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Geometrical Structure and Layer Orientation Effects on Strength, Material Consumption and Building Time of FDM Rapid Prototyped Samples

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Abstract**—**Rapid Prototyping (RP) technologies enable physical parts to be produced from various materials without depending on the conventional tooling. Fused Deposition Modeling (FDM) is one of the famous RP processes used at present. Tensile strength and compressive strength resistance will be identified for different sample structures and different layer orientations of ABS rapid prototype solid models. The samples will be fabricated by a FDM rapid prototyping machine in different layer orientations with variations in internal geometrical structure. The 0° orientation where layers were deposited along the length of the samples displayed superior strength and impact resistance over all the other orientations. The anisotropic properties were probably caused by weak interlayer bonding and interlayer porosity.

Keywords**—**Building orientation, compression strength, rapid prototyping, tensile strength.

I. INTRODUCTION

RAPID Prototyping (RP) is a general term for technologies that produce the physical components without using conventional machining. RP is also known as Solid Freeform Fabrication (SFF), Layered Manufacturing (LM) or desktop manufacturing [1]. Besides, RP processes are classified in the Additive Manufacturing (AM) technologies as the parts are fabricated by stacking layers of material until the final geometry part is completed. Basically, RP technologies are formed by 5 main manufacturing processes which are binding process, curing process, dispensing process, sheeting process and sintering process [2]. Among 40 types of RP technologies have been developed, the most famous RP processes in use included Three Dimensional Printing (3DP) [3], Fused Deposition Modelling (FDM) [4], Laminated Object Manufacturing (LOM) [5], Multi-Jet Modelling (MJM) [2], Stereolithography (SLA) [6] and Selective Laser Sintering (SLS) [7]. These manufacturing processes have its ability to produce random shapes of product including high complexity shape product.

Today, RP technologies are used to build concept models and functional components made from polymers, metal and ceramics [8]. Beside fabrication for assembly testing purposes, development of RP technologies had brought to the production of functional parts, semi-functional components, production tooling and direct tooling. RP technologies are widely used in investment casting industry, sample modeling in automotive and aerospace industry. Almost all RP processes have common advantages in manufacturing process. The building time is normally short, wide range of raw materials can be used by the machine, and variety of high complexity shape can be produced.

Researches on the binder formulation, raw materials, manufacturing process parameter, accuracy issues and many others have been done to improve the quality of the RP products. Because of most RP products show poor mechanical properties, study on the impact of the sample geometrical structures to tensile strength and compression strength seem to be very important. Besides, building orientation will always affect the strength of the product. In this study, concentration has been focused on FDM product. Among the RP technologies available, FDM had shown a better functional quality of part [9]. Previous researches had proved that FDM is suitable to build amorphous material due to its low shrinkage process properties [10]. The advantages such as easy to operate and environmental friendly raw materials make FDM a popular manufacturing process.

Therefore, the main objectives of this study was set to determine the effect of structure and layer orientation on both tensile and compression strengths of FDM samples. At the end of this study, it is also expected that the manufacturing time and cost can be reduced to improve the manufacturing efficiency of RP technologies in the future.

II. EQUIPMENTS, MATERIALS, AND METHODS

A. Equipment

"Dimension SST 1200es" was the FDM machine model used in the experiment. This machine is easy to operate and it is suitable for RP manufacturing purposes. It is suitable to fabricate small and medium size of ABS product. Pro ENGINEER was used to prepare the samples drawing and Catalyst Ex Version 4.2 was the software used to arrange and test the samples before fabrication. Crest ultrasonic generator was used to remove the supporting material attached to the

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specimens as a post-processing process. The universal testing machine model INSTRON 4469 was used for both tensile and compression testing of the specimen.

B. Material

ABS model P430 was selected as the raw material to fabricate all the specimens.

C. Method

In both tensile and compression testing experiment, three manipulating variables were set in the experiments which were sample structure shape, layer orientation and base alignment. A set of full solid sample was used as the constant variable to compare the testing result. For tensile testing, three sets of hollow samples are: long stripes, short stripes and hollow-square as shown in Fig. 1. On the other hand, only one set of hollow sample was used in compression testing as shown in Fig. 2.

D. Layer Orientation

There are a few possible building orientations can be achieved using FDM. Two important building orientations were considered in the tensile testing (Fig. 3): (i) the longest length of the specimen oriented towards X-axis (ii) the longest length of the specimen oriented towards Y-axis. It was assumed that the building orientation towards Z-axis would exhibit the weakest tensile strength due to its material stacking direction was perpendicular towards the tensile force applied. Because of long building time and high material consumption, building orientation with the longest length of the specimen towards Z-axis was voided in the tensile testing experiment. Since the specimens of the compression testing were circular in shape, there were only two important building orientations (Fig. 4): (i) the circular surface oriented towards Y- axis and (ii) the circular surface oriented towards Z- axis. Two important specimen's surfaces were considered as the building base of the specimens: (i) largest surface area of the specimen, b and (ii) thickness of the specimen, t.

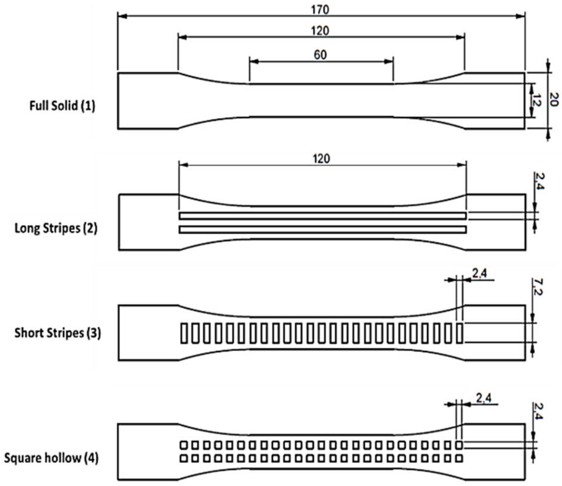


Fig. 1 Type tensile testing specimen's structures and dimensions

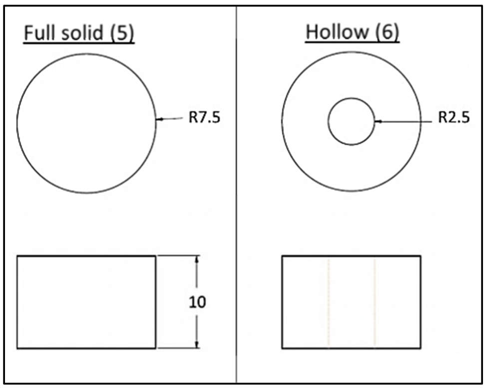


Fig. 2 Type of compression testing specimen's structures and dimensions

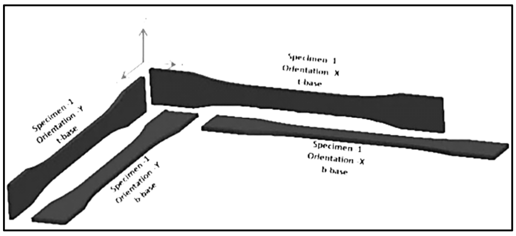


Fig. 3 Building orientation of tensile test specimens

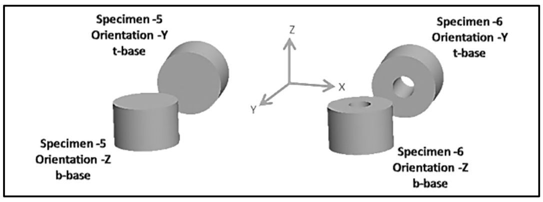


Fig. 4 Building orientation of compression test specimens

A combination of a digit and two alphabets was used as the processing factor during the experiment is shown in Tables I and II. The first digit in the label represents the type of structures, the middle alphabet in the label represents the building orientation and the last alphabet in the label represents the building base.

The estimated amount of raw material needed and the building cost was analyzed before fabrication. In order to save the building cost and time, the specimens were arranged in such a way that all the specimens were able to fit in a building tray (Fig. 5).

Fig. 5 Specimens on the building tray

TABLE I
EXPERIMENT LABELS OF TENSILE TESTING SPECIMENS

structure	Full solid (1)				Long Stripes (2)			
Orientation	X		Y		X		Y	
Base	b	t	b	t	b	t	b	t
Exp. Label	1Xb	1Xt	1Yb	1Yt	2Xb	2Xt	2Yb	2Yt
structure	Short stripes (3)				Square hollow (4)			
Orientation	X		Y		X		Y	
Base	b	t	b	t	b	t	b	t
Exp. Label	3Xb	3Xt	3Yb	3Yt	4Xb	4Xt	4Yb	4Yt

TABLE II
EXPERIMENT LABELS OF COMPRESSION TESTING SPECIMENS

Structure	Full solid (5)		Hollow (6)	
Orientation	Y	Z	Y	Z
Base	b	t	b	t
Experiment Label	5Yb	5Zt	6Yb	6Zt

E. Testing

There were a total of 16 tensile specimens being tested and 4 specimens used in compression testing. In tensile testing, the extension of the specimen was set at a constant rate of 1mm per minute. While in compression testing, the compression of the specimens was set constant at the rate of 1mm per minute.

III. RESULTS AND DISCUSSION

A. Material Usage and Building Time

The volume of model materials, volume of supporting materials are shown in Figs. 6 and 7 while the estimated build time of each samples is shown in Fig. 8.

The cost of the model material and support material are almost same, therefore the total volume of raw material usage, V can be consider as the summation volume of both material.

Fig. 9 shows the total volume of raw material versus building time. As can be seen in Fig. 9, the relationship between the volume of material usage and the build time is not directly proportional to each other. Increment of material usage does not increase the building time of the specimen.

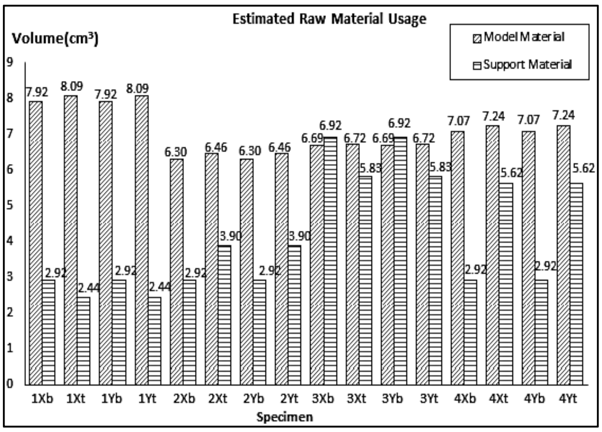


Fig. 6 Estimated raw material needed to build tensile specimens

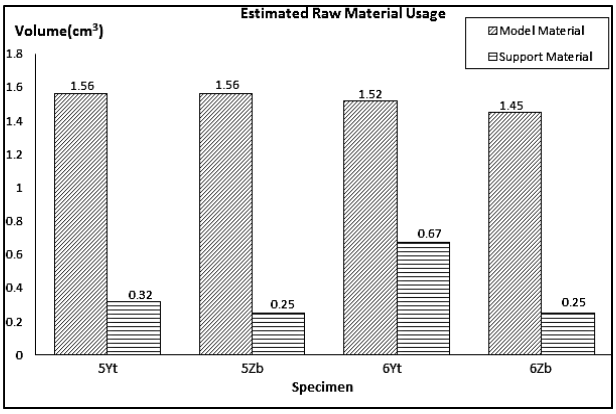


Fig. 7 Estimated raw material needed to build compression specimen

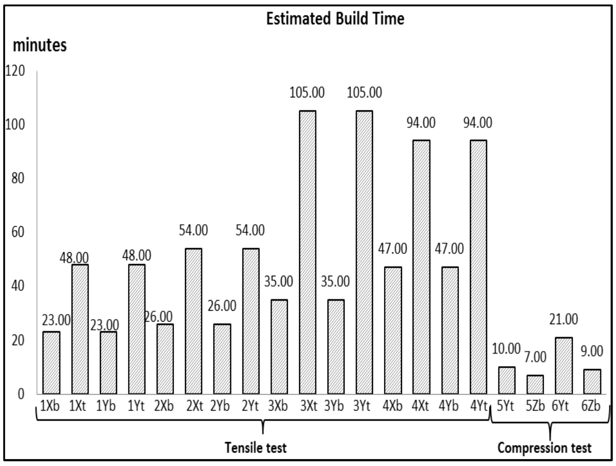


Fig. 8 Estimated build time of specimens

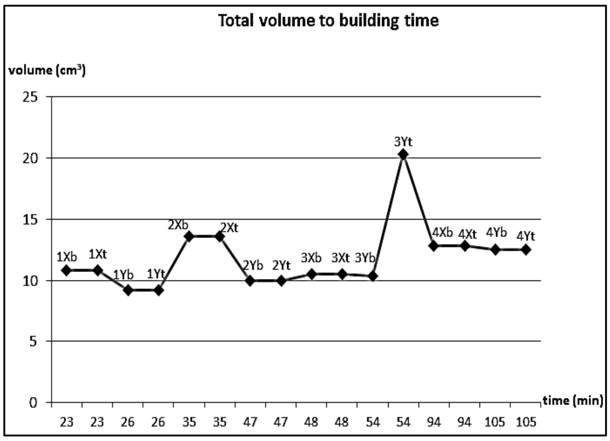


Fig. 9 Total volume of raw material versus building time

In order to find out the best structure and orientation design, (1) is suggested to find the building factor (BF) of each specimen.

$$\textbf{Prototype Building factor}, (\mathbf{BF}) = \mathbf{V} \cdot \mathbf{t} \tag{1}$$

where V is the total volume of raw material used and t is the building time of specimens.

Fig. 10 shows results of the prototype building factor. As can be seen in Fig. 10, the low value of building factor meaning that less raw material is needed to build the specimen and the building time is short. In the condition of same building base, the building factor of tensile specimen oriented towards X-axis is the same as the building factor of tensile specimen oriented towards Y-axis (i.e. the building factor of 1Xb and 1Yb have the same value 249).

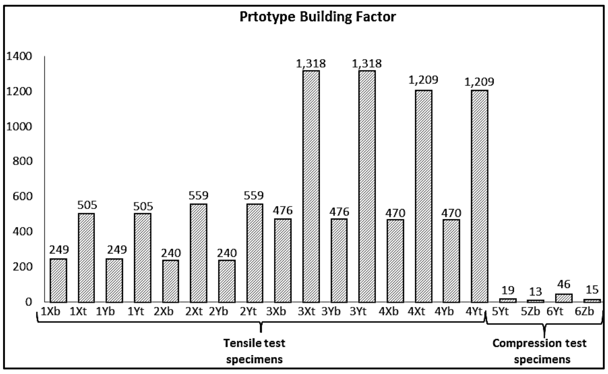


Fig. 10 Prototype building factor

B. Tensile Test

Fig. 11 shows the tensile specimens after tensile test. For the ease of data comparison, a series of chart has been prepared by grouping the results of similar layer orientation specimens, shown in Figs. 12 to 15.

As can be seen in Figs. 12-15, the specimen with full solid structure (1) exhibits the highest yield strength, ultimate tensile strength and fracture strength in all cases. The largest cross section area of full solid structure (1) able to withstand higher load before fracture compare to other specimens. In layer orientation-X, base-b, specimen 2Xb and specimen 4Xb show extremely small yield strength. This is cause by weak structure of the specimens.

To identify the best layer orientation, the tensile strength of specimen (1) (full solid) is constant as shown in Fig. 16. The strength of the specimen 1Xt is almost the same as the strength of the specimen 1Yt. On the other hand, the strength of the specimen 1Xb is close to the strength of 1Yb. Specimen with building base-t has higher tensile strength compare to the specimen with building base-b.

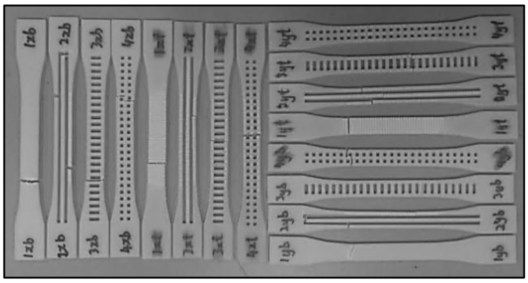


Fig. 9 Tensile specimens after tensile test

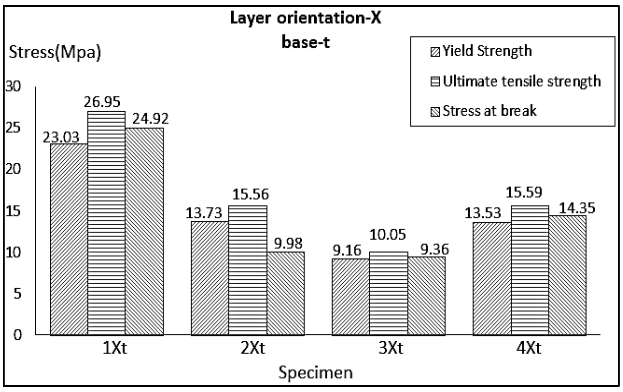


Fig. 10 Tensile strength of specimen with layer orientation-X and base-t

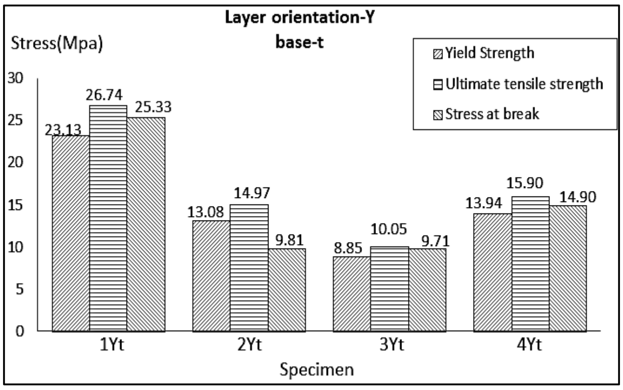


Fig. 11 Tensile strength of specimen with layer orientation-Y and base-t

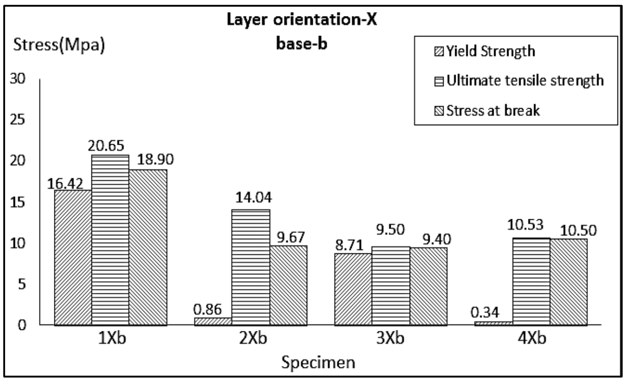


Fig. 12 Tensile strength of specimen with layer orientation-X and base-b

To find out the best combination of structure with consideration of raw material usage and time consumption, index $\frac{S}{BF}$ has been suggested, where S is the strength of the material and BF is the prototype building factor.

Fig. 17 shows the index of ultimate strength to prototype building factor. From the result in Fig. 17, specimen 1Xb shows the highest index value among all the specimens. This shows that solid structure with layer orientation-X and build base-b is able to provide higher tensile strength with minimum usage of material and short building time. In contrast, specimen 3Xt and 3Yt is the least efficiency specimen in providing tensile strength. For the all sample performance, Fig. 18 shows the percentage of reduction compare to specimen 1Xb.

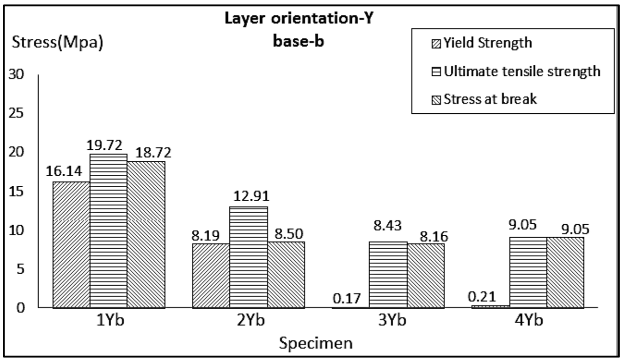


Fig. 13 Tensile strength of specimen with layer orientation-Y and base-b

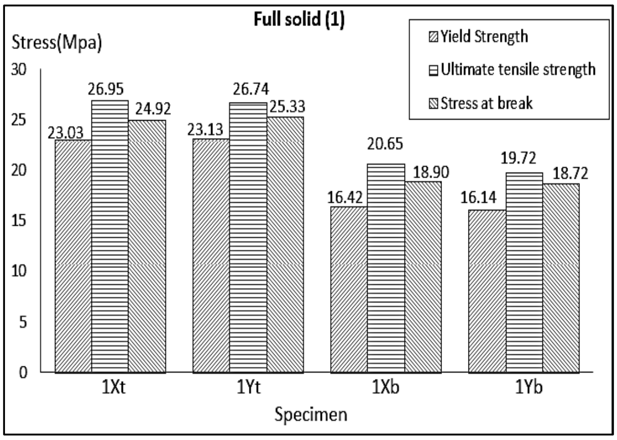


Fig. 14 Tensile strength of specimen 1 (full solid)

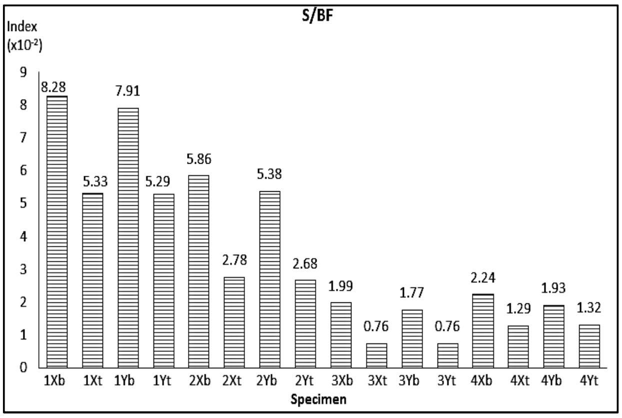
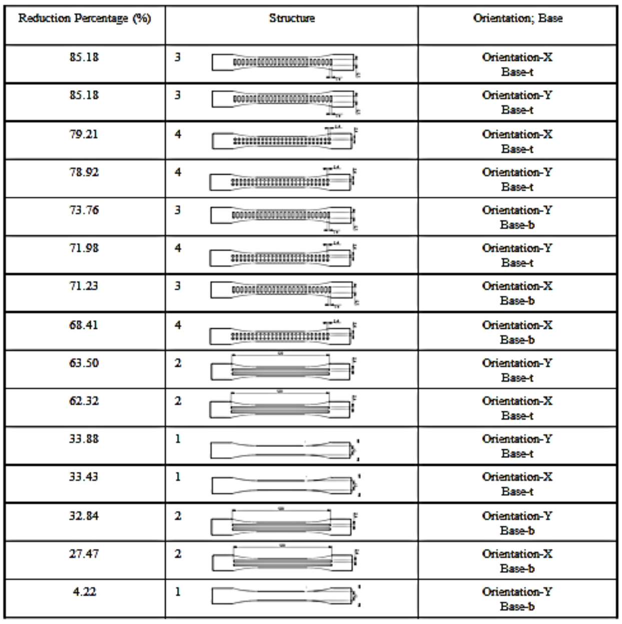


Fig. 17 Index of ultimate strength to prototype building factor



Reduction Percentage (%)	Structure	Orientation; Base
85.18	3	Orientation-X Base-t
85.18	3	Orientation-Y Base-t
79.21	4	Orientation-X Base-t
78.92	4	Orientation-Y Base-t
73.76	3	Orientation-Y Base-b
71.98	4	Orientation-Y Base-t
71.23	3	Orientation-X Base-b
68.41	4	Orientation-X Base-b
63.50	2	Orientation-Y Base-t
62.32	2	Orientation-X Base-t
33.88	1	Orientation-Y Base-t
33.43	1	Orientation-X Base-t
32.84	2	Orientation-Y Base-b
27.47	2	Orientation-X Base-b
4.22	1	Orientation-Y Base-b

Fig. 18 Percentage of reduction compare to specimen 1Xb

C. Compression Test

Fig. 19 shows the compression specimens after compression test while Fig. 20 shows the compression strength of specimen 5 (full solid) and specimen 6 (hollow). As can be seen in Fig. 20, specimen 5Yt shows the highest compression strength due to its building layer is parallel to the compression force applied. The large contact area of the specimen 5Yt made it able to withstand high compression stress.

Similar to tensile test, index $\frac{S}{BF}$ is also applied in the analysis of compression test specimens. Fig. 21 shows the index of stress at maximum load to prototype building factor. As can be seen in Fig. 21, specimen 5Zb has the highest index value. Although Fig. 20 shows that specimen 5Yt has the highest compression strength, but it is low effective in provide compression strength compare to specimen 5Zb. Both Specimen 6Yt and 6Zb have the same compression strength but specimen 6Zb shows lower index value due to its high material consumption and long building time.

For the all sample performance, Fig. 22 shows the percentage of reduction compare to specimen 5Zb.

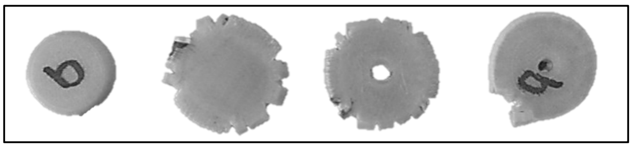


Fig. 19 Compression specimens after compression test

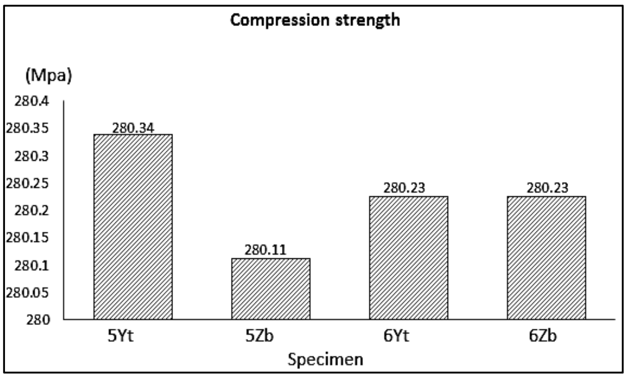


Fig. 20 Compression strength of specimen 5 (full solid) and specimen 6 (hollow)

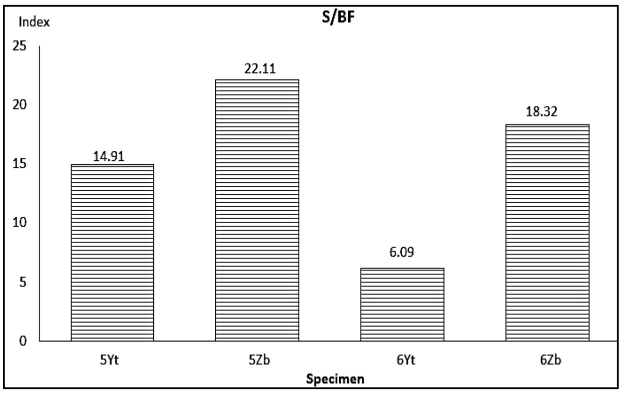
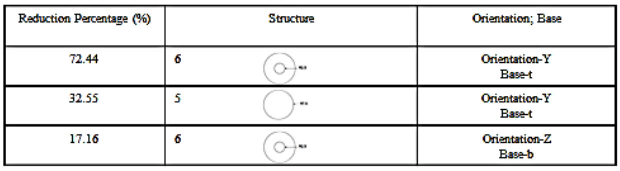


Fig. 21 Index of stress at maximum load to prototype building factor



Reduction Percentage (%)	Structure	Orientation; Base
72.44	6	Orientation-Y Base-t
32.55	5	Orientation-Y Base-t
17.16	6	Orientation-Z Base-b

Fig. 22 Percentage of reduction compare to specimen 5Zb

IV. CONCLUSION

The main objectives of this study was to determine the effect of structure and layer orientation on both tensile and compression strengths of FDM samples. As a conclusion,

1- The layer orientation in X-axis and Y-axis will not affect much on the tensile strength of the specimen when the building base is remaining constant. On the other hand, specimen structure and building base will greatly affect the tensile strength of the specimens.
2- The strength to prototype building factor index applied in the analysis proved that the specimen with the highest strength may not be able to provide the strength effectively.
3- Reduced the amount of raw material, supporting material and building time will significantly increase the efficiency of the FDM manufacturing process.
4- Amount of material usage will not increase the mechanical properties of the products but increase the cost and the weight of a product.
5- A suitable structure design and the layer orientation are the important factors need to be considered in FDM technology.
6- Further research and analysis on different raw materials and more combination of structures and building orientations can be carried out in the future to improve the RP technology.

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In 2009, Dr. Sarhan joined University of Malaya, Kuala Lumpur, Malaysia. Throughout his engineering career, he have completed several major research projects funded by the public and private sectors and has also undertaken various consulting assignments in the field of machining (higher accuracy and higher productivity machining technologies) and cutting tool technology (metal cutting operations using multiple sensors, data acquisition, and signal processing technology). He published more than (120) technical papers in reputable journals and conferences, granted 19 patents and won several gold, silver and bronze medals in local and international exhibitions. Currently, Dr. Sarhan undertaking 5 projects in commercialization. In addition, He is a reviewer for many Master and PhD theses, some reputable engineering journals and refereed international conferences.