piece (11) is held still while the top piece (10) is rotated by a fastening tool, the inner support with a ball-end (13) will slide up. The ball-end will expand the flexible fingers (12) and pull them up to clamp the workpieces together. A number of patented temporary fasteners could be categorized into the ball-end type, including the following:

- R. A. Gage; L. N. Hazlehurst and M. R. Jack, “Tack Fastener,” U.S. Patent 6056283, 2000.
- T. D. McClure, “Radial-type Temporary Fastener, Components and Tool,” U.S. Patent 7300042, 2007.

Temporary fasteners of the inner-screw type have the driving threads located on the inner side of the shaft with flexible fingers. A typical example of inner-screw type temporary fastener is shown in Figure 2.1d. It has an elongated body (14), an inner hollow body (15) and a shaft (16). The inner surface of the elongated body (14) has a non-circular shape in the bottom and the outer surface of the inner hollow body (15) has a corresponding shape. They can slide relative to each other, but they cannot rotate relative to each other. The shaft (16) has external threads, and the inner hollow body (15) has internal threads. When the elongated body (14) is held still while the shaft (16) is rotated by a fastening tool, the inner hollow body (15) will slide up. The flexible fingers on the bottom of the inner hollow body (15) will expand and slide up to clamp the workpieces together. A number of patented temporary fasteners could be categorized into the inner-screw type, including the following:

- D. Ruddck and L. Blattmann, “Fasteners, Especially Temporary Fasteners,” U.S. Patent 0216292, 2008.
- J. A. Kelley; R. A. Luepke; L. M. Vestal; E. J. Kush; M. L. Hestness; E. C. Patty and J. Langevin, “Method of Manufacturing Aircraft Using Temporary Fasteners,” U.S. Patent 0308171, 2010.

- J. Niklewicz and D. A. Carran, “Removable Blind Fastener,” U.S. Patent 0008124, 2011.

2.2. TEMPORARY FASTENERS CURRENTLY USED IN INDUSTRY

Examples of companies producing commercial temporary fasteners in industry include Monogram Aerospace and Centrix. Some typical temporary fastener products of these companies are shown in Figure 2.2. Monogram Aerospace produces top-spring and outer-screw types of temporary fasteners, such as the M Series and the HNX Series, as shown in Figures 2.2a and 2.2b, respectively. Centrix produces ball-end and inner-screw types of temporary fasteners, such as the CL Series and the TACK Series, as shown in Figures 2.2c and 2.2d, respectively.

(a) Monogram Aerospace Model M Series

(b) Monogram Aerospace Model HNX series

(c) Centrix Model TACK Series

(d) Centrix Model CL Series

Figure 2.2. Example commercial temporary fasteners: (a) top-spring type, (b) outer-screw type, (c) ball-end type, and (d) inner-screw type

There are some advantages and disadvantages in each type of the reviewed temporary fasteners. A top-spring type fastener is easy to operate, but it cannot provide a large clamping force; the maximum clamping pressure is determined by the strength of the internal spring. An outer-screw type fastener allows its flexible fingers fitting into small holes; however, it requires a longer head. A ball-end type fastener can distribute load more evenly to protect workpieces from damage, but it requires a longer head length as well. An inner-screw type fastener could have a short head length, but the inner-screw type temporary fasteners often have relatively complicated structure, so to manufacture them for use on small holes may be difficult and expensive.

3. GENERATION OF NEW DESIGN CONCEPTS

Based on the research objective and the reviewed data, potential solutions were brainstormed. As a result, six new design concepts were developed. The CAD model of each design was generated to represent the design concept. The new design concepts were compared based on the design criteria. The invention disclosure was made for the selected design concept.

3.1. NEW DESIGN CONCEPTS

The description of each new design concept is described below with an illustration.

Design #1 is shown in Figure 3.1. A handle (1) with a cam is designed to push down a spreader (2) which forces the flexible fingers (3) moving upward. The flexible fingers are expanded by a pin (4). Then, the workpieces will be clamped by the spreader (2) and the flexible fingers (3). When the handle turns up, the spreader is disengaged, and the flexible fingers collapse without support of the pine (4), so it can be removed from the hole.

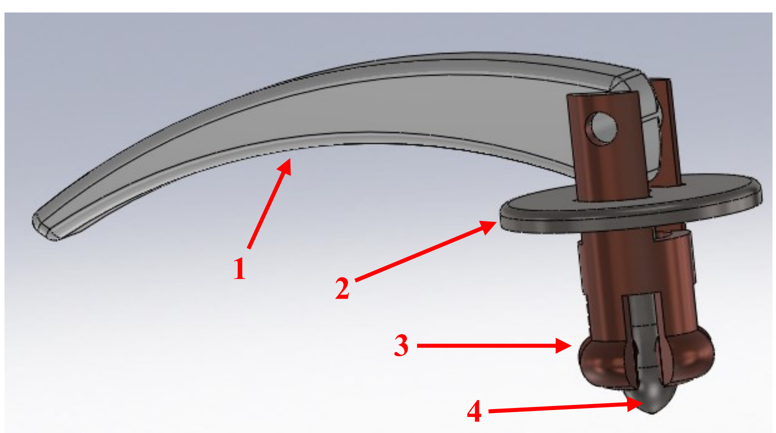


Figure 3.1. Design concept #1

Design #2 is shown in Figure 3.2. During operation, the fastening tool holds the blue part (2), which has inner threads. The red shaft (1) has outer threads. When a hex-headed screwdriver turns the red shaft (1) in the counterclockwise direction inside the blue part, the ball end will move up to expand the flexible fingers and push the yellow part moving upward. Then, the head of the blue part (2) and the flexible fingers will clamp the workpieces together. Parts (2) and (3) each have extensions that act as guides to keep them from relative rotation as the screw turns.

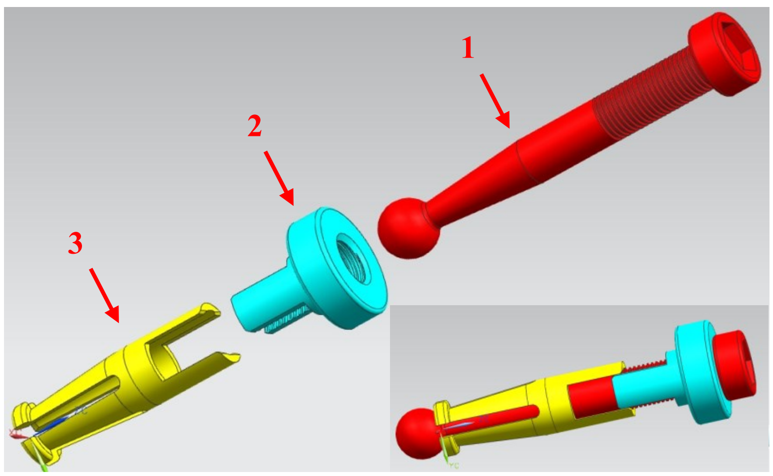


Figure 3.2. Design concept #2

Design #3 is shown in Figure 3.3. The blue part (1) has a hex- head and inner threads. The brown part (4) has a ball end and outer threads. These two parts are connected together. During operation, the hexagonal piece (2) is held still by a fastening tool. When Part (1) is turned in the clockwise direction, it drives Part (4) to slide up inside part (3), which has flexible fingers. The ball end exerts pressure on the flexible fingers and pushes the part (3) to move upward. The flexible fingers and the head of the hexagonal piece (2) will clamp the workpieces together.

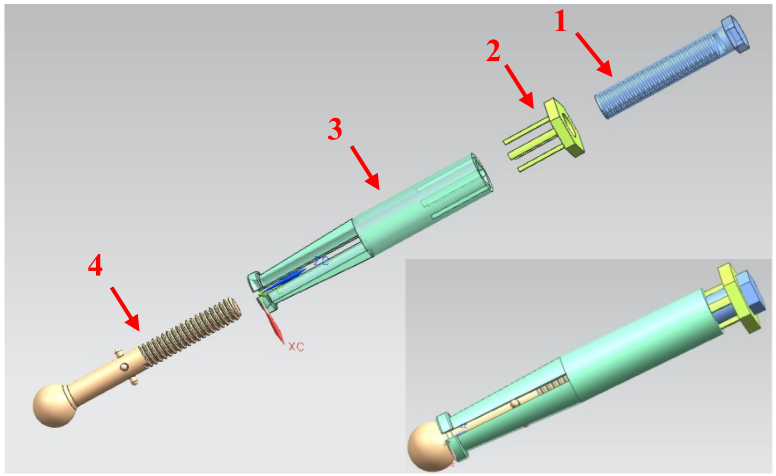


Figure 3.3. Design concept #3

Design #4 is shown in Figure 3.4. The black part (5) is held still by a fastening tool during operation. When the red part (1), which has a hex head and inner threads, is turned in the clockwise direction, the purple part (2), which has outer threads, slides upward to clamp the workpieces. The washer (3) and the bar (4) are used together with part (5) to restrain part (2) from rotating when part (1) rotates.

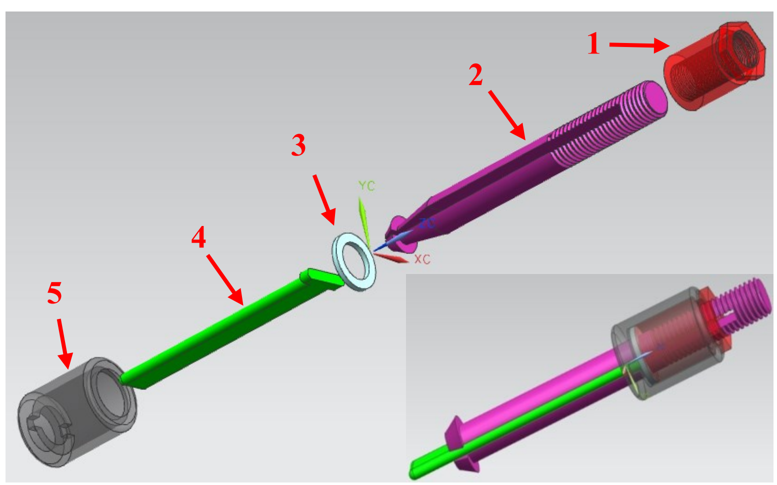


Figure 3.4. Design concept #4

Design #5 is shown in Figure 3.5. The hollow body (2) has flexible fingers, a coiled spring, and inner threads. Its head is fixed by the fastening tool during the fastener installation. When the part (1) with a hexagonal head and outer threads is turned in the clockwise direction, it will expand the flexible fingers. Continued rotating of part (1) will eventually compress the spring, causing the flexible fingers to slide upwards to clamp the workpieces. A wave spring as shown on the left top corner of Figure 3.5 can be used to replace the coiled spring in this design concept.

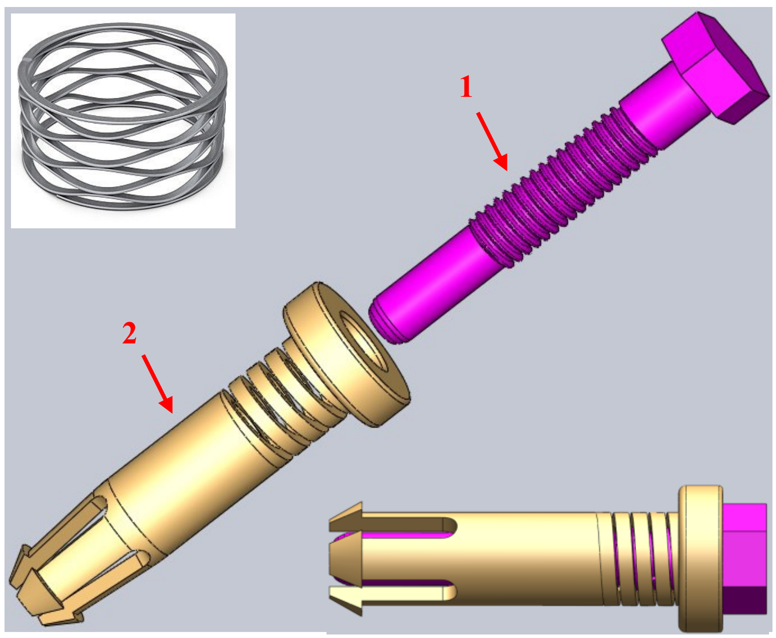


Figure 3.5. Design concept #5

Design #6 is shown in Figure 3.6. The hollow body (3) has flexible fingers, two cantilever-type springs, and inner threads. During operation, the springs are in touch with the inside of the hole, and the head of the green part (2) has its head fixed still by a fastening tool. When the shaft (1), which has a hexagonal head and outer threads, is turned in the clockwise direction, it will cause part (3) to move upward to clamp the workpieces. The friction force between part (3) and the hole should be sufficient to prevent part (3) from rotating during the fastening operation.

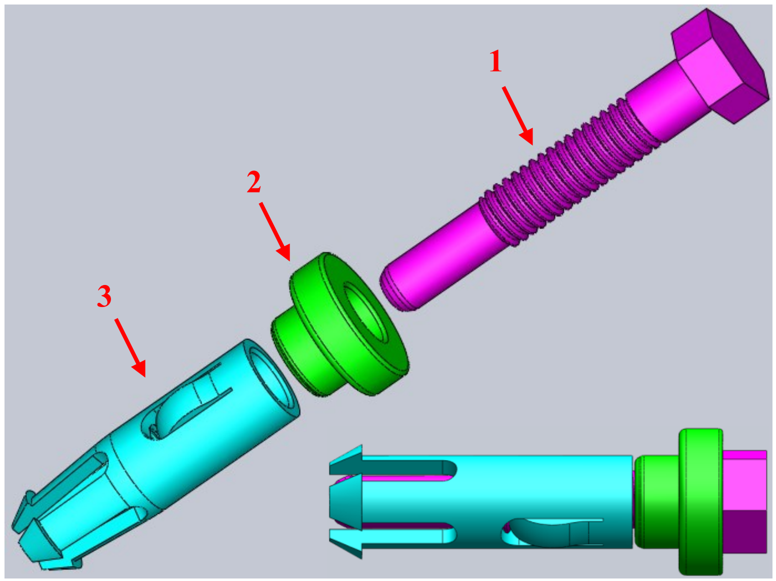


Figure 3.6. Design concept #6

3.2. COMPARISON OF NEW DESIGN CONCEPTS

The six new design concepts were compared in Table 3.1. Seven design criteria were considered in the comparison. The scores were ranged from 0 to 3 in the table; where 0 being the worst, and 3 being the best. Based on the data of comparison generated in Table 1, design concepts #5 and #6 were regarded most favorable. The design concepts #5 and #6 were also compared with the temporary fasteners currently used in the industry, and the comparison results are given in Table 3.2.

Table 3.1. Comparisons of the six developed new concepts

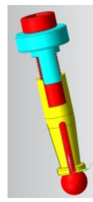
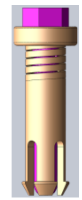
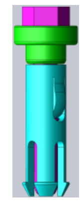
	Design #1	Design #2	Design #3	Design #4	Design #5	Design #6
						
One sided operation	3	3	3	3	3	3
Head length	1	1	1	0	3	3
Hole protection	3	3	3	2	3	2
Adjustable thickness	0	1	2	3	2	3
Operability	2	3	3	3	3	2
Manufacturability	3	1	0	3	2	2
Clamping force	1	3	3	3	3	3
Total score	13	15	15	17	19	18

Table 3.2. Comparison of the temporary fasteners used in the industry and the developed concepts #5 and #6

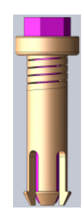
	Monogram M-1/4	Monogram CBX-BF-1/4	Centrix LP-C-8	Centrix CL-B-0.185	Design #5	Design #6
						
One sided operation	3	3	3	3	3	3
Head length	1	1	3	1	3	3
Hole protection	2	2	3	3	3	2

Table 3.2. Comparison of the temporary fasteners used in the industry and the developed concepts #5 and #6 (cont.)

Adjustable thickness	3	3	2	3	2	3
Operability	3	3	3	3	3	2
Manufacturability	3	2	1	2	2	2
Clamping force	1	3	3	3	3	3
Total score	16	17	18	18	19	18

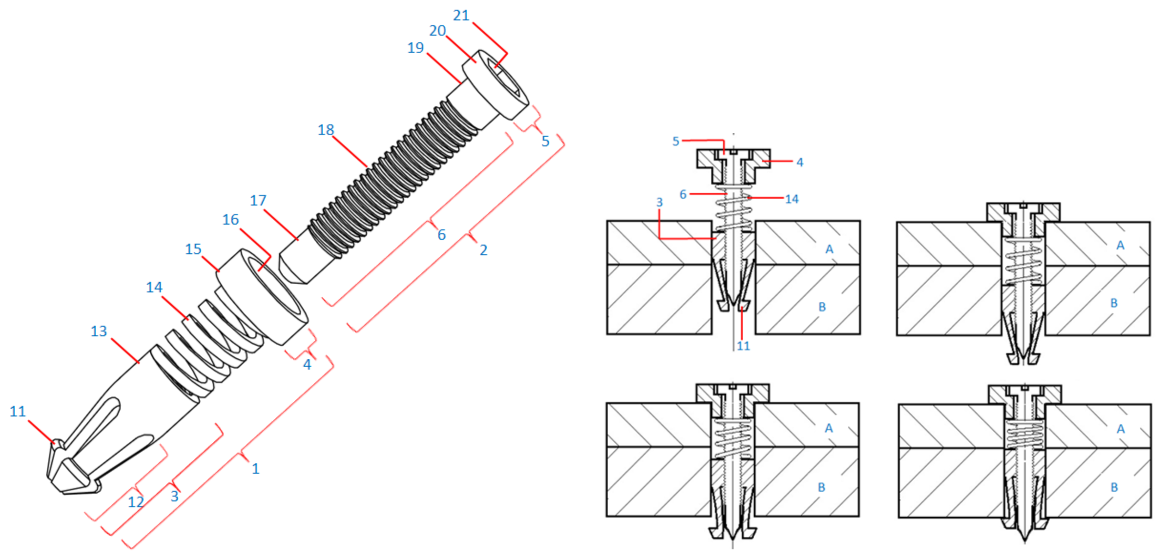
Based on the comparison data in Tables 3.1 and 3.2, design concept #5 was chosen as the final design. It has the following advantages:

- simple structure that can be easily fabricated
- short head length to save assembly time
- adjustable workpiece thickness and clamping load
- single-sided one-man operation

3.3. INVENTION DISCLOSURE

The uniqueness of the selected new design concept has been identified. It has an embedded spring to prevent the rotation between the top head and the flexible fingers. The spring can be compressed and extended, so it has the capability to adjust clamping thickness. Additionally, the top head of the developed temporary fastener as shown in Figure 3.5 has a simple structure that is short in order to shorten the retraction time of the drilling machine and to reduce the risk of collision between the drilling machine and the head of temporary fastener. A description of the designed temporary fastener in patent application format has been written, and an invention disclosure has been filed at Missouri S&T. Two drawings in the invention disclosure are shown in Figure 3.7. Figure

3.7a shows an exploded view of the temporary fastener with identification numbers for the different components. Figure 3.7b shows a typical working process of the designed temporary fastener. In this figure, the working process of the fastener installation, flexible fingers expanding, and workpieces clamping is illustrated.



(a) (b)

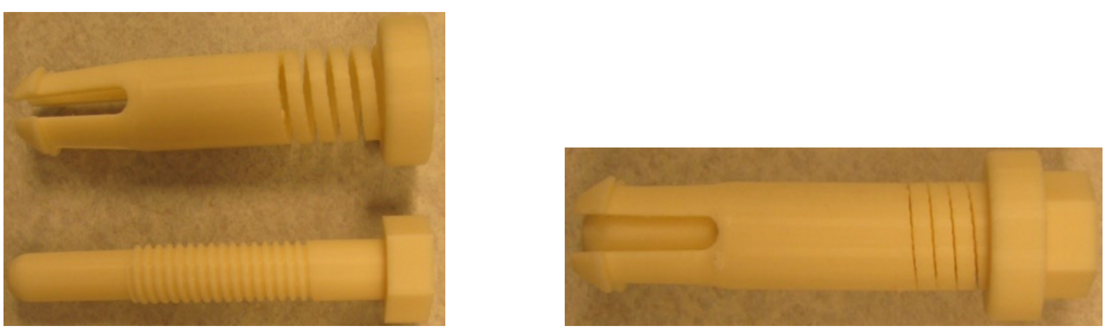
Figure 3.7. Patent application: (a) components of the fastener and (b) working process of the fastener

4. MANUFACTURABILITY AND MANUFACTURING PROCESS STUDY

Rapid prototypes of the selected new temporary fastener design have been fabricated using a Stratasys Fortus 400 FDM machine to demonstrate the fastener's working process. The manufacturing process to fabricate the designed temporary fastener with functional material was also studied.

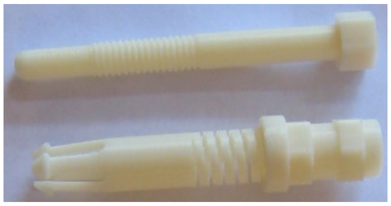
4.1. RAPID PROTOTYPES AND OPERATION DEMONSTRATION

The prototype was produced by a Stratasys Fortus 400 FDM machine as shown in Figure 4.1. The unassembled model is shown in Figures 4.1a. The assembled model with the spring compressed and flexible fingers expanded is shown in Figures 4.1b. In order to demonstrate the working process of the designed temporary fastener with the fastener installation tool currently used in industry, a rapid prototype model was developed to fit the fastener tool as shown in Figure 4.2a. The model has been tested with the fastener installation tool to demonstrate its proper working. The physical model operated by the fastener installation tool is shown in Figure 4.2b.



(a) (b)

Figure 4.1. A rapid prototype of the designed temporary fastener: (a) unassembled model and (b) assembled model



(a) (b)

Figure 4.2. Rapid prototype for the existing fastening tool: (a) Rapid prototype and (b) model installed in the fastening tool

4.2. MANUFACTURABILITY AND MANUFACTURING PROCESS STUDY

Different manufacturing approaches to fabricate the designed temporary fastener with functional material were studied and described below.

One approach is to manufacture the clamping bottom, the spring, and the hex head of the hollow body separately, then to weld them together as one part. The advantage of this approach is the clamping bottom and hex head are easy to manufacture, and commercially available springs in industry can be used in this case. The main challenge of this approach is to weld the three parts together because the temporary fastener has to work with 0.25 inch holes which are very small parts for the welding process. Figure 4.3 shows the components of the temporary fastener. The clamping bottom was fabricated at Missouri S&T mechanical engineering workshop, while the spring, hex head, and bolt were bought from the market. In order to weld the components together, traditional welding process and laser welding process were implemented. However, good result could not be achieved from those welding processes. It may need special welding technique, such as spot welding for jewelry manufacturing, to properly weld the components together. Figure 4.4 shows a laser welding process, but the laser beam was too large to weld the components together.

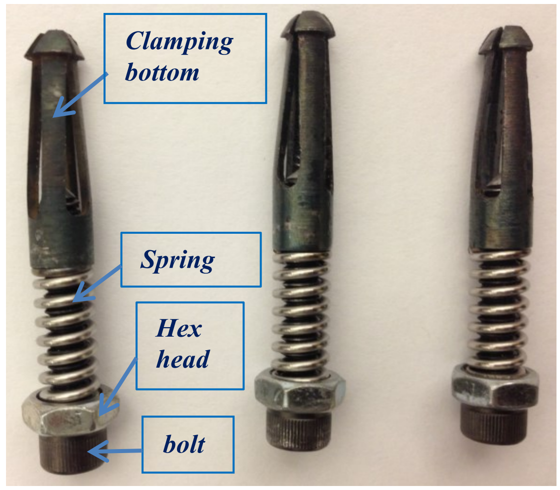


Figure 4.3. Components of the temporary fastener

Figure 4.4. Laser welding process

Another approach is to manufacture the clamping bottom, the spring, and the hex head of the hollow body as a single part. The advantage of this approach is that the components of the fastener are connected together strongly. The challenge of this approach is that some research on existing manufacturing process has to be studied to achieve the desired result.

Through the manufacturability and manufacturing process studies, the process to produce the hollow body as a single part has been developed. The manufacturing process to fabricate the new prototype of the temporary fastener is shown in Figure 4.5. A hex shape bar is chosen as raw material. The first step is to turn the outer shape, slot hole, and thread hole of the hollow body. The second step is to turn the spring when the cylindrical body for the spring is still solid inside. The third step is to use EDM to cut the inside hole of the spring and the slots located on the bottom. The final step is to turn the threads.

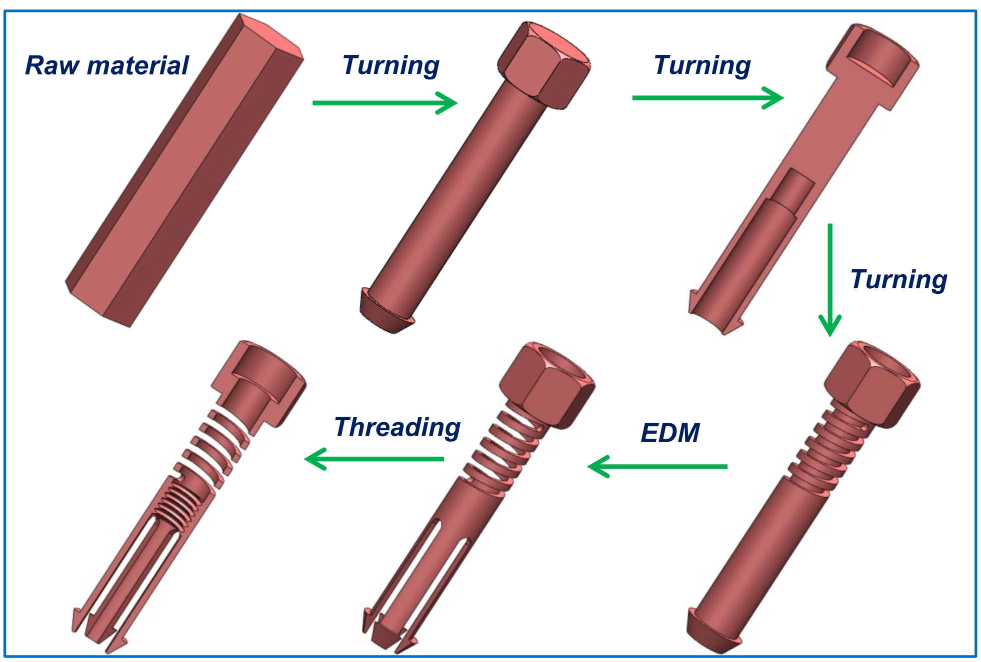


Figure 4.5. Manufacturing process developed for the new prototypes

5. TEMPORARY FASTENER FABRICATION PROCESS AND DEMONSTRATION

Temporary fasteners were fabricated using material VascoMax C300 nickel alloy with three different slot lengths. After the manufacturing process, the flexible fingers of the temporary fasteners were held together to perform heat treatment to form a collapsed shape. A fixture for the fastening tool currently used in industry was designed to operate the fabricated temporary fasteners.

5.1. MATERIAL SELECTION AND FASTENERS FABRICATION

Material VascoMax C300, 18% nickel maraging steel, was selected as the material to fabricate the designed temporary fastener. VascoMax C300 in the market is furnished in the solution annealed condition. It is very tough, relatively soft and therefore, readily machined and formed. It has high yield and ultimate tensile strength and has low furnace temperature heat treatment characteristics.

For different hole depths, three different slot lengths were specified to manufacture the temporary fasteners to work with a hole diameter of 0.25”. The manufactured parts are shown in Figure 5.1.

Figure 5.1. Manufactured new physical parts

5.2. HEAT TREATMENT OF THE TEMPORARY FASTENERS

After the parts were fabricated, the next step was to heat treat the temporary fastener with flexible fingers collapsed together. Steel wires were used to hold the flexible fingers in the collapsed state as shown in Figure 5.2a. Then the temporary fasteners were sealed in a steel foil bag and put into a furnace for heat treatment. First, they were annealed at 816 ℃ for 30 minutes and air cooled to release the residual stress. Afterward, they were aged at 482 ℃ for 10 hours and air cooled to increase the yield strength and ultimate strength. Figure 5.2b shows the shape of temporary fastener after heat treatment. It shows the flexible fingers are deformed and collapsed together after the heat treatment process.

(a) (b)

Figure 5.2. Fastener heat treatment: (a) fasteners held by steel wires and (b) fasteners after heat treatment

5.3. WORKING PROCESS DEMONSTRATION OF THE PROTOTYPES

The physical prototypes after heat treatment were used to demonstrate the working processes of the temporary fastener. When the hex head of the hollow body is held, the bolt was turned to expand the flexible fingers. While the bolt was being turned, the clamping bottom was driven up and the spring was compressed. Eventually, the clamping feet slid up to clamp the workpieces. The temporary fasteners with the state of flexible finger expanded and the spring compressed is shown in Figure 5.3.

Figure 5.3. Working of the fastener – flexible finger expanded and spring compressed

In order to operate the fabricated temporary fastener with the fastening tool currently used in the industry, a fixture was designed as shown in Figure 5.4 to fit the fastening tool and the temporary fastener. The hex pin was used to turn the hex top of the bolt, and the hex shape on the top of the cover was designed to fit the hex head of the hollow body. The cover of the fixture has a spring structure which can be compressed and extended to following the bolt movement. The designed fixture was fabricated using a Stratasys Fortus 400 FDM machine. Then the fabricated temporary fasteners were demonstrated using the modified fastening tool to show the working process.

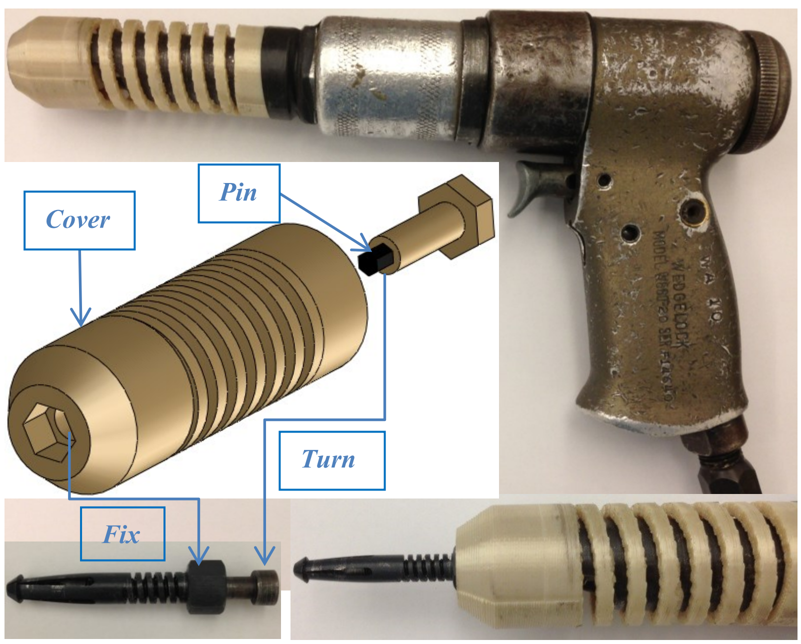


Figure 5.4. Fixture design for the fastening tool

6. FINITE ELEMENT ANALYSIS OF TEMPORARY FASTENERS

ABAQUS was used to preform FEA in order to study the effects of the design parameters of the temporary fastener. In practice, the temporary fastener is used with the flexible fingers in the collapsed state, so the first step was to simulate the deformed shape of the temporary fastener after heat treatment. After getting the FEA result of the deformed shape, the design parameters of the flexible fingers were analyzed. The design parameters of the spring were also analyzed. Afterwards, in order to get the analytical data of the tightening torque and the clamping load of the temporary fastener during the working process, the whole fastener operation was simulated.

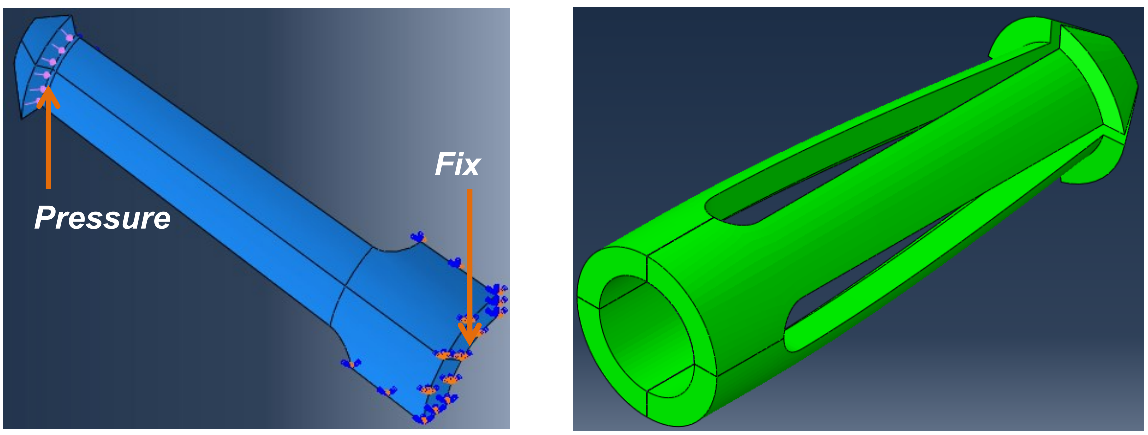
As mentioned above, VascoMax 300 Nickel alloy was used as the material for the temporary fastener, and 2117-T4 Aluminum alloy was used as the material for the workpiece in the analysis. The material properties of VascoMax 300 steel alloy and 2117-T4 Aluminum alloy are given in Table 6.1.

Table 6.1. Material properties of VascoMax 300 and 2117-T4 [26] [27]

Material	Young's modulus (MPa)	Poisson's ratio	Yield stress (MPa)
VascoMax 300	189,605	0.3	1,999
2117-T4	71,700	0.33	310

6.1. DEFORMED SHAPE SIMULATION

In order to manufacture the hollow body easily, the flexible fingers were fabricated with a straight shape in the machining process. After the heat treatment process, the flexible fingers were deformed and collapsed together. During the operation, the initial state of the flexible fingers is in the collapsed shape. In order to study the effects of the design parameters, the deformed shape should be identified first. FEA approach was used to get the shape of the deformed flexible fingers. The FEA simulation and results are shown in Figure 6.1. A quarter FEA model of the flexible fingers is shown in Figure 6.1a. While the top of the flexible finger is fixed, a pressure is applied to the area next to the foot of the flexible finger to simulate the steel wire holding process. The FEA result of the deformed geometric shape is shown in Figure 6.1b. It shows the geometry of the flexible fingers changes from a straight shape to a curved shape.



(a) (b)

Figure 6.1. Deformed shape simulation: (a) FEA modeling and (b) FEA result of deformed shape

6.2. ANALYSIS OF FLEXIBLE FINGERS DESIGN PARAMETERS

To study the design parameters of the flexible fingers, the deformed FEA shapes were imported to new FEA models to study the flexible fingers expanding and loading operation processes. A quarter model of the clamping bottom is shown in Figure 6.2. Step one of the simulation was to slide the bolt to expand the flexible finger. Then step two was to apply 300 lb load to the top of the workpiece to simulate the clamping process. For three different slot lengths, based on different tolerance gaps between the inner diameter of the hollow body and outer diameter of the bolt, FEA was performed to study the effects of the wall thickness of the hollow body. The design parameters are shown in Figure 6.3, where L is the slot length of the flexible fingers, T is the wall thickness of the flexible fingers, and D is the tolerance gap between the inner diameter of the hollow body and the outer diameter of the bolt. In order to let the bolt easily go through the hollow body, the gap D is needed in the structure.

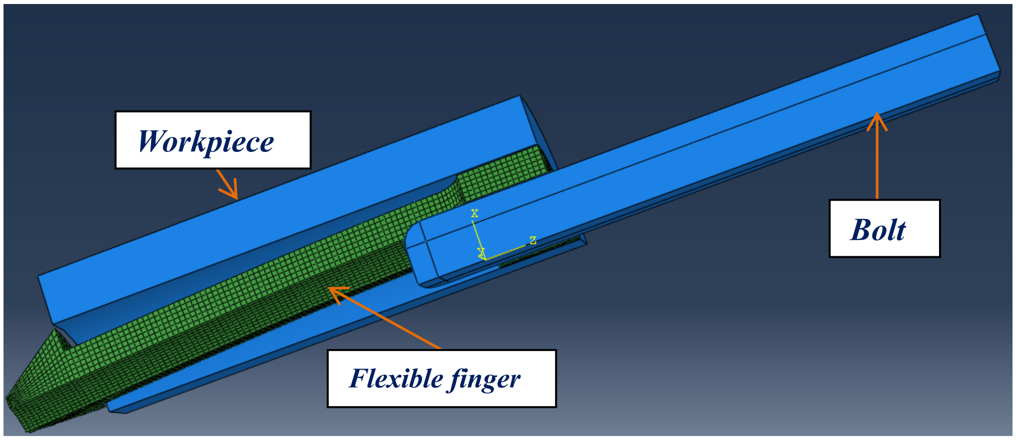


Figure 6.2. Quarter FEA model of the clamping bottom

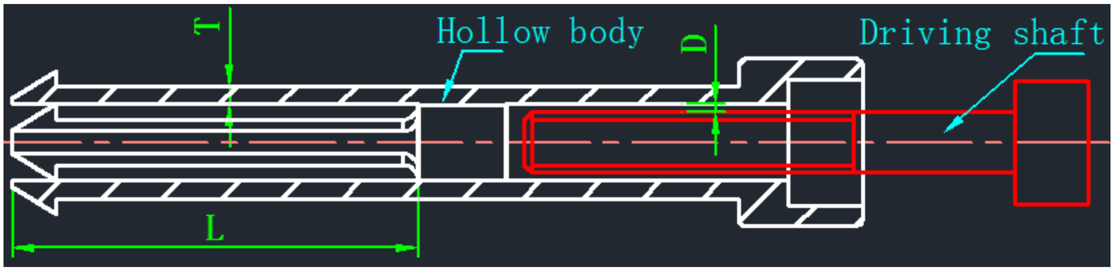
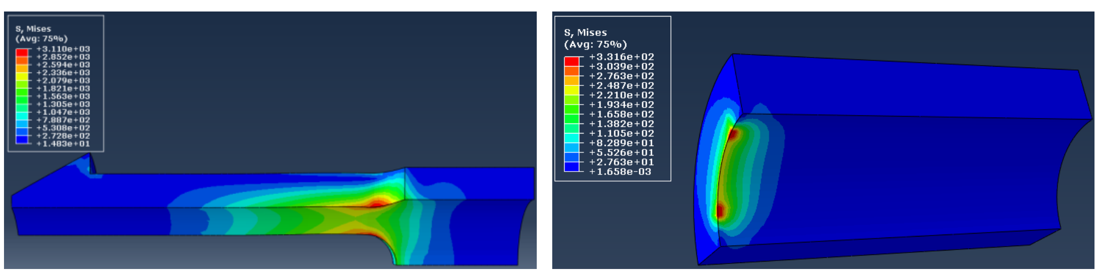


Figure 6.3. Design parameter of the temporary fastener (L – Slot length, T – Wall thickness, D – Gap between the inner diameter of the hollow body and outer diameter of the bolt)

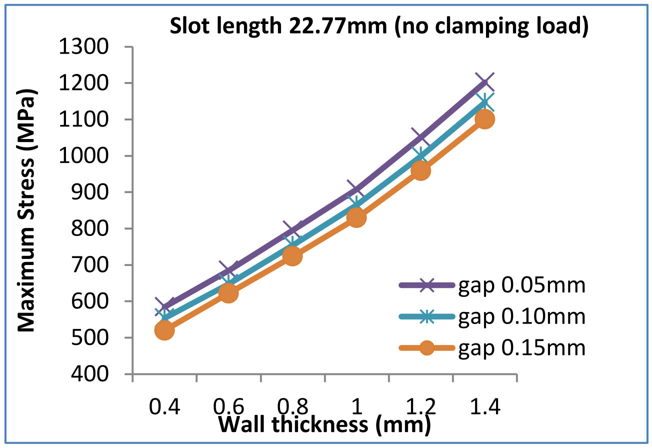
The stresses on the flexible finger and the workpiece are shown in Figure 6.4. Figure 6.4a shows the stress on the flexible finger after the flexible finger expanded and

300 lb load applied on its foot. Figure 6.4b shows the stress on the workpiece after 300 lb clamping load applied. Three different tolerance gaps (D), 0.05, 0.1 and 0.15mm, were studied. For three different slots lengths, 12.77, 17.77, and 22.77mm, when the flexible fingers were expanded with no load applied on their feet, the maximum stresses on flexible finger are shown in Figure 6.5. After 1334N (300 lb) load is applied on the flexible finger feet, the maximum stresses on flexible finger while slots lengths is 12.77, 17.77, and 22.77mm are shown in Figure 6.6. When the flexible fingers apply 1334N (300 lb) clamping load to the workpiece, for three different slots lengths, 12.77, 17.77, and 22.77mm, the stresses on the workpiece are shown in Figure 6.7. Since the stresses on the workpiece after 1334N (300 lb) applied are relatively high for the aluminum alloy, 890N (200 lb) and 445N (100 lb) clamping loads on the workpiece were also analyzed. The stresses on the workpiece when 890N (200 lb) and 445N (100 lb) clamping load applied are shown in Figure 6.8 and 6.9, respectively.

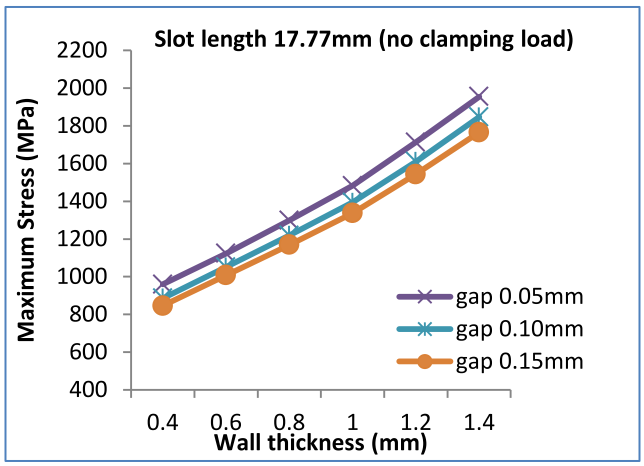


(a) (b)

Figure 6.4. FEA results: (a) stress on flexible finger and (b) stress on workpiece



(a)



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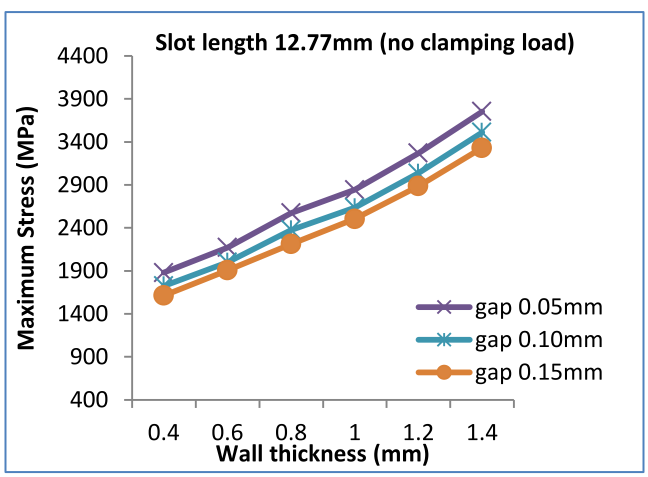
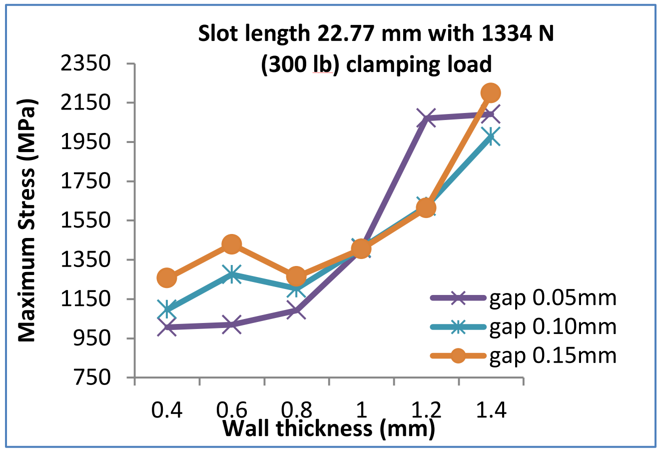
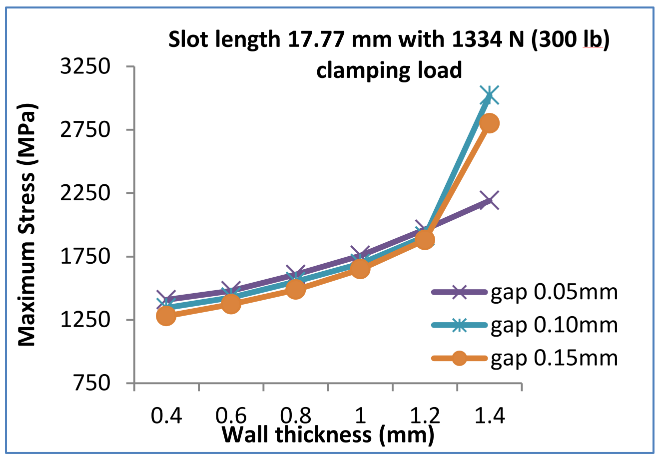


(c)

Figure 6.5. Stress on the flexible fingers after the fingers were expanded: (a) slot length 22.77mm, (b) slot length 17.77mm, and (c) slot length 12.77mm



(a)



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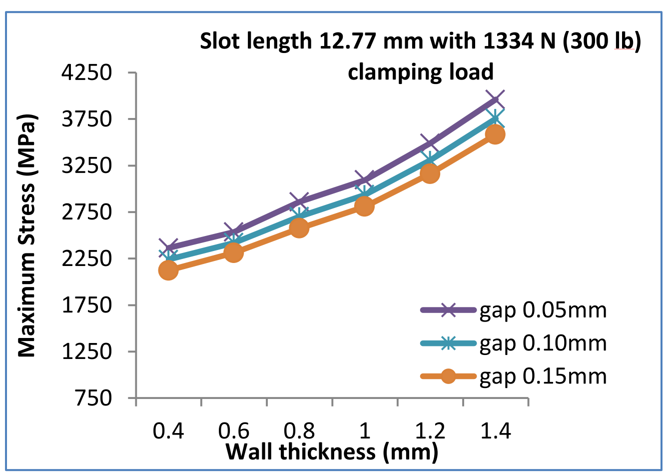
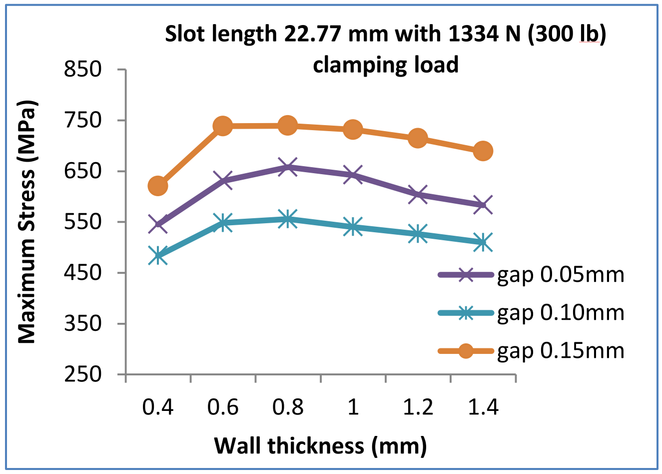
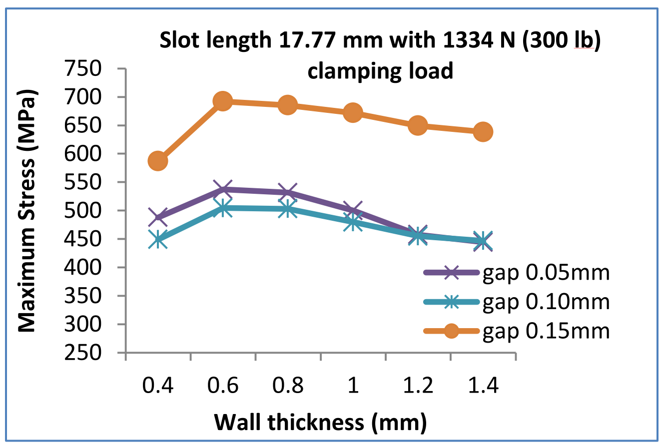


(c)

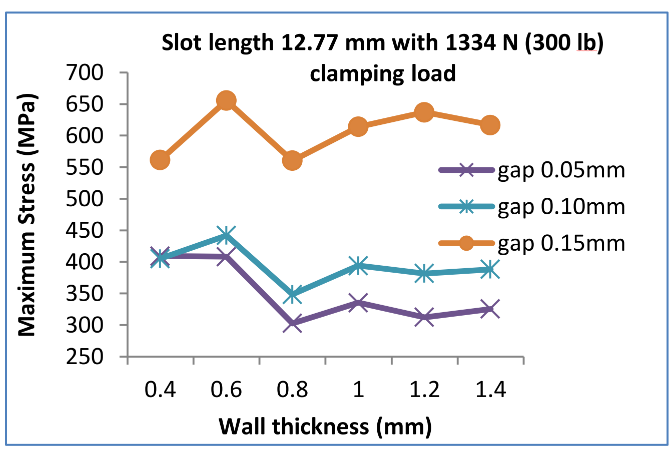
Figure 6.6. Stress on the flexible fingers after 1334 N clamping load applied: (a) slot length 22.77mm, (b) slot length 17.77mm, and (c) slot length 12.77mm



(a)

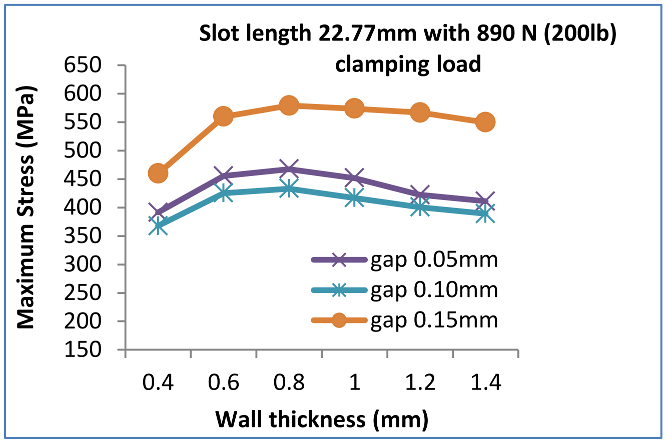


(b)

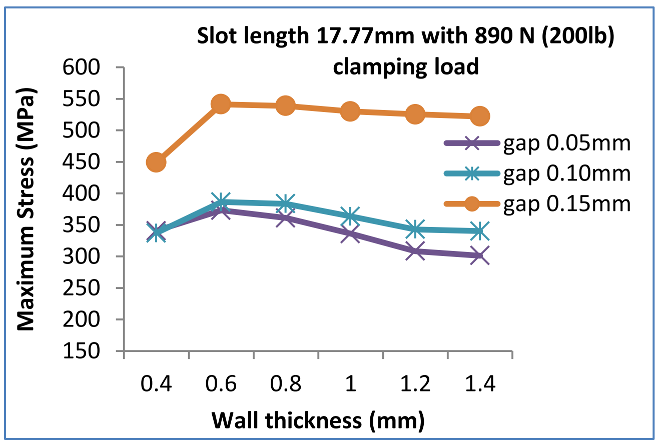


(c)

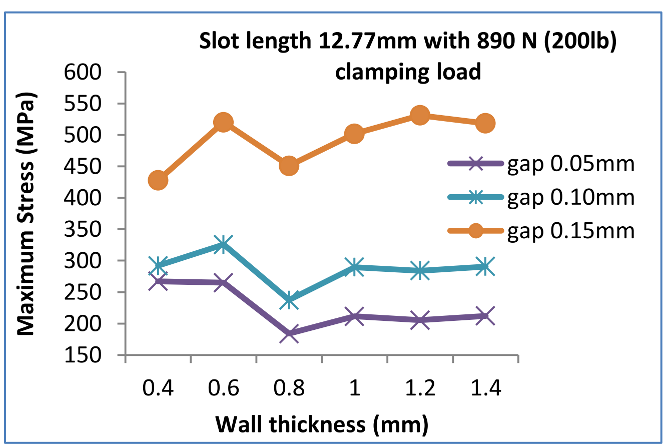
Figure 6.7. Stress on the workpiece after 1334 N clamping load applied: (a) slot length 22.77mm, (b) slot length 17.77mm, and (c) slot length 12.77mm



(a)

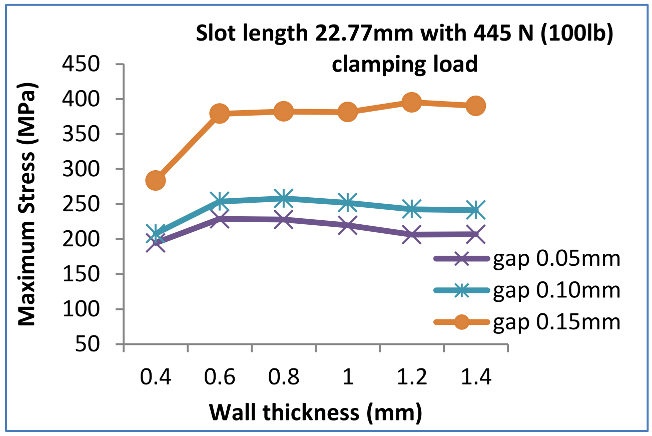


(b)

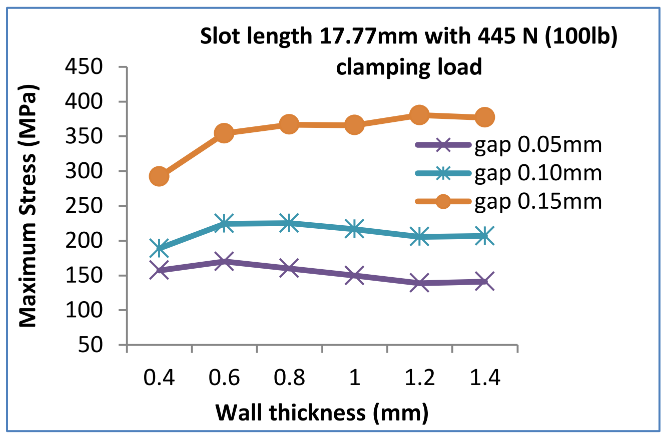


(c)

Figure 6.8. Stress on the workpiece after 890 N clamping load applied: (a) slot length 22.77mm, (b) slot length 17.77mm, and (c) slot length 12.77mm



(a)



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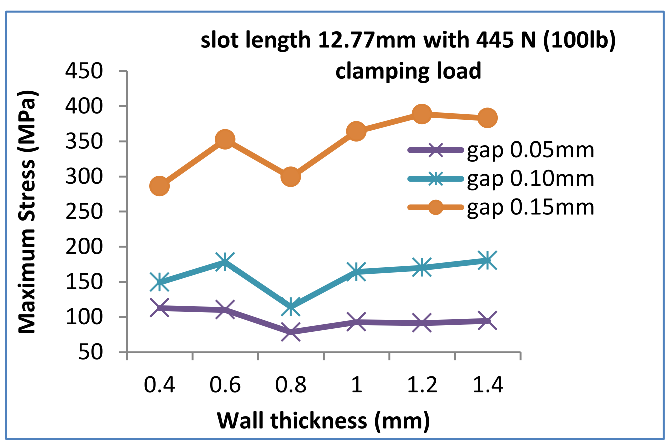


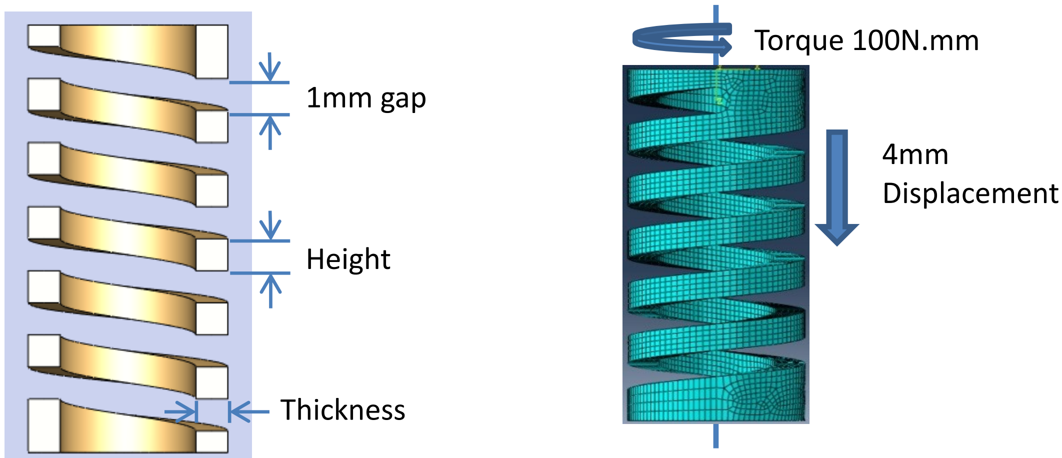
(c)

Figure 6.9. Stress on the workpiece after 445 N clamping load applied: (a) slot length 22.77mm, (b) slot length 17.77mm, and (c) slot length 12.77mm

The stress data shown above indicates that when the slot length L increases, the stress on the flexible fingers decreases. When the tolerance gap D is increased from 0.05 to 0.15mm, the stress on the flexible finger decreases, but the stress on the workpiece increases. The yield stress of the VascoMax C300 is 1999 MPa. From the simulation data, for 1334N (300 lb) clamping load requirement, slot length 12.77mm is not long enough to keep the stress on the flexible finger within 1999 MPa. For the 17.77 and 22.77mm slot length, the wall thickness should not exceed 1.2mm. From the stress data on the workpiece, if the aluminum alloy is used, the clamping load should not exceed 445N (100 lb), and the tolerance gap D should be 0.05 or 0.1mm. The maximum clamping load depends on the hardness of the workpiece material.

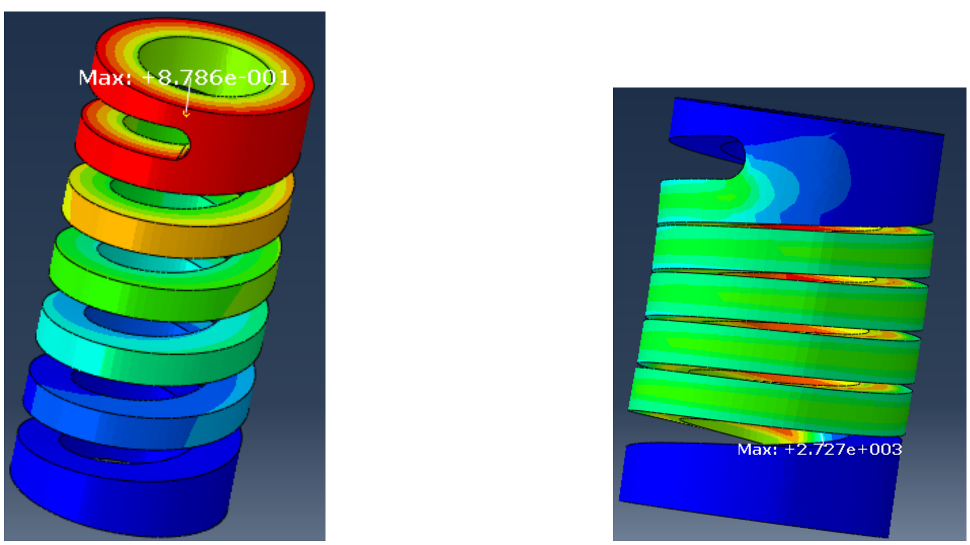
6.3. ANALYSIS OF SPRING DESIGN PARAMETERS

The spring of the temporary fastener is a key component of the temporary fastener. The studied parameters of the spring are shown in Figure 6.10a. The gap of the spring is 1mm. The height and thickness of the spring cross section vary from 0.6mm to 1.4 mm. The FEA model of the spring is shown in Figure 6.10b. During the FEA, the bottom of the spring was fixed. The first step was to apply a 100N.mm torque on the top of the spring. The second step was to apply a 4 mm displacement on the top of the spring to compress it. After the 100N.mm torque was applied, the displacement on the spring is shown in Figure 6.11a. Then after the spring was compressed 4mm, the maximum stress on the spring is shown in Figure 6.11b. The analytical data of the displacement on the spring after 100 N·mm torque applied is shown in Figure 6.12. The analytical data of the maximum stresses on the spring after 100 N·mm torque and 4mm displacement applied is shown in Figure 6.13. These two FEA results have been taken into consideration to design the spring because both the rotational displacement and the maximum stress concentration on the spring should be as small as possible.



(a) (b)

Figure 6.10. FEA modeling of the spring: (a) design parameters and (b) simulation process



(a) (b)

Figure 6.11. FEA results of the spring: (a) Displacement after torque applied and (b) Stress after compressed

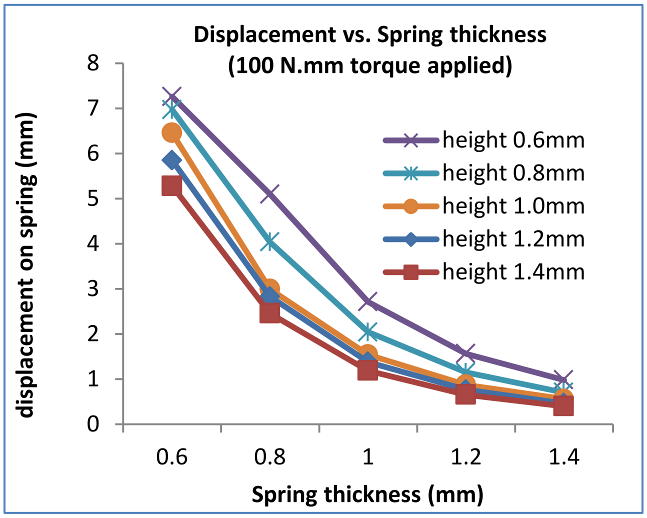


Figure 6.12. Displacement on the spring after torque applied

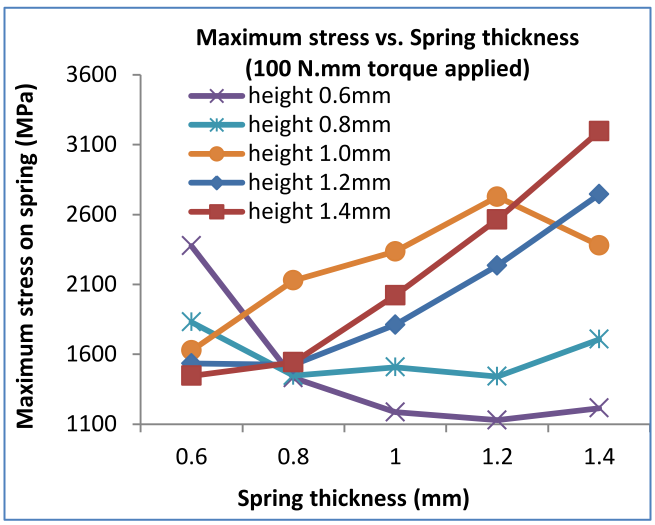
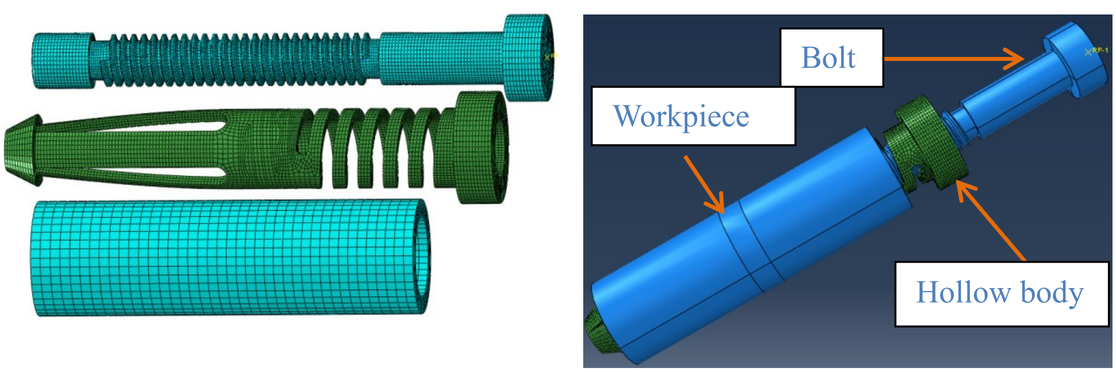


Figure 6.13. Stress on the spring after compressed

From the simulation data of the spring above, it shows that increasing the height or thickness of the spring cross section, the displacement on the spring decreases. However, if the height of the spring's cross section is larger than 1mm, the maximum stress on the spring increases as the spring thickness increases. To keep the stress less than 1999MPa, which is the yield stress of the VascoMax C300, and to make the rotational displacement on the spring smaller than 1.5mm, the spring should be designed as thickness 1.2 or 1.4mm with height 0.8mm, or spring thickness 1.4mm with height 0.6mm.

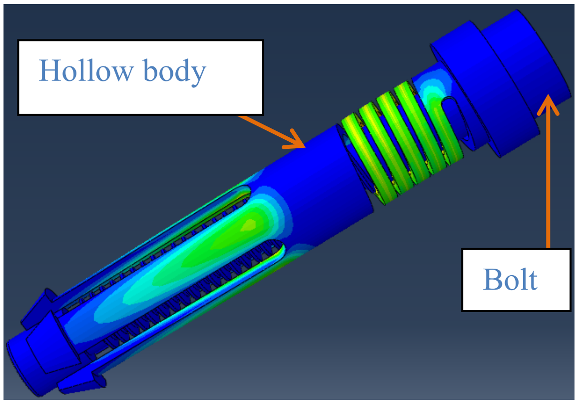
6.4. FINITE ELEMENT ANALYSIS OF TORQUE VS. CLAMPING LOAD

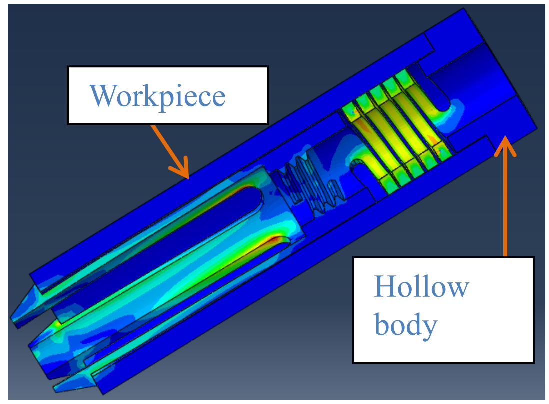
To get the analytical data of the torque and clamping load, a whole temporary fastener working process was simulated. Figure 6.14a shows the mesh of the temporary fastener components. The bolt is shown on the top, the hollow body on the middle, and the workpiece on the bottom. Figure 6.14b shows the assembly of the temporary fastener. Figure 6.15a shows the FEA result of the isometric view of the flexible fingers expanded; the workpiece is hidden in the figure. Figure 6.15b shows the FEA result of the section view of the workpiece clamped; the bolt is hidden in the figure.



(a) (b)

Figure 6.14. FEA of torque vs. clamping load: (a) Mesh of the temporary fastener and workpiece and (b) FEA assembly





(a) (b)

Figure 6.15. FEA result of torque vs. clamping load: (a) flexible finger expanded and (b) workpiece clamped

The temporary fasteners with three different slot lengths were simulated. From the FEA results, the analytical data of the tightening torque and clamping load during the operation process were extracted. The data are plot in Figure 6.16, 6.17, and 6.18 for the three different slot lengths.

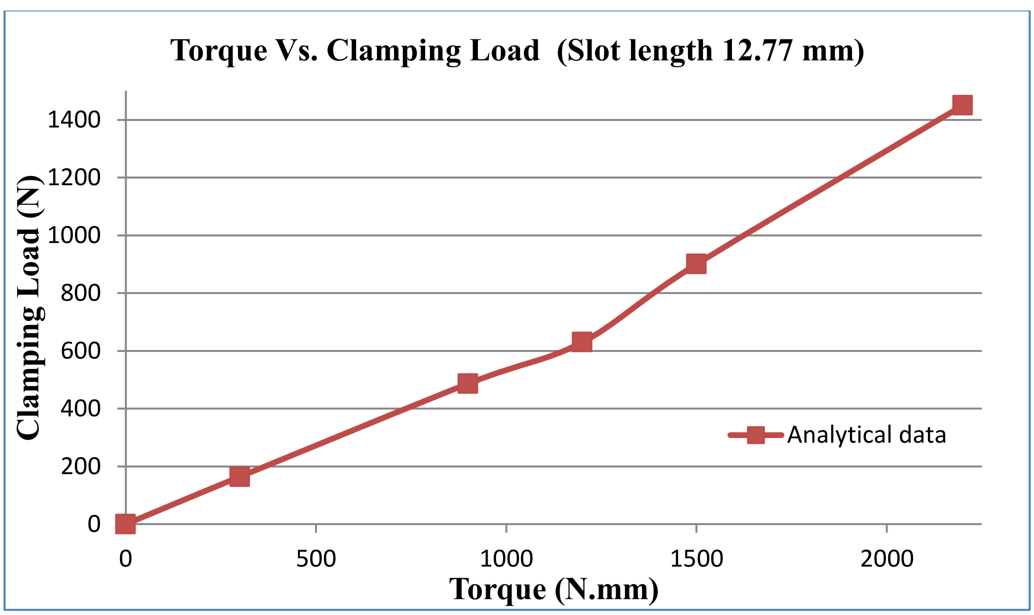


Figure 6.16. Analytical data of torque vs. clamping load (slot length: 12.77 mm)

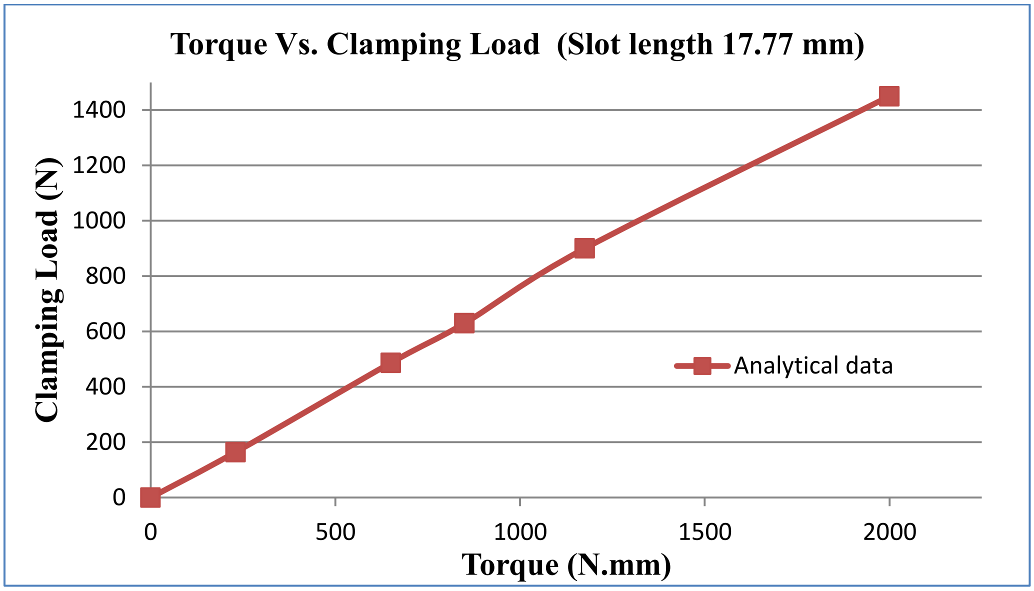


Figure 6.17. Analytical data of torque vs. clamping load (slot length: 17.77 mm)

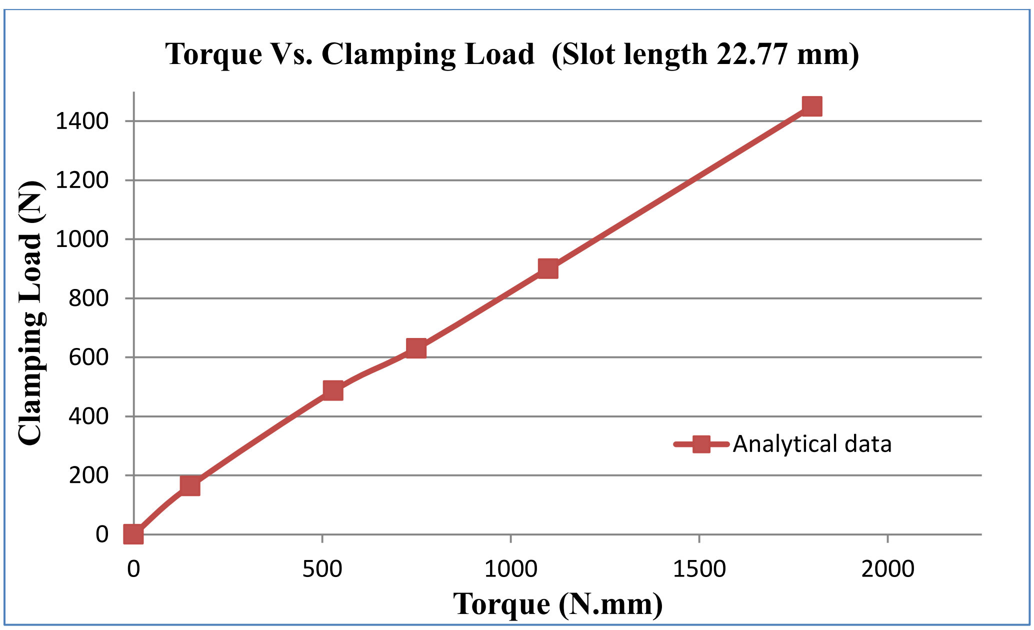


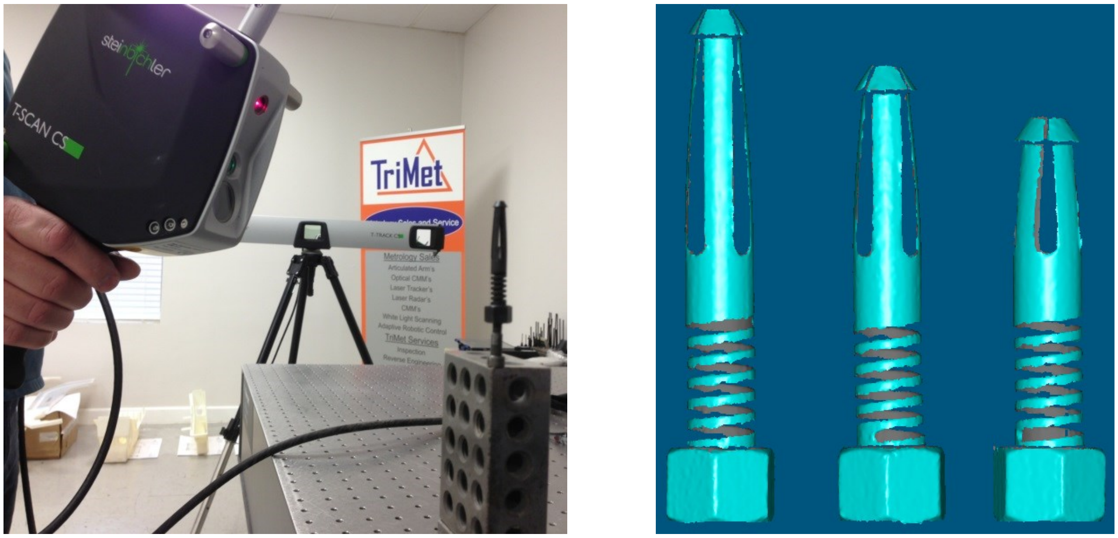
Figure 6.18. Analytical data of torque vs. clamping load (slot length: 22.77 mm)

7. EXPERIMENTAL VALIDATION OF FINITE ELEMENT RESULTS

To validate the deformed shape of the flexible finger from the FEA result, a 3D scanner was used to scan physical temporary fastener's deformed shape after heat treatment. The scanned shapes of the flexible fingers for the three different slot lengths were compared to the analytical shapes. To measure the strains on the flexile fingers, strain gages from Micro-Measurement were attached to the flexible fingers of the temporary fasteners, and a Wheatstone circuit was formed to obtain the data. A load cell and a torque sensor were used to measure the clamping load and tightening torque of the fabricated temporary fasteners during the working process, respectively.

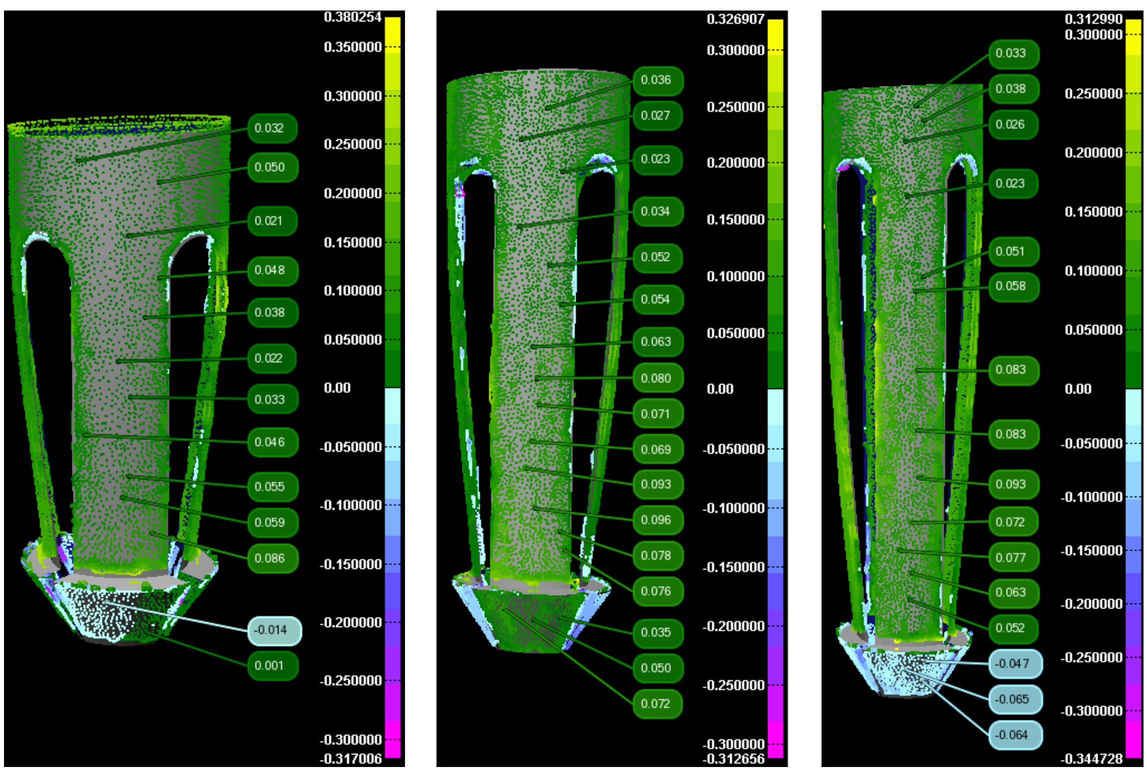
7.1. DEFORMED SHAPE VALIDATION

A Steinbichler laser T-scanner was used to scan the physical temporary fasteners after heat treatment, and thus obtain the geometry of the prototype's actual deformed shape. The laser scanner and the scanned data are shown in Figure 7.1. Afterwards, the scanned shapes were compared to the FEA predicted shapes. For the temporary fasteners with different slot lengths, the comparison results are shown in Figure 7.2. From the comparison results, the predicted shapes were validated since the differences between the FEA results and scanned shapes were very small.



(a) (b)

Figure 7.1. Deformed shape scanning: (a) Steinbichler laser scanner and (b) Scanned data



(a) (b) (c)

Figure 7.2. Comparison between the FEA predicted and scanned actual shapes: (a) shortest slot length, (b) medium slot length, and (c) longest slot length

7.2. STRAIN VALIDATION

In order to validate the analytical strains, strain gages from Micro-Measurement were employed. Since the area of the stress concentration on the flexible fingers was very small, and the predicted area of high stress was also difficult to access, the strain gages were attached to the outer side of a flexible finger, which is the area where the highest compressive stress was located. Then the strain gages were connected to three resistors to form a Wheatstone bridge circuit to measure the strain.

7.2.1. Strain Gages and Bondable Terminals. Micro strain gages from Micro Measurement were used to measure the strains on the temporary fasteners. The strain gage is shown in Figure 7.3. Because the feet on the micro strain gage were very small, bondable terminals shown in Figure 7.4 were used as a bridge to connect the feet of the strain gage and wires. To attach the strain gage to the temporary fastener, the first step is to bond the strain gages and the terminals on the temporary fasteners as shown in Figure 7.5. Next, two very small wires were soldered to connect the feet of the micro strain gage to the terminal. Finally, three wires were soldered to the terminals as shown in Figure 7.6.

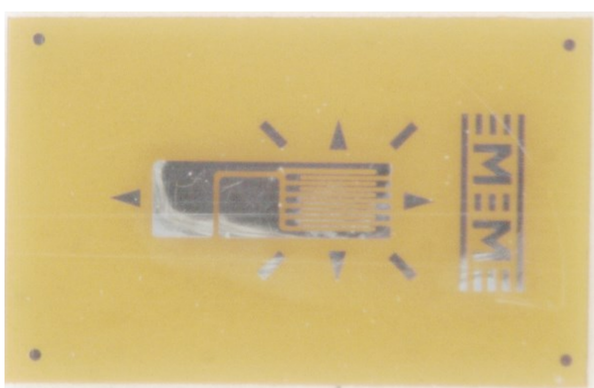


Figure 7.3. Strain gage from Micro-Measurement

Figure 7.4. Bondable terminals

Figure 7.5. Temporary fasteners with bonded strain gage and terminals

Figure 7.6. Wires soldered to the strain gages and terminals

7.2.2. Wheatstone Circuit. In order to eliminate the effect of the resistance of the lead wires, a three-wire connection scheme was used to form a Wheatstone bridge circuit as shown in Figure 7.7. After three wires were attached to the strain gage, three 120 ohm resistors and the strain gage were connected to from a Wheatstone bridge circuit. A data acquisition module was connected to the circuit to not only supply the excitation voltage but also measure the output voltage during the experiment as shown in Figure 7.8.

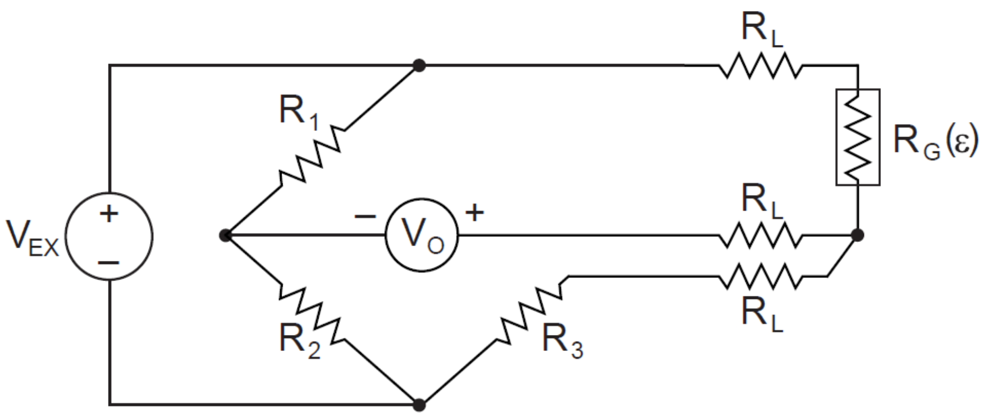


Figure 7.7. Three-wire connection Wheatstone bridge circuit

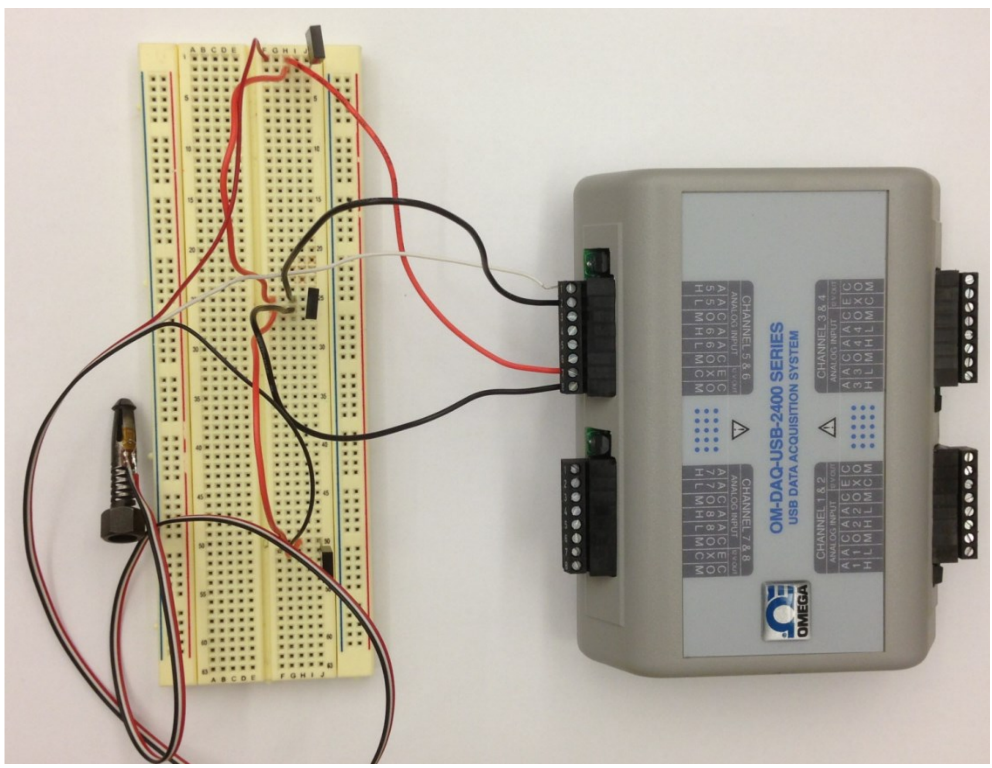


Figure 7.8. Wheatstone bridge circuit used in study

7.2.3. Bracket Design and Experimental Setup. After the strain gage and the attached wires were attached to the temporary fastener, the outer diameter of the fastener body becomes bigger. Therefore, the fastener body cannot go through the hole of the load cell. In order to get the stresses on the flexible fingers under certain loads, a bracket as shown in Figure 7.9 was designed to transfer the clamping load to the load cell and thus to obtain the strains on the flexible fingers. During the fastener operation, when the flexible fingers of the temporary fastener expanded and the spring of the temporary fastener compressed, the top of the fastener applied a pressure on the red part to push the green part down to press the load cell (refer to Fig. 7.9). Meanwhile, the brown hollow frame was pulled up by the feet of the fastener to press the load cell. So, the clamping load can be measured in this structure. The experimental process is depicted in Figure 7.10. Figure 7.10a shows the temporary fastener installed, and Figure 7.10b shows the temporary fastener tightened and a clamping force applied on the workpiece and load cell.

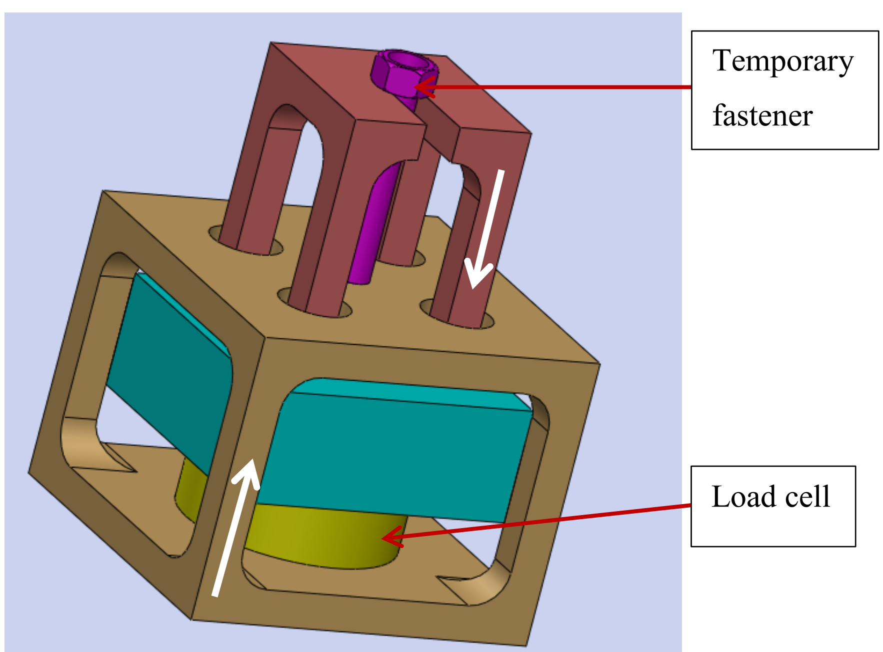
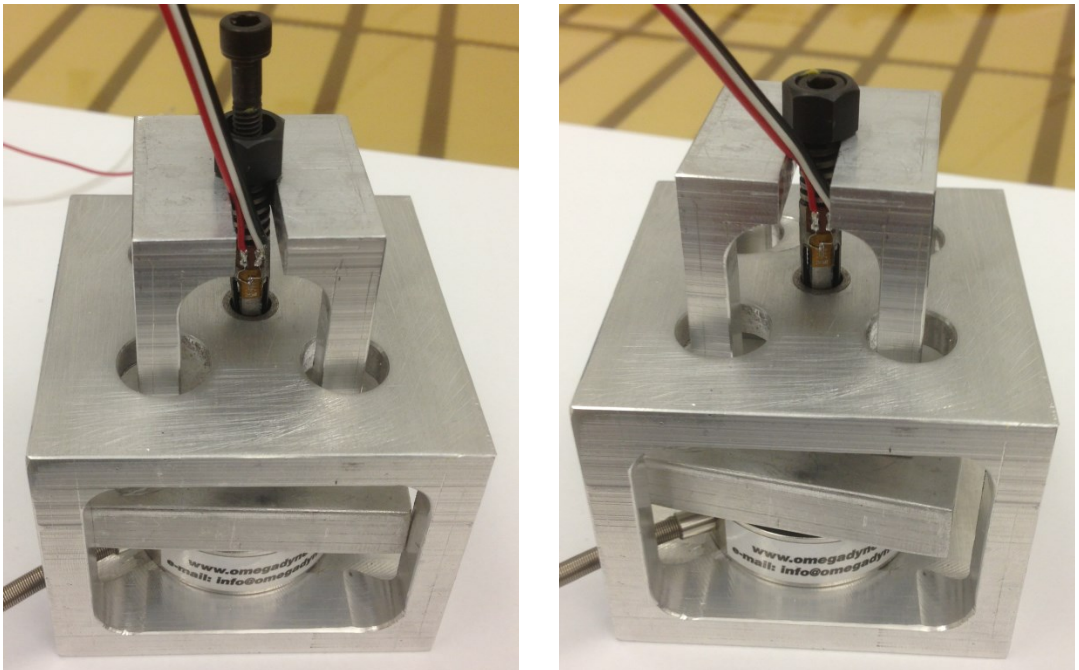


Figure 7.9. Bracket design



(a) (b)

Figure 7.10. Bracket design for loading experiment of the temporary fastener with strain gage attached: (a) temporary fastener installed and (b) clamping force applied

7.2.4. FEA Prediction and Experimental Measurement Comparison. The strain data on the temporary fasteners was measured with the strain gages and the data acquisition module shown in Figure 7.8. From the FEA prediction, the maximum compressive strain on the flexible finger is shown in Figure 7.11. The strain gages were attached to the yellow area, which highlighted by a red rectangular box. The strain on each node of the area was extracted as presented in the table inside Figure 7.11. The average of the strains was calculated as the predicted strain on this area, which was used to compare with the measured strain. The comparison between the FEA prediction and experimental data is given in Table 7.1. From the data on the table, the experimental data and analytical data have a good agreement.

node	strain	node	strain
1	0.00656	12	0.00735
2	0.00671	13	0.00732
3	0.00656	14	0.00752
4	0.00698	15	0.00732
5	0.00716	16	0.00722
6	0.00698	17	0.00743
7	0.00722	18	0.00722
8	0.00743	19	0.00710
9	0.00723	20	0.00731
10	0.00735	21	0.00710
11	0.00755		

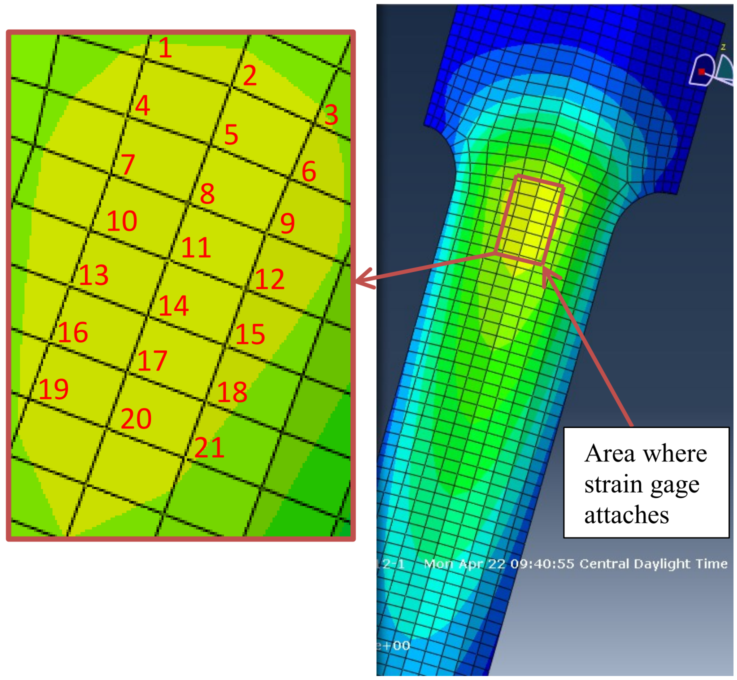


Figure 7.11. FEA predicted maximum compressive strain on the flexible fingers

Table 7.1. Comparison between the FEA predicted strains and experimentally measured strains

	1st specimen	2nd specimen	3rd specimen	average	FEA prediction	difference
Optimized long	0.00112	0.00176	0.00165	0.00151	0.00143	5.19%
Optimized medium	0.00226	0.00238	0.00208	0.00224	0.00204	9.34%
Optimized short	0.00381	0.00365	0.00345	0.00363	0.00370	-1.82%
Initial long	0.00224	0.00206	0.00232	0.00220	0.00212	3.88%
Initial medium	0.00304	0.00368	0.00354	0.00342	0.00312	9.66%
Initial short	0.00636	0.00716	0.00668	0.00674	0.00685	2.29%

7.3. MEASUREMENT OF TIGHTENING TORQUE AND CLAMPING LOAD

Temporary fasteners are used to align aerospace parts of a multiple layer structure and apply a clamping load to these parts. During the temporary fastener operation process, a torque is applied using a fastening tool to operate the temporary fastener. To obtain a properly clamping load, the relationship of the tightening torque and the clamping load was measured.

7.3.1. Experimental Setup. A load cell and a torque sensor were employed to study the clamping force and tightening torque of the temporary fastener. The experimental equipment is shown in Figure 7.12. The load cell, the torque sensor, and the data acquisition module are the products of Omega Engineering. The bracket was designed to support the load cell. The plates with different thicknesses represent the different hole depths, so the temporary fasteners with different slot lengths can be measured. The experimental setup is shown in Figure 7.13. The bracket was fixed with a clamp to a table. The load cell was located on the inside groove of the bracket. A plate was put to align the load cell on the other side. A temporary fastener was then passed through the holes on the plate, the load cell, and the bracket. A wrench was used to hold the top hex head of the temporary fastener. Then an Allen wrench, which is attached with a torque sensor, was used to turn the hex shape of the bolt top. In this experiment, the torque and the clamping load were measured simultaneously.

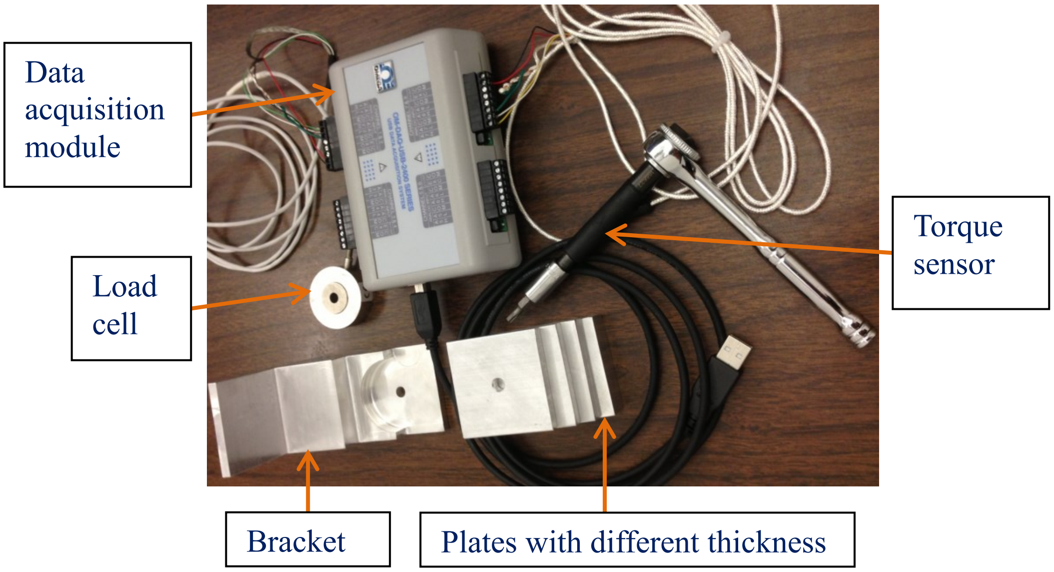


Figure 7.12. Experimental equipment for measuring torque vs. clamping load

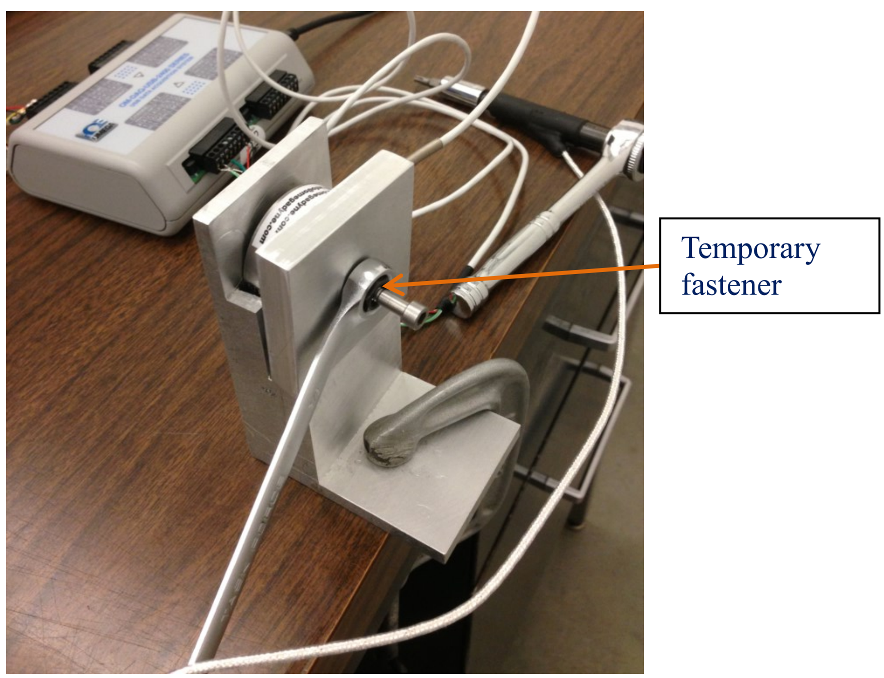


Figure 7.13. Experimental setup for measuring torque vs. clamping load

7.3.2. Comparison of Analytical and Experimental Data. The torque versus clamping load measured for the temporary fasteners with slot lengths 12.77mm, 17.77mm, and 22.77mm are plotted in Figures 7.14, 7.15, and 7.16, respectively. The comparison between the experimental data and the analytical data as illustrated in each figure indicates a good agreement.

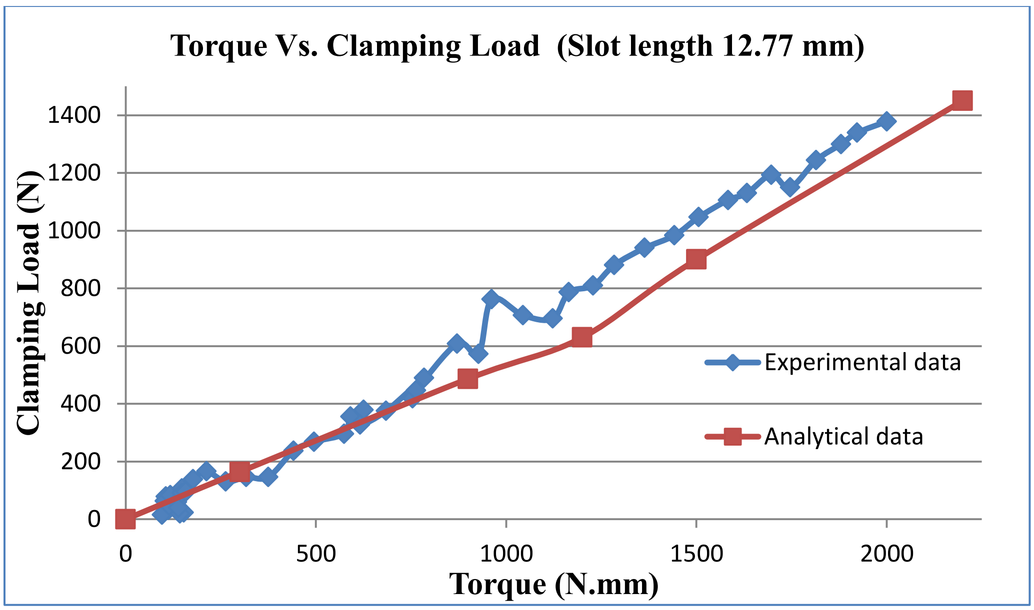


Figure 7.14. Analytical and experimental data of torque vs. clamping load (slot length: 12.77 mm)

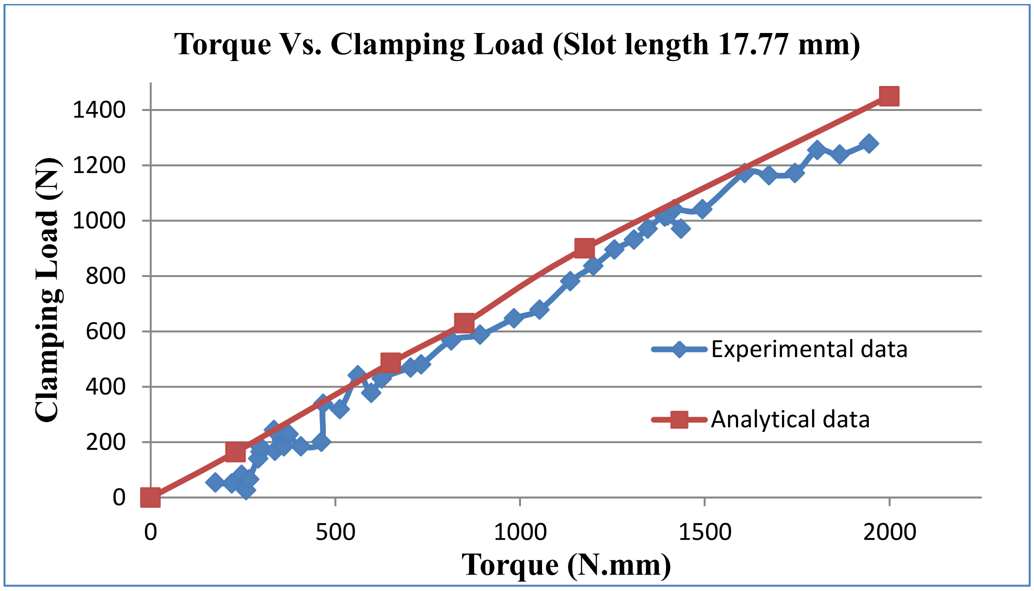


Figure 7.15. Analytical and experimental data of torque vs. clamping load (slot length: 17.77 mm)

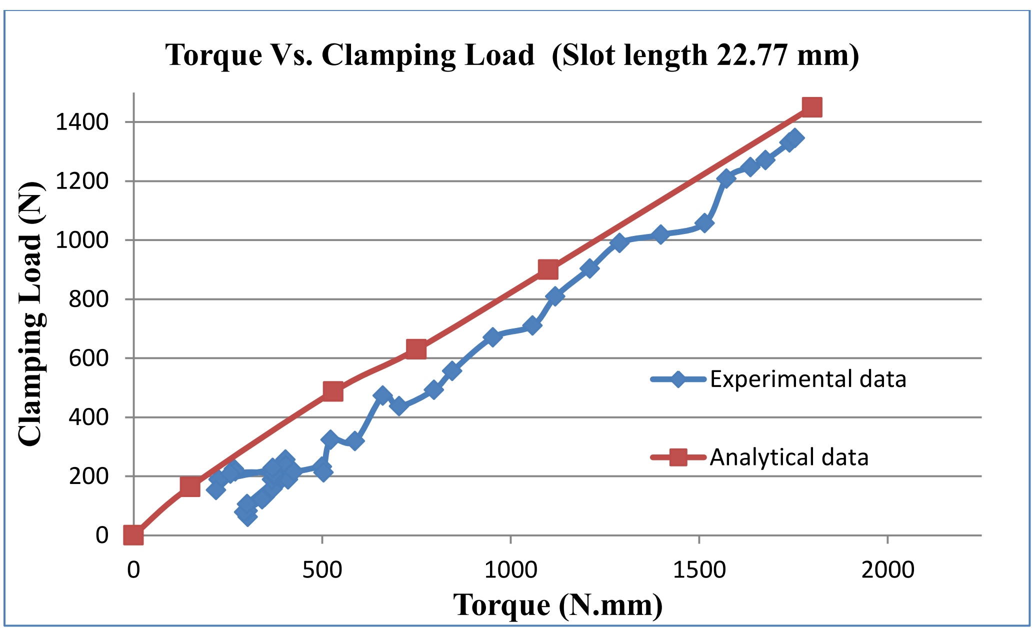


Figure 7.16. Analytical and experimental data of torque vs. clamping load (slot length: 22.77 mm)

8. DESIGN OPTIMIZATION

From the analytical data of the flexible fingers and the springs, the thickness of the flexible fingers should be designed as thin as possible, for example, 0.4mm. The thickness of the spring should be larger than 1mm. Since the thickness of the flexible finger is smaller than the thickness of the spring, and the diameter of the bolt is nearly the same as (only very slightly less than) the inner diameter of the spring, there is a gap between the bolt and the inner diameter of the flexible finger. The bolt cannot properly expand the flexible fingers, thus a bolt cap is designed to fit the end of the bolt. The optimized design is shown in Figure 8.1. The assembly process is to install the bolt from the top of the hollow body. Then put the bolt cap to press fit the end of the bolt from the bottom of the hollow body. So the bolt can go through the inside of the spring, and the bolt cap is able to expand the flexible fingers properly. Figure 8.2 shows a cross-section view of the optimized temporary fastener in the assembly state.

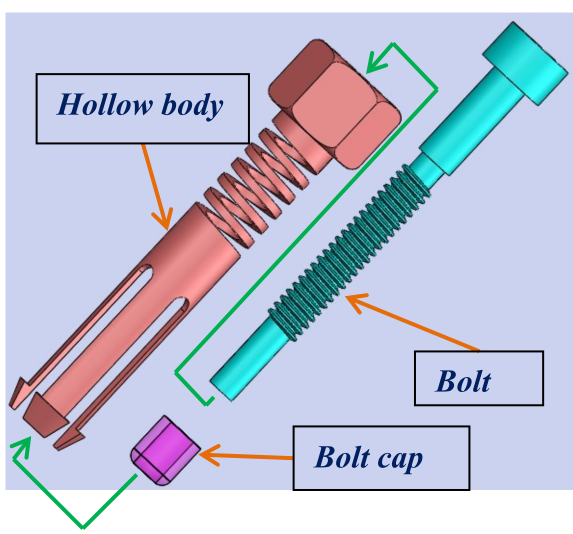


Figure 8.1. Temporary fastener components and assembly process

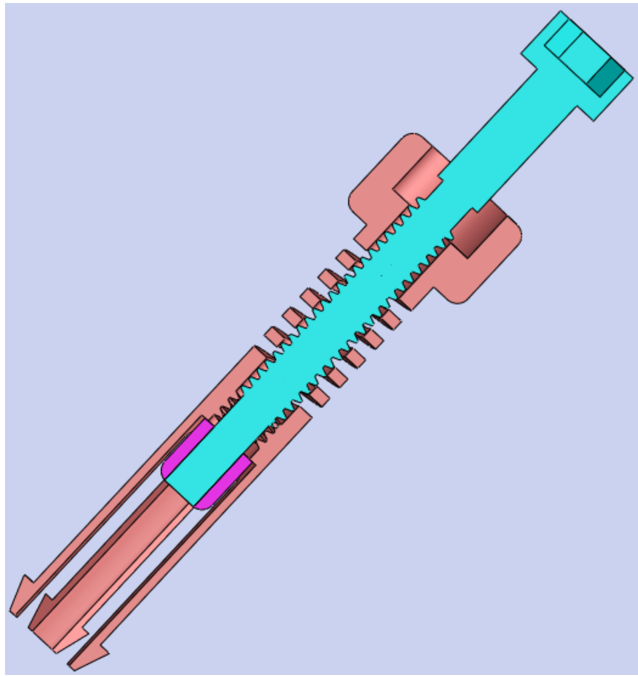


Figure 8.2. Cross section of the assembled temporary fastener

The new drawings with the optimized design parameters are generated to manufacture the temporary fasteners. Based on the FEA data, the optimized parameters include the following:

- decrease the hex head length from 7mm to 4mm
- change the cross section of the spring from height 1mm with thickness 0.8mm to height 0.8mm with thickness 1.2mm
- change the direction of the spring from right-hand to left-hand
- decrease the length of the thread on the hollow body from 5mm to 3.5mm
- increase the slot length by 3.5mm
- change the slot thickness from 0.8mm to 0.4mm
- put a thread cap on the bottom of the bolt

- change bolt size from 8-32 to 6-32

The fabricated new temporary fasteners with optimized design parameters and the pervious fabricated temporary fasteners are shown in Figure 8.3 below. The overall length of the optimized fastener and the previous fastener for the each type (short, medium, long) is the same.

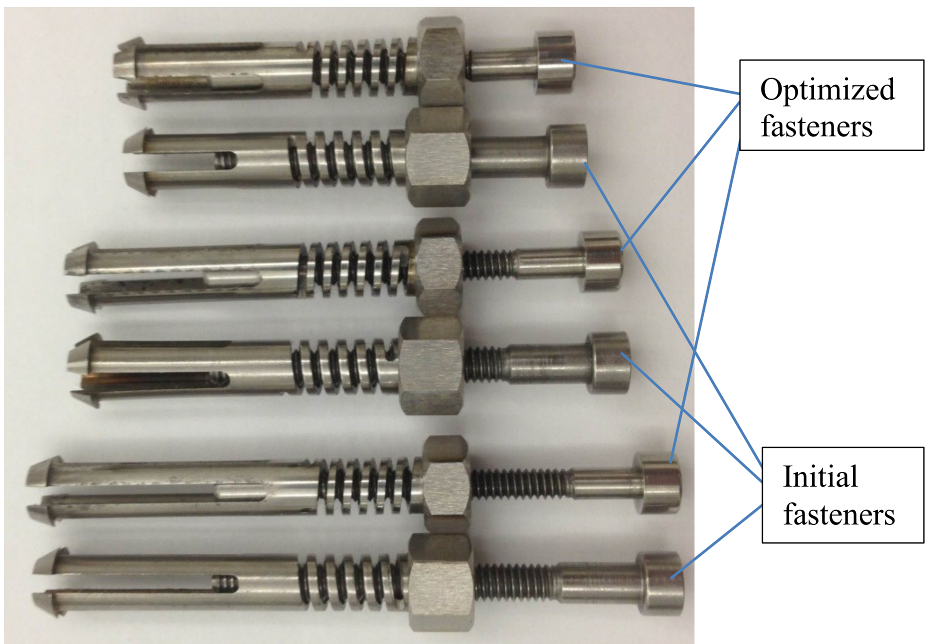


Figure 8.3. Optimized vs. initial temporary fasteners

Two optimized temporary fasteners were used to test their fatigue life, by applying a clamping load that varied between 0 and 1334N (300lb) to the feet of these temporary fasteners. After 1000 tightening and loosening cycles, there were no failure on the temporary fasteners, and these fasteners were still good to use with the designed functionalities. The temporary fasteners after 1000 cycles fatigue test are shown in Figure 8.4.

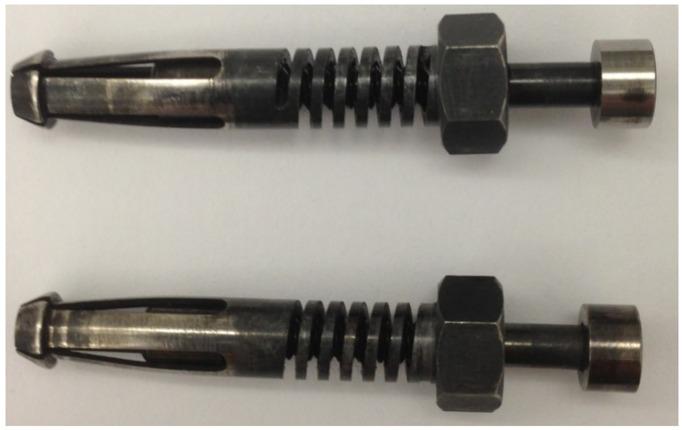


Figure 8.4. Temporary fasteners after 1000 cycles in a fatigue test

9. CONCLUSION

Published papers, web pages, and patents relating to temporary fasteners have been reviewed in this study. The surveyed temporary fasteners were categorized into 4 types: top-spring type, outer-screw type, ball-end type and inner-screw type. Six new design concepts for temporary fasteners have been developed. Comparisons were made among these designs and several commercial temporary fasteners. The advantages of the most promising new design have been identified. These advantages include cost-effectiveness, reduced assembly time, adjustable workpiece thickness, and adjustable clamping load.

Rapid prototypes of the final design were fabricated to demonstrate the fastener's working process. Manufacturability and manufacturing processes were studied for the selected temporary fastener. The temporary fasteners were fabricated with VascoMax C300 material. A fixture was designed to operate the temporary fastener with a fastening tool currently used in industry.

FEA was performed on the final design to evaluate the effects of the clamping load, the slot length, and wall thickness of the flexible fingers on the maximum stress generated during the operation of the temporary fastener. The analytical strain results were validated with strain gages. Tightening torque versus clamping load were simulated and measured; the measured data agrees well with the simulated results. The design parameters of the temporary fastener were optimized, and the temporary fastener with the optimized design parameters was fabricated.

BIBLIOGRAPHY

[1] http://www.airspacemag.com/flight-today/Airliner_Repair_247.html#, "Airliner Repair, 24/7", S. Joiner, 2013

[2] S.O. Smith and T. McClure, "New Blind, Doweling, Temporary Fastener Design and Testing," SAE Technical Paper 2009-01-3184, 2009.

[3] C. J. Koenig, "Fastener," U.S. Patent 2317201, 1943.

[4] D. H. Finkle, "Fastener," U.S. Patent 2324687, 1943.

[5] R. W. Edwards, "Temporary Fastener," U.S. Patent 2343499, 1944.

[6] K. C. Bugg, "Temporary Fastener," U.S. Patent 2393587, 1946.

[7] P. Van Sittert, "Fastener," U.S. Patent 2397892, 1946.

[8] F. E. Johnson, "Temporary Positioning and Holding Means for Aperture Members," U.S. Patent 2398644, 1946.

[9] P. Van Sittert, "Fastener," U.S. Patent 2411914, 1946.

[10] P. Van Sittert, "Fastener," U.S. Patent 2430486, 1947.

[11] J. M. Kosterubanic, "Fastener," U.S. Patent 2463700, 1949.

[12] E. Werner, "Nut and Plate Temporary," U.S. Patent 2570618, 1951.

[13] S. B. Jones, "Clamping Device," U.S. Patent 3883129, 1975.

[14] J. D. Pratt, "Wedge-type Low Profile Fastener," U.S. Patent 4537542, 1985.

[15] T. E. Armstrong and G. M. Moon, "Limited Force Cartridge for Temporary Fasteners," U.S. Patent 5240361, 1993.

[16] T. O. Blankenship and J. L. Morrison, "Spring Loaded Bushed Wedgelock," U.S. Patent 5927919, 1999.

[17] R. A. Gage; L. N. Hazlehurst and M. R. Jack, "Tack Fastener," U.S. Patent 6056283, 2000.

[18] R. G. Falk, "Temporary Fastener with Projecting Tool-guide Bushing," U.S. Patent 6196779, 2001.

[19] V. T. Olson and S. T. Ulinski, “Tool Clamp and Method,” U.S. Patent 6755407, 2004.

[20] M. L. Anderson and W. J. Koch, “Wedge-lock Fastener and Associated Installation and Assembly Methods,” U.S. Patent 6827345, 2004.

[21] D. G. Starr, “Device and Method for Temporarily Fastening a Plurality of Workpieces in Response to the Introduction of Pressurized Fluid,” U.S. Patent 7048266, 2006.

[22] T. D. McClure, “Radial-type Temporary Fastener, Components and Tool,” U.S. Patent 7300042, 2007.

[23] D. Ruddck and L. Blattmann, “Fasteners, Especially Temporary Fasteners,” U.S. Patent 0216292, 2008.

[24] J. A. Kelley; R. A. Luepke; L. M. Vestal; E. J. Kush; M. L. Hestness; E. C. Patty and J. Langevin, “Method of Manufacturing Aircraft Using Temporary Fasteners,” U.S. Patent 0308171, 2010.

[25] J. Niklewicz and D. A. Carran, “Removable Blind Fastener,” U.S. Patent 0008124, 2011.

[26] http://www.atimetals.com/Documents/ati_vascomax_c-300_tds_en.pdf, “Technical Data Sheet of C-200/C-250/C-300/C-350 Alloys,” ATI Allvac, 2013.

[27] G.Li, G.Shi, and N.C.Bellinger, “Stress in Triple-Row Riveted Lap Joints Under the Influence of Specific Factors,” JOURNAL OF AIRCRAFT, 2011.

[28] A. Saunier, “Bolting Up Device and Temporary Fastener,” U.S. Patent 1487184, 1924.

[29] F. L. Moler, “Article Used for Holding Sheets of Material Together,” U.S. Patent 2284834, 1942.

[30] N. E. Cole, “Body Structure for Vehicles,” U.S. Patent 2561098, 1951.

[31] D. G. Starr, “Alignment Device with Radially Expandable Tube,” U.S. Patent 5527023, 1996.

[32] C. Chupick, “Free-floating Hydraulic Clamping Device With Edge-gripping Arbor,” U.S. Patent 6978988, 2005.

[33] J. J. Luner; L.A. Hoeckelman and D. W. Kleine, “Fastener Grip Length Selector,” U.S. Patent 7065897, 2006.

[34] L. A. Hoeckelman, “Clamping Fastener Grip Length Indicator,” U.S. Patent 7070375, 2006.

[35] A. Scapa, “Hole-filling Three-prong Temporary Fastener,” U.S. Patent 0170142, 2006.

[36] J. D. Pratt, “Dual Action Disposable Clamp,” U.S. Patent 0191020, 2009.

[37] K. P. Dammermann, “Device and Method for Fastening,” U.S. Patent 0257707, 2010.

[38] C. Krejci, “Automatic Feeding of Temporary Fasteners in Confined Spaces,” SAE International, 2010.

[39] C. Krejci and J. Westley, “Automatic Bolt Feeding on a Multifunction,” SAE International, 2011.

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