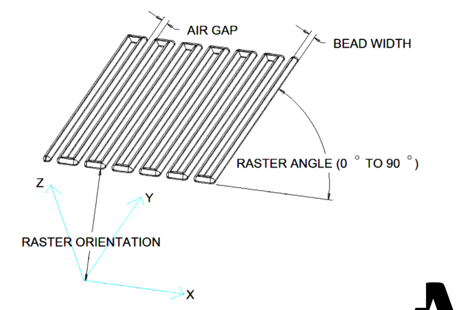

Analysis of Assumptions of a Failure Modes Model for Fused Deposition Modeled Parts

Kendall McKenzie, Mechanical Engineering

Mentor: Dr. Mehrdad Haghi

Kellogg Honors College Capstone Project

Abstract: Failure mode models are important tools in Materials Science and are crucial in Mechanical design. These models predict the manner in which materials will fail and are used to prevent material failure and allow designers to utilize as much of the part's strength as possible. For metals these models are fairly simple, but they can become increasingly intricate for some modern materials, which have more complex structures. Fused Deposition Modeling (FDM) is a 3-D printing process that has been developed to allow designers to be create cheap, rapid prototypes of parts for visualization. Interest is growing in the possibility of using FDM processes to create production grade parts and a much greater knowledge of the mechanical behavior and failure criteria of FDM parts is needed. A failure modes model for FDM parts has been previously developed and analyzed by Dr. Haghi and prior students. This model is based on similar models for oriented fiber composite materials and correlates well with experimental data in simple situations. This project will examine the assumptions inherent to this model to determine if they are reasonable and possible sources of error they may introduce. Particular attention will be paid to whether FDM parts can be modeled using theories originally developed for fiber composites and whether there are size dependent effects that are intrinsic to FDM.

Background:

Failure Modes Models: Failure modes models are important tools in Materials Science and are crucial in Mechanical design. Failure modes models predict the conditions under which a material will fail. Material failure can be defined in several ways. One common failure criteria for metals is yield, which is the point at which a metal begins to plastically deform. Plastic deformation permanently changes the shape of the material and is primarily seen in metals. In more brittle materials there tends to be a period of bending and then a rapid, unexpected break, known as fracture. For these brittle materials failure is more often defined at the point of fracture. Fracture normally involves the complete breaking of a piece and is usually straightforward to observe.

Fused Deposition Modeling: Fused Deposition Modeling (FDM) is a 3-D printing technique that was developed in the late 1980s. [1] FDM works by heating a polymer and depositing it in layers onto a special plate. The way that FDM machines work is similar to a conventional 2-D printer but with polymer instead of ink and with vertically stacked layers. FDM is commonly used to create low cost physical representations of proposed designs to allow engineers to see and touch their design and evaluate it in ways that cannot be done on paper. These prototypes can be used for visualization, ergonomic and aesthetic evaluations, and low cost experimentation. FDM prototypes are significantly faster and less expensive to produce than conventionally produced metal prototypes. FDM parts are becoming more and more widely used and it is desirable to have a better understanding of their failure behavior.

Failure Mode Model:

The paper that describes the Failure Modes Model that was analyzed was published by Nevin Hill and Cal Poly Pomona's Dr. Mehrdad Haghi in 2014. Tension tests were carried out to determine the failure strength of the material at different orientations material deposition. The parts were altered from normal in that they had one primary direction that the material is laid down in. Regular parts place material in two contrasting directions to counter the effect of the directionality, these experiments used only one direction to better study the effect of direction on strength. A 90˚ sample is taken to have the material direction aligned with the length of the sample and a 0 ˚ has the material at a right angel to the length. The model followed ASTM standards for tension test samples as seen below. The results showed that the parts failed in three distinct manners, depending on the orientation of the material. At low angles the material failed when the welds between the beads failed. Intermediate angles failed in a combination of weld and material failure, and high angle samples failed when the material itself fractured.

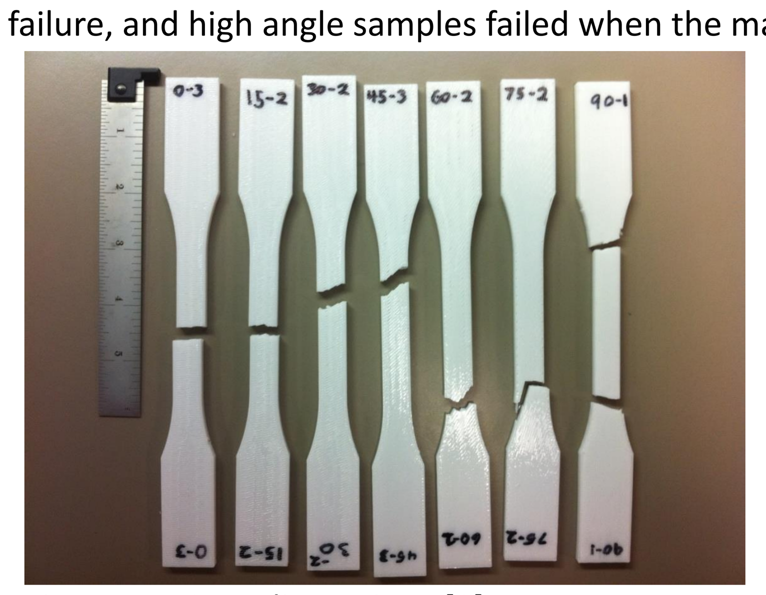

Figure 1. ASTM dimensions [2]

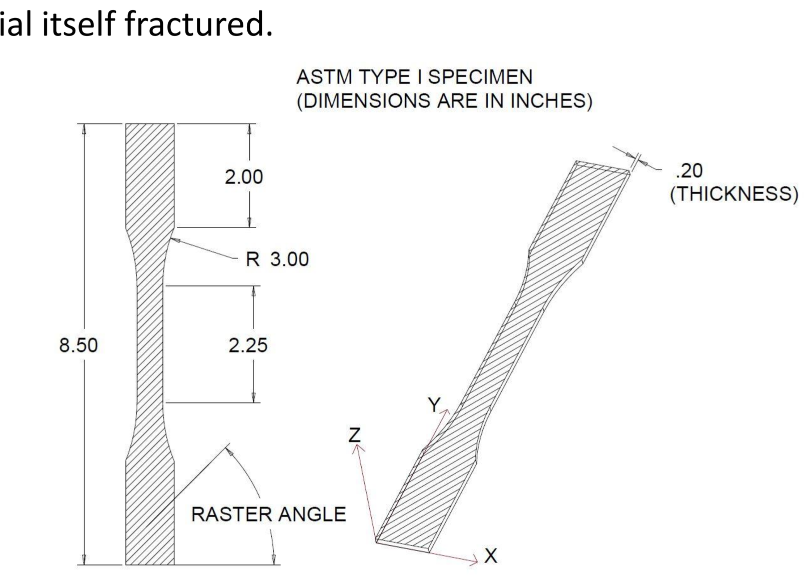

Figure 2. Fractured Samples [2]

Assumptions:

The FDM model is based off of another analysis model from fiber composites are known as Composite Laminate Theory (CLT). The assumptions from CLT will be examined as well as the assumptions from the FDM model itself.

Assumptions of the Failure Modes Model (CLT):

-CLT assumptions:

1) Lamina are thin
2) All lamina are perfectly bonded
3) All bonds are infinitesimally thin
4) Lines perpendicular to the middle surface of the laminate remain so
5) Strain perpendicular to the middle surface is ignored. [3]

Analysis: 1) For most common deposition rates the thin lamina assumption is valid.

2) Perfectly bonded lamina is a function of several variables but these can easily be selected such that bonding is not an issue. This assumption is not always valid and alert designers will be aware that proper parameters must be used to avoid inaccuracies.

3) The bonds in FDM parts are zero thickness because the adjacent fibers are bonded directly to each other, this assumption is valid.

4) Perpendicular lines will remain perpendicular for straight, simple parts. This assumption may not hold for complex geometries but the divergence from perpendicular should not be enough to cause significant problems.

5) Side strain effects are minimal in tension, this assumption holds.

Assumptions of the Failure Modes Model (FDM):

-FDM Model assumptions:

A) All layers are at the same angle relative the global printing axes
B) Edge effects are negligible
C) Bead width is a uniform constant
D) Air gap is a uniform constant
E) The material is essentially homogeneous

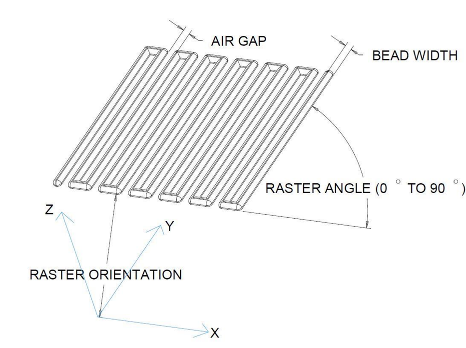

Figure 3. FDM variables [2]

Analysis: 1) This is not the normal arrangement for FDM parts but is a valid assumption for the model. Care must be taken when applying the model to real parts to compensate for the difference.

2) There is a single 90˚ layer at the edge of each part. When there are many layers in a large part this edge layer is negligible. However this is clearly not true for small parts, this assumption is conditional.

3) Unless the FDM machine is experiencing problems this is valid.

4) Unless the FDM machine is experiencing problems this is valid.

5) For some settings this is valid, for others it is less valid and may introduce some error.

Conclusions:

By and large the assumptions used in the model are valid and introduce little source of error. The assumptions from CLT are not a significant concern as CLT is an established theory. The only concern in using CLT is applicability to FDM parts. FDM parts can be readily modeled as fiber composites with the fiber properties being used for both the fibers and the matrix. The assumptions of the model itself also appear to be reasonable and valid, with three small exceptions. Assumption A is a special case and care is needed when using the model on more general case parts. Assumption E is valid for parts with consistent fusion, which will be achieved with proper setup considerations. Further work should be carried out to determine combinations of parameters that will ensure the validity of this model assumption. The largest concern is assumption B. The effect of a continuous 90˚ band around a part is dependent on the orientation of that part and the number of total fibers. A 90˚ fiber will have the most effect on a 0˚ part with decreasing effect as the orientation angle approaches 90˚. Larger parts will be less effected by a single layer as it will represent a small volume fraction of the material. Further research is being carried out to determine the effect of this edge effect on smaller samples. It is hoped that a size cutoff limit can be established over which edge effects can be neglected. This cutoff limit may be dependent on orientation but it is more desirable to have a single value for all orientations and this will be the goal.

In summary, the assumptions are valid and cause little error. The results of the model seem to correlate well with experiment and are judged to be useful as a design aid.

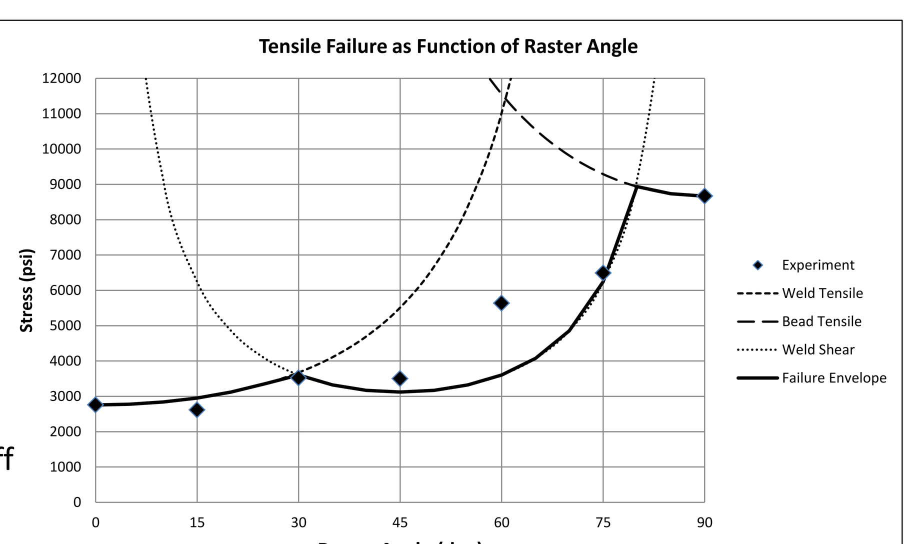

Figure 4. Failure stress vs. Raster Angle [2]

Citations:

[1] Kalpakjian, Serope, and Stephen Schmid. *Manufacturing Engineering and Technilogy.* New York: Pearson, 2014. Print.

[2] Hill, Nevin, and Mehrdad Haghi. "Deposition direction-depended failure criteria for fused deposition modeling polycarbonate" *Rapid Prototyping Journal* 20.3 (2014): 221-227. Web. 3 Mar. 2015.

[3] Jones, Robert. *Mechanics of Composite Materials.* New York: Taylor and Francis Group. 1999. Print.