The Study of On-line Waste Material Removal Procedures for Bridge Laminated Object Manufacturing (LOM) Process

Y.Y. Chiu*, Y.S. Liao** and C.C. Hou***

*Associate professor, Department of Industrial Design, Oriental Institute of Technology, 58, Sec. 2, Syh-Chuan Rd., Baan Chyan, 220, Taipei, Taiwan, Fax: +886 2 29544672, E-mail: petecyy@ms19.hinet.net

**Professor, Department of Mechanical Engineering, National Taiwan University, Taipei, Taiwan

***Graduate student, Department of Mechanical Engineering, National Taiwan University, Taipei, Taiwan

Abstract

Focusing on the drawbacks inhered in the laminated object manufacturing (LOM), a new Bridge-LOM process and its associated building algorithm are proposed in this paper. The proposed Bridge-LOM process starts with the construction of the bridge structures to link a stack of 2-D geometry contours to the outer frame based on the proposed bridge building algorithm. Afterwards, laser is directed to cut along the contours, and then the upper pressing head is pushed down and the layers are bonded. This is followed by spraying some adhesive on the top of bonded layers. The procedures of cutting, bonding and adhesive spraying are repeated until the complete 3D part is produced. From the experiments, it is verified that the proposed Bridge-LOM process not only saves laser-cutting time, the time on waste material removal is also reduced significantly by more than 80%. Furthermore, the hollow bottle can even be fabricated.

Keywords: laminated object manufacturing (LOM), Bridge-LOM, waste material removal

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* Correspondence addressee

1. Introduction

"A diagram serves better than one thousand words for description, whereas a solid model serves better than one thousand diagrams for illustration." This saying shows the importance of a solid model. Nowadays, rapid prototyping (referred to as "RP," hereinafter) can achieve this goal rapidly. The first step of the product development is to design the necessary CAD file. Next, build a prototype of the product according to the file, so as to confirm the design, revise the product, test its function and then further develop its mold. Laminated object manufacturing process (referred to as "LOM," hereinafter) carries the advantages of using low-price materials, as well as speedy and processing etc. It adopts the LOM process by using paper as the laminated materials. It uses the "bond－then－cut" principle. A sheet is laminated to the previously laid and bonded layers by a hot roller. The roller applies heat and pressure as it is rolling over the sheet, which has a thin layer of thermoplastic adhesive on the down–facing surface. After the new layer is bonded, a focused beam of CO_2 laser incises the outline of the part. Laser power is adjusted to cut through only one layer of lamination. The unused material is left in place, however, diced with crosshatch into small pieces called "tiles" for easy removal. The iterative process of bonding and laser cutting is repeated until the construction of the final layer is completed. Once all layers have been laminated and cut, excess material is removed to expose the finished part.

Nevertheless, in the LOM process of paper lamination, there exist a lot of demerits and problems [1-3]. For example, the LOM process adopts a "bond then cut" method where every layers of work-piece's region supported by waste material. By using such method, the waste material and work-piece would co-exist. Upon the completion of processing, labors are needed to de-cube the unnecessary waste material. This is also called de-cubing process. And in the process of de-cubing, not only would it waste the manpower and working hours, but also damage the work-piece itself. Besides, since the waste material surrounds with the work-piece, many geometrical parts (hollow part, vase-shaped part, thin wall part, etc.) cannot be fabricated by LOM process. As the waste material also has to be crosshatched during the laser cutting process and also consumes plenty of laser cutting energy.

In order to improve the problems of waste material removal process, Klosterman *et al.* developed an adaptive crosshatches method [4-7]. It uses the fine crosshatch laser cut to reduce the bonding strength at the contact area between the work-piece and waste material. However, as the fine crosshatch laser cut applied by this method is not the efficient method, it would induce an excessive laser-processing path. Besides, the intensive laser cut will produce a very great amount of thermal effect, which would affect and restrict the bonding strength and precision of work-piece. Moreover, though the fine crosshatch method is applied, much time was still consumed on the waste material removal process. Apart from these, the laser cutting of waste material is not just an immense waste of energy, but also a considerable increase of time for laser cutting.

Thomas proposes the method of "cut then bond" to solve the de-cubing problem encountered in LOM process [8]. The principle of this method is to use laser to cut the 2D contour from slicing 3D CAD file on the working table. After that, by means of conveyance mechanism, the sheet-based material being cut is sent to another working table to carry out the pressing and bonding process. All the unnecessary waste material is removed during the process. Repeated the procedures 3D part is finished. Although the "cut then bond" method would not produce problem of waste material, the natural supporting feature of the waste material for LOM process is also lost. Moreover, the conveyance mechanism would not hold the sheet-based materials in a fixed position during the conveying process, which is also a serious problem.

Chi, Dodin and Pak attempt to expand the application of LOM by using metal sheet-based material to fabricate metal prototype directly [9]. The proposed method adopts "bond then cut" method, which uses a clamp to fix the layer of materials, and then bond by spot welding. Then, laser is used to cut the layer material. But this method also has its weaknesses. The cutting can affect the next layer easily, and the de-cubing of waste material cannot be carried out smoothly since the brittle material.

As de-cubing process plays a very importance role in the LOM process, the adhesive invalidation approach is developed [10]. Making use of the control of laser processing path planning, it reduces the bonding strength between waste material and work-piece. After that, an adaptive crosshatch approach to improve working efficiency and to alleviate the effort involved in the de-cubing process is also developed [11]. In order to obtain a more extensive application of LOM in the aspect of complicated geometrical parts, as well as to achieve a higher efficiency of manufacturing and de-cubing process, the Bridge-LOM process and its associated building algorithm are proposed in this paper. It uses the bridge structure to connect all the 2D sections after slicing 3D CAD file. Based on the "cut then bond" method for lamination, the bridge structure not only provides a natural supporting feature, but also replaces the supporting function of waste material as comparing with the current LOM process. Besides, over 60% ~ 70% of waste materials would naturally be removed on line. This proposed method intends to solve the problems of waste materials removing process in LOM process, also promotes the efficiency of processing as well, avoids the waste of unnecessary laser processing consumption, fabricates the complicated geometrical part that cannot be fabricated by the current LOM process, and expands the application area of LOM process.

2.1 Bridge-LOM Process

The proposed Bridge-LOM process adopts "feed-cut-press then adhesive spraying" method to laminate successive layers and a work-piece is finally produced. Figure 1 shows the flow chart of Bridge-LOM process. The "feed" process adds new layer, "cut" the new layer by controlling laser path, "press" the layer with a pressing head, then the adhesive spraying process is done by nozzle. Repeat the procedures until the part is finished.

The frame structure of Bridge-LOM process approach is shown in Figure 2. The layer material is a roll of sheet-based material. There are two rolls, a material supply roll which is used to feed the new layer, and a take-up roll which is used to collect the used layer, both are applied to control its forward movement and keep it at a certain tension. During the lamination process, the work-piece is placed on a table that lies beneath the layer material. The pressing head with vertical bonding movement is above the sheet of material, whereas a nozzle for spraying adhesive moves along X-Y direction.

The detail description of the procedures of Bridge-LOM processing is stated as below:

Step 1. Make an extra outer frame to the 3D model established by CAD as shown in Figure 3. A stack of 2D geometry contours is formed after slicing the 3D model. According to bridge building algorithm (will specify the method in details in the following section), convert it into a 2D geometry contours to the outer frame with bridge structure, called bridge-files as shown in Figure 4.

Step 2. Process and laminate the bridge-files accordingly. As shown in Figure 5, after the machine receives a bridge-file, make a complete laser cutting according to the contour of the file. One thing that is noteworthy: the most outer contour of each bridge file has not been cut completely, in other words, the most outer contour still has a little bonding strength. After cutting the contour, the waste material inside the work-piece would drop completely, making an automatic de-cubing function. Finally, there are only three mutually connecting work-pieces left each layer: outer frame, work-piece region and bridge. While the waste material is dropping, a simple sliding track mechanism used to receive the waste materials and then move them to the disposal bucket. Figure 5 does not demonstrate this sliding track mechanism.

Step 3. As shown in Figure 6, after cutting the contour, the working table below moves upward and the pressing head above push down to bond with the previous layers together tightly that has just been cut.

Step 4. As shown in Figure 7, the pressing head and the working table to move downward together, so that the cut layer and sheet-based material would separate completely. Also, this would ensure that this cut layer would bond with the previous layer tightly. In order to make the semi-cut contour separated from the outer contour of the cut layer, the edge of the upper pressing head can more or less be made into a knife shape. In doing so, when the pressing head moves downward, the knife shape at the outermost edge can create a cutting force to separate the contour smoothly.

Step 5. After the separation of the cut layer, the pressing head moves upward and retreats to the original position on top of the sheet-based material. The working table also retreats to the original position. Now the nozzle sprays adhesive as shown in Figure 8.

Step 6. After the spraying of adhesive, the sheet-based material moves forward. The processing of one layer is then completed. Repeat this cycle to complete the whole processing.

Step 7. The work-piece will be exposed after the outer frame and bridge structure are removed.

2.2 Bridge building algorithm approach

The process developed under the principles of “cut then bond” has to face two important problems: support and position. Regarding the function of position, in order to ensure the proper bonding treatment, as well as holding a precise position between layers, the processes from cutting to bonding in the Bridge-LOM process should maintain the same X-Y position. Therefore, worries of not having a fixed positioning would then be eliminated. Regarding the function of support, bridge has taken the place of the supporting function of waste material in the traditional LOM process. In other words, in the bridge building process, it moves upwards from bottom up, naturally a supporting function towards the upper layer is reached. However, there is a phenomenal difference compared to Bridge-LOM and the traditional LOM process. The waste material support in the traditional LOM refers to the waste material existed in every part of the work-piece, exerting the support towards every part of the work-piece. As to the function of the bridge for Bridge-LOM process, apart from the bonding to the different contours of the same layer, it also builds bridge wherever support is required; so that the supporting function is formed to virtually anywhere the work-piece needs support. In this way, during the post processing process of waste material removal, not only would the space occupied by the waste material of the bridge is less than that of the traditional LOM, but also the time spend on de-cubing is considerably reduced.

Bridge building algorithm approach is divided into three parts as follows:

2.3 Work-piece’s contour capture approach

The purpose of work-piece’s contour capture approach is to give every contour an attributive name, so as to follow up with the bridge building process.

As shown in Figure 9, the idea of work-piece’s contour capture approach is to “capture from the work-piece’s outmost outer to the inner,” with an order of A, B and C accordingly. For instance, the attributive name B_{mn}, B refers to Bth layer, *m* refers to the *m*th group and *n* refers to the *n*th contour of Bth layer. In the most outer frame, the contour of the inner layer is defined as "*out-path*." as shown Figure 9

From work-piece's contour capture approach, it is known that the out-path area going inwards from A_1 to A_n regions is waste material. The area from the region of A_1 to A_n running inward to the region of B_{11} to B_{mn} is just the work-piece. Bearing such analogy in mind, the bridge can smoothly be established on the region of waste material to connect the different work-piece's region.

2.4 Bridge building algorithm 1

The purpose of the bridge building algorithm **1** is that while considering the X-Y direction of the work-piece, allow mutual connection be possible between two contours of islands through the building of bridges, and in times of cutting, avoid the island from dropping together with the waste material. The categories of the bridge building algorithm **1** can be stated as below:

(1) Building bridge in the same sub-layer of the work-piece:

The contour attribute resulted from the work-piece's contour capture approach is used for connecting each of the island's contours of the same sub-layer together. The letter representing the contour attribute can judge whether it is of the same sub-layer. For example A_1, A_2 and A_3 belong to the same sub-layer. The method of building bridge process stated as follow. First of all, find the centers of A_1 and A_2 islands respectively. If draw a line come across these two centers, it will intersect with A_1 and A_2 contours, forming two intersecting points on different contour. On A_1 contour, take an intersecting point b that is closer to A_2 center. On A_2 contour, take an intersecting point c that is closer to A_1 center. Then the line bc is obtained. Extend to both sides at half the width of the offset preset bridge. Immediately the bridge connection is obtained as shown in Figure 10. The purpose of this bridge building process in the same sub-layer of the work-piece is that prevent from the islands fall with the waste material due to their weights.

(2) Building bridge in the different sub-layer of work-piece's region:

If work-piece's region still exists within a closed region that's called the different sub-layer here, it is necessary to combine two regions together to prevent dropping. The way of combination is shown in Figure 11. Establish a bridge on the X-Y direction respectively for connecting the C_{21} region and B_{21} region. The function of the bridge here is to connect the inner island with outer pocket within a closed region. Hence, the bonding strength of bridge between island and pocket will be formed.

(3) Make bridge between sub-layer A contours and the outer frame:

Upon completion of bridge building and connection between two islands or pockets discussed earlier, the outermost layer of work-piece (i.e. sub-layer A contours) has to be connected with the outer frame. The method is to build a bridge along the X-axis and Y-axis direction come across the centers of sub-layer A contours and the outer frame, as shown in Figure 12.

2.5 Bridge building algorithm 2

The purpose of bridge building algorithm 2 is that consideration of the Z-axis direction of the work-piece, building bridges to prevent the creation of deflection caused by the weight of the work-piece's material.

(1) 1st part of algorithm 2

The difference of areas between the layers makes the following upper layer, after laminated, deflected at the protruding position because of insufficient support. Then incomplete bonding problems would appear in the lamination of the next layer in this case.

If the work-piece shown as in Figure 13, there are small circular rods above and below, and an protruding shape in the middle. Upon completion of bridge building approach **1**, the bridges can only be built along x-axis and y-axis direction. Therefore, the protrusion shape can be easily deflected at 45 degrees as shown in Figure 14, and the next layer cannot be completely bonded during the lamination process.

Viewing these issues at the viewpoint of material Kinematics as shown in Figure 15, allow the edge of the small cylinder in the lower work-piece be the fulcrum of the suspended arm. Then the deflection (δ) of the free end is expressed as equation (1) below. The symbols are also shown in Figure 15.

$$\delta = \frac{wL^4}{8EI} \tag{1}$$

If the acceptable δ_{max} value is put in the equation, the acceptable L_{max} value can be obtained. Then take the more conservative $L_{adaptive}$ value as a basis for bridge building reference. Compare the actual L value with the $L_{adaptive}$ value. When $L \geqq L_{adaptive}$ value, build a supporting bridge on this point to prevent deflection. The completion of this bridge building process is shown in Figure 16.

This establishment is processed when there is a spatial difference between the upper and the lower layers. In order to make the established bridge to support the following laminated weight, a ***Boolean*** value should be established for reference. In this case, even though the ***Boolean*** value is true, build bridge on the several consecutive layers of the same point, so that the bridges there can be the support . By so doing, it would avoid deflection created from the following laminated weight.

(2) 2nd part of algorithm 2

Upon completion of cutting the sheet-based material, the contour difference of the same layer makes the more protruded contour bend seriously because of its own weight. Under this situation, wrinkles would appear during bonding process.

Using the work-piece demonstrated in Figure 17 as an explanation, the cross-section of the work-piece is entirely in the form of a protruding rod along z-axis direction. When the work-piece has gone through the process of laser cutting, the portion of protruding rod will bend downwards due to its own weight. When the pressing table undertakes bonding process downwards, wrinkles can be formed easily at the protrusion portion. Hence, a bridge still has to be built at the protruding rod for supporting. The bridge upon completion of building is also the same as Figure 16.

3. Conclusion

The paper focuses on the laminated object manufacturing (LOM) of rapid prototype technologies, and proposes the improvements for many of the demerits of the process. The proposed Bridge-LOM process and its associate bridge algorithm approach take "cut then bond" as the basic criteria, and then execute the processes of cutting and bonding on the same position. No fixed positioning and supporting problems will occur by experiment. Moreover, Bridge-LOM process also possesses the following advantages from the results of the experiment:

1. Bridge-LOM process and its associate bridge building algorithm approach can undertake on line waste material removing of over 60 ~ 70% by its weight in the process. Afterwards, the time spent on de-cubing in the post processing process can be greatly decreased by over 80%.
2. Through the bridge building approach, the process of crosshatching on the waste material as required in the original LOM process can be omitted. Not only can it save time on laser cutting, but also the consumption of laser power. It is, therefore, a great improvement to the processing efficiency.
3. The on line de-cubing feature of Bridge-LOM process can smoothly complete the

fabrication of work-piece in geometrical patterns, such as hollow object, vase, etc. As for the fabrication of thin-wall work-piece, all one has to do is to remove the bridge during the post processing process, so that the thin wall would not be damaged easily. Therefore, Bridge-LOM process can also fabricate the thin-wall part, the original LOM process still cannot build it.

4. Since Bridge-LOM process is extremely efficient in on line de-cubing, it is very suitable for the fabrication of metal work-piece and mold. There will be more researches in the filed. To extend the superiority of de-cubing of metal laminated sheets in the Bridge-LOM process, and study the possibility of metal mold fabrication by Bridge-LOM process, such as injection mold [12]. Investigate the heat-resistance situation, strength difference and numbers of injected parts after application of heat-resisting adhesive for bonding of metal molds. Meanwhile, investigate the expansion of Z-axis direction after layer-to-layer bonding. The design of the addition of conformal cooling channel to laminated processing can possibly improve the expansion of Z-axis direction.

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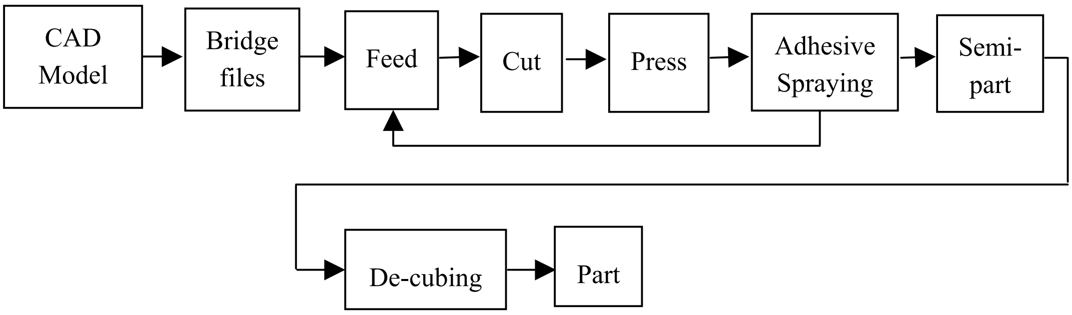

Figure 1. Flow chart of Bridge-LOM process

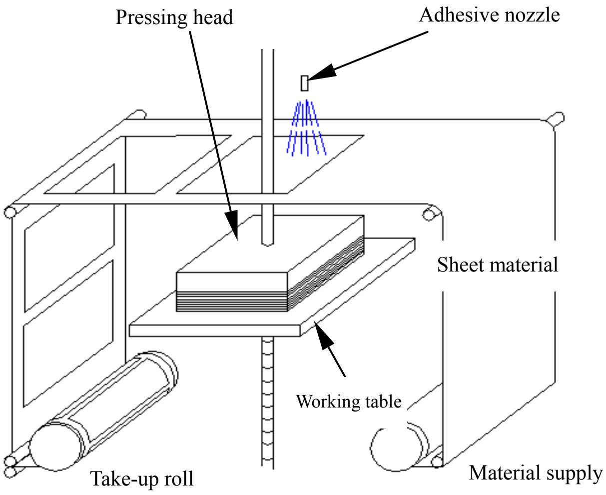

Figure 2. Illustration of Bridge-LOM equipment

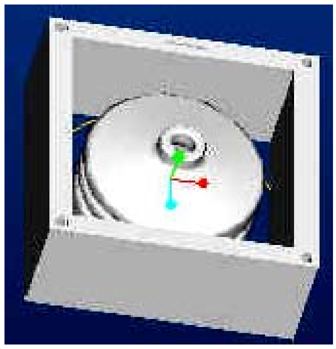

Figure 3. Diagram of 3D model of hollow bottle and outer frame

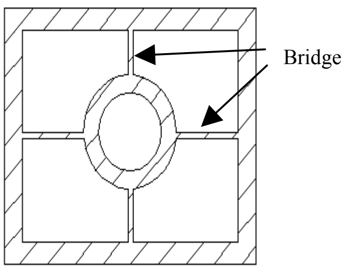

Figure 4. Diagram of 2D contour after bridge

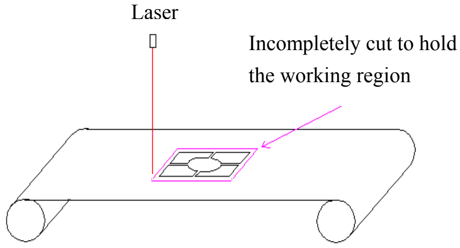

Figure 5. Illustration of laser cut bridge-file

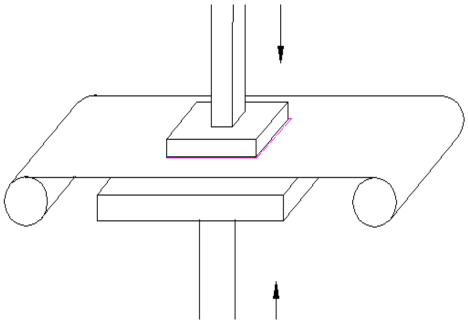

Figure 6. Illustration of downward pushing of pressing head and upward pressing of working table for bonding building algorithm

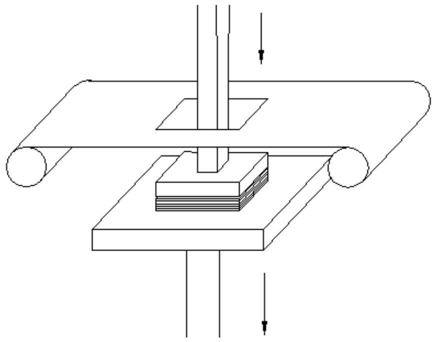

Figure 7. Illustration of separating the cut layer from the sheet-based material

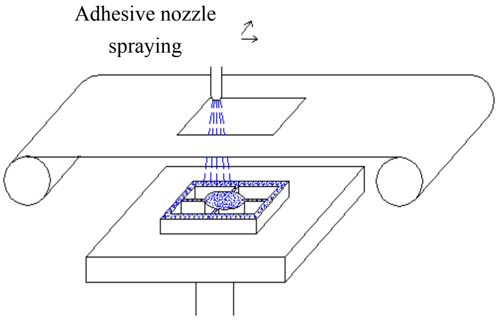

Figure 8. Illustration of adhesive spraying by nozzle

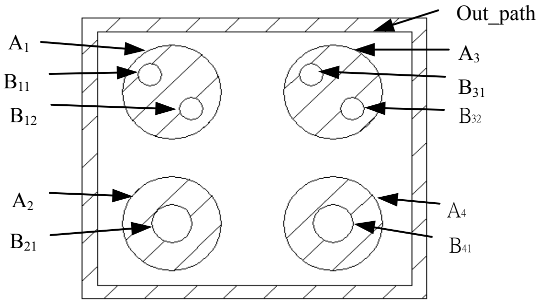

Figure 9. Illustration of definition of attributive name of work-piece's contour capture approach

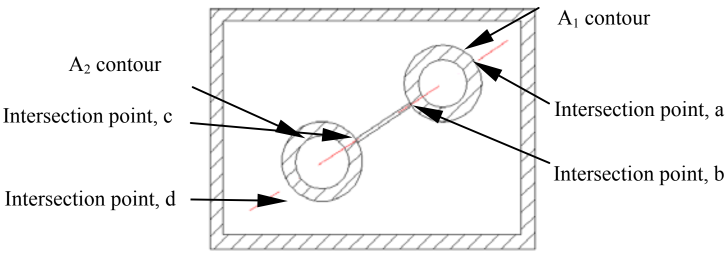

Figure 10. Illustration of bridge building approach on the same sub-layer

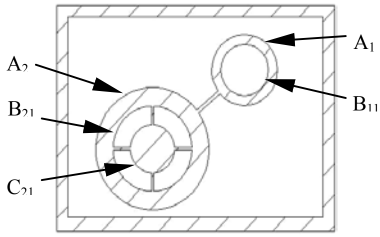

Figure 11. Illustration of building bridge on the different sub-layers C_{21} region and B_{21} region

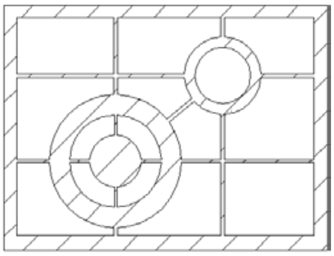

Figure 12. Illustration of bridge building between sub-layer A contour and the outer frame

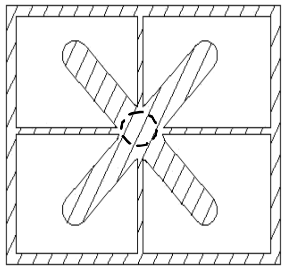

Figure 13. Illustration of bridge building on the protruding rod according to bridge building algorithm 1

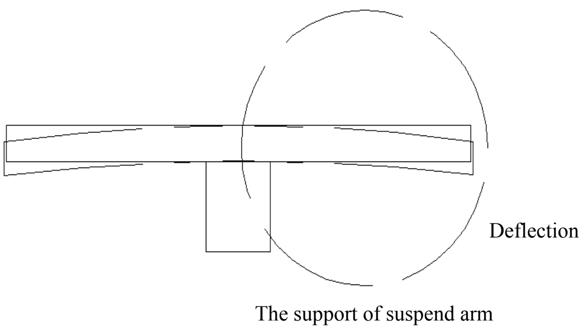

Figure 14. Illustration of deflection caused to the protruding rod

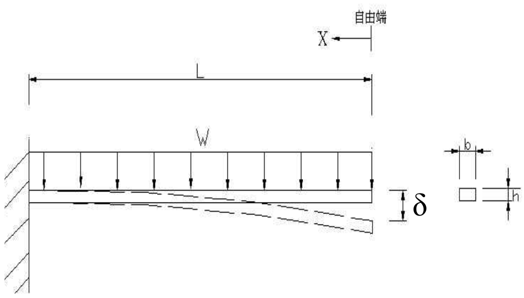

Figure 15. Illustration of deflection viewed as suspended arm

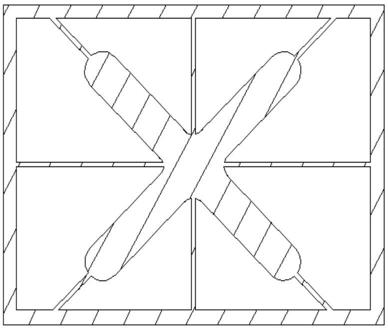

Figure 16. Illustration of bridge building algorithm 2

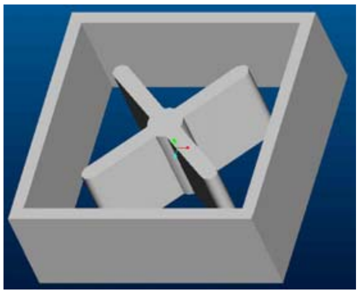

Figure 17. Diagram of protrusion rods with consistent X-Y cross-section