Design and structural analysis of 3D-printed modular furniture joints

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Abstract. Modular furniture joint defined as a connection used to connect two or more wood pieces to produce furniture with multiple functions. Notofusy furniture joint made from plywood was less expensive. However, during the manufacturing process, it was occasionally caused tear-out of wood fibre. Therefore, this research has been carried out to investigate and compare the existing material and Fused Deposition Modelling (FDM) fabrication method on the designed modular furniture joint. Finite Element Analysis (FEA) of elasto-plastic method from ABAQUS CAE software and three-point bending test were used to evaluate the structural analysis of designed modular furniture joint. In this research, the final concept selected was able to withstand load up to 730 kg and it only weights 113.59 g. The long-term goal for this research was to evaluate the possibility of producing end products using FDM technology. It was found that FDM contributed to cost effective in low volume production. In this research, the material focused were Acrylonitrile Butadiene Styrene (ABS) and Polyethylene Terephthalate (PETG). However, future studies can be conducted to evaluate the possibility of using other 3D printing materials.

1. Introduction

Nowadays, modular furniture has become a trend. Modular furniture defined as a ready-made furniture which provides accessibility, convenience and flexibility to users. It can be assembled according to one’s preference and easily dismantle or assembled in a short period of time [1]. Joints which also known as connectors, combine pieces together to produce a complex object. Joints play an important role in furniture as it was the weakest part of the furniture [2]. Modular furniture joints can be manufactured in many ways, and progressively changing with the technology’s advancement. In traditional manufacturing, complex forming tooling such as drilling and cutting were used which increase wastage in material and expenses. However, there were a significant advantages where addictive manufacturing (AM) has less wastage compared to traditional manufacturing process [3].

In order to design a modular furniture joint that achieves its functional requirements and ability to withstand a certain load, structural analysis was used to determine the capability of the design. Structural analysis evaluates the effects of different loads on the structure and identifies the type of deformation which may occur such as elastic or inelastic deformation. It is an important findings as it helps to ensure that the design has a proper strength, rigidity and safety [4].

According to Benedikt Neyses [5], Modos furniture joints which were made from aluminium was too expensive, and it was against the purpose of modular furniture. A Notofusy furniture joint which uses plywood was less expensive compared to aluminium, however, the manufacturing process were
more complex. In this study, 3D printing was chosen as the method to manufacture modular furniture joints. Joint was the weakest part in furniture, therefore selection of material for 3D printing and the design of the joint will affect the stability of the modular furniture. Thus, in order to obtain the 3D printed modular furniture joints with the best structural analysis, a suitable 3D printing material and design of modular furniture joint was investigated.

2. Methodology
There were two objectives designed for this study. First objective was to investigate the mechanical properties of ABS and PETG filament. Second objective was to investigate and compare the structural analysis of the designed 3D printed modular furniture joints.

Before applying 3D printing material on designed modular furniture joints, mechanical properties of the material will be determined. As for the first objective, ABS and PETG were chosen as the materials. For tensile test, the specimens were 3D printed according to ASTM D638. Type I specimen shape was selected as the standard shape for this tensile test as shown in Figure 1. For flexural test, the specimens were printed out in rectangular bar according to ASTM D790 with the dimensions as shown in Figure 2 [6, 7]. Five similar specimens were printed for each material with 100% infill.

**Figure 1.** Dimensions (units in mm) of tensile test specimen D638 Type I chosen according to ASTM D638.

**Figure 2.** Dimensions (units in mm) of flexural test specimen according to ASTM D790.

As for the second objective, which was to investigate and compare the structural analysis in simulation and experimental of designed 3D printed modular furniture joint, two types of structural analysis were conducted. The Finite Element Analysis (FEA) was conducted using ABAQUS for static analysis to optimize the structural strength of the 3D printed modular joint. Then, the validation of the results will be conducted by 3-point bending test. The engineering stress and engineering strain obtained through the tensile test were converted to true stress-strain in ABAQUS before it was imported into material library. To simulate a damage occurred during simulation, an elasto-plastic method with ductile damage parameters such as fracture strain, \(\varepsilon_p\), strain rate, E and stress triaxiality, \(\sigma_m/\sigma_e\) from experimental data were inserted [8]. The fracture strain was given value of 0.05. The strain rate value calculated was 0.037 and stress triaxiality obtained was 0.4 for PETG ductile damage criterion.

A second order hexahedral elements (C3D8R) with reduced integration and hourglass control was assigned to a 3D printed modular joint structure. An average mesh element size of 0.6 mm was applied and concentrated to every corner feature of the joint and the rest with mesh size of 2 mm in term of accuracy and simulation time as shown in Figure 3. Based on convergent study it shows that the mesh size that has been applied with the total number of elements 28520 was converged.
In FEA simulation setup, the joints were oriented vertically connected with the horizontal board. A uniformly distributed force of 1500N was applied onto the horizontal board, similar to a 150kg load placed on it. The boundary conditions defined as $U_2=U_3=U_R1=U_R2=U_R3=0$ where all directions were fixed at bottom except $U_1$ direction, which the translational at x-axis of both vertical boards as shown in Figure 4. Load boundary condition was also defined to only allow displacement at $U_2$ direction. After defining the boundary conditions, a uniform concentrated force of -1500N was applied in CF2 direction, where the force was applied downwards onto the top face of the horizontal board.

For experimental test validation, a 3-point bending test was used as the physical test for this study. The test assembly consists of two 3D-printed modular furniture joint prototypes and three boards were tested using a Universal Testing Machine (UTM). The joints were oriented vertically, connecting with the horizontal board as shown in Figure 5. The force was applied perpendicularly to the middle of the horizontal board. As the test could not be run with the normal 3-point bending test setup, the assembly was tested to the failure point so that the maximum force applied to the modular furniture joint can be obtained.

According to V.Vega [9], it was reported that print layers perpendicular to bending load provides the strongest 3D printing structure. However, in this study, in order to produce the strongest structure, more supports were needed during printing process. Therefore, in consideration of both cost and structure strength, print orientation shown in Figure 6 was selected as lesser print layers which parallel to the bending load and less support while printing.
3. Results and discussion
For the first objective, the average tensile test results for both ABS and PETG material were shown in Table 1.

![Figure 6. Printing orientation for all modular furniture joint prototypes.](image)

| Specimen | Average Ultimate Stress (MPa) | Average Elongation at Break (%) | Average Modulus of Elasticity (MPa) | Average Ultimate Stress (MPa) | Average Ultimate Strain (%) | Average Flexural Modulus (MPa) |
|----------|------------------------------|---------------------------------|-------------------------------------|-----------------------------|-----------------------------|-------------------------------|
| ABS      | 21.84                        | 2.97                            | 1349.39                             | 58.58                       | 4.84                        | 1729.94                       |
| PETG     | 43.42                        | 5.14                            | 1620.23                             | 93.45                       | 5.02                        | 1968.94                       |

From the average data obtained, it can be concluded that PETG was better than ABS in mechanical properties, therefore, PETG was selected as the material to be applied onto designed modular furniture joint in this study. After determine which 3D printing material to be used, 4 concepts were drawn using CAD software. The concepts were designed to achieve the target specifications as shown in Table 2.

| Item | Attribute | Value | Unit |
|------|-----------|-------|------|
| 1    | Amount of required tools for assembly and dismantle | 0 | Subject |
| 2    | Load capacity | >150 | Kg |
| 3    | Amount of assembly steps | <5 | Subject |
| 4    | Production cost per joint | <10 (<47.31) | (RM) |

After designing the concepts, comparison of the structural analysis of the designed modular furniture joints was conducted. Each concept experienced structural test with 1500N force and the results were shown in Figure 7 and tabulated as shown in Table 3.
Table 3. Summary FEA results on designed modular furniture joint after application of 1500N force.

| Concept | Maximum von misses stress (MPa) | PEEQ | Weight (g) |
|---------|--------------------------------|------|------------|
| 1       | 119.4                          | 0.26 | 88.72      |
| 2       | 31.39                          | 0    | 160.37     |
| 3       | 112.7                          | 0.19 | 79.55      |
| 4       | 237.6                          | 1.44 | 259.60     |

From the result obtained, it can be seen that only concept 2 did not experience plastic deformation, the maximum von misses stress was below the yield strength of PETG material, which was 93.45 MPa and its PEEQ value also did not exceed 0. The data obtained was used in concept screening and concept 2 and concept 3 were chosen to be revised.

Concept 2 was revised to concept 2A by reducing its overall width from 1 inch (25.4 mm) to 0.8 inch (20.32 mm) and bridge width from 0.4 inch (10.15 mm) to 0.3 inch (7.62 mm). For concept 3, an addition of bridge was added between the jaws of the joint as from previous test, it was proven that additional of bridge increases the structural stability of the joint. Refinement for concept 2 and concept 3 were shown in Figure 8 and Figure 9 consecutively.
The chosen concepts were then built by 3D printed machine and experienced actual bending test. In the bending test, it was tested to the failure point where the maximum force applied to the modular furniture joint can be obtained. The first bending test was conducted on concept 2 with plywood board. However, the maximum load of the 3D-printed using concept 2 cannot be identified as the joint does not break and the extreme bends of the plywood board. The maximum force recorded was 4060N as shown in Figure 10. Therefore, for further test of concept 2 joint until it breaks, a stiffer wood than plywood was used. In this paper, the type of solid wood used was Nyatoh. It was proven that with stiffer wood, the joint breaks and the maximum force it can withstand was 7568 N as shown in Figure 10. Another bending test was conducted on concept 2A with Nyatoh wood. It can be seen in Figure 11 that concept 2A joint can withstand a maximum of 7300 N force, whereas for concept 3A can withstand up to 6473N. All the results obtained in bending test were tabulated in Table 4.

**Figure 8.** Refinement of concept 2 to concept 2A on left and final part design of concept 2A on right.

**Figure 9.** Refinement of concept 3 to 3A on top and final part design of concept 3A on bottom.

**Figure 10.** Line graph of force vs displacement of concept 2 with plywood and Nyatoh wood.

**Figure 11.** Line graph of force vs displacement of 3D-printed concept 2A and 3A modular furniture joint with Nyatoh wood.
Table 4. Summary results of bending test conducted on 3D-printed modular furniture joint concepts combined with different type of wood.

| Concept | Wood Material      | Maximum Force (N) | Weight (g) |
|---------|--------------------|-------------------|------------|
| 2       | Plywood            | 4060              | 160.37     |
| 2       | Nyatoh Wood        | 7568              | 160.37     |
| 2A      | Nyatoh Wood        | 7300              | 113.59     |
| 3A      | Nyatoh Wood        | 6473              | 159.68     |

Concept 2 was capable to withstand the highest maximum force with a value of 7568N. The results also indicate the weight of PETG 3D printing material used for the chosen concepts. Concept 2A used the least material with only 113.59g. After conducting concept scoring, the concept chosen to be developed into final prototype in this study was concept 2A, as ranked first in concept scoring. Its maximum load capacity was slightly lower than reference, which was concept 2, however the production cost per joint was cheaper. Figure 12 shows the final prototype developed and Figure 13 shows sample products that can be made from the final prototype.

Figure 12. Final prototype developed.

Figure 13. Sample applications of final prototype.

4. Conclusion
As conclusion, two objectives of this study have been achieved. For the first objective, PETG was selected to be used as the material for all design concepts and to fabricate the final prototype as its mechanical properties was better than ABS. For second objective, the final prototype chosen for this study was concept 2A. The final prototype was able withstand load up to 7300 N, equivalent to 730 kg. In terms of material usage, concept 2A used 29% less material than other concepts, which means lesser production cost per joint. When comparing 3D-printed concept 2A with existing modular furniture joint, it was identified that 3D-printed concept 2A was much better than existing modular furniture joint in terms of load capacity. The production cost per joint for 3D-printed concept 2A was lower and requires one manufacturing process, which was the FDM. In this study, the 3D-printed modular furniture joint was more stable than expected and being tested to be fully functional. In the future, more studies can be conducted to evaluate the possibility of using other 3D printing materials as an end product.
5. References
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