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3D printing. An alternative for small projects?

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3D printing. An alternative for small projects?

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Abstract. 3D printing is one of the big top up-to-date technologies. Our aim is to show that up to a point 3D prints can successfully replace traditionally manufactured assemblies in the case of educational projects or lab experiments. We have considered a 3D printed simple-frame robotic arm upon which we have performed FEA analyses. They have shown promising results against its steel-based peer up to certain loads under the same working conditions in terms of safety factor and safety margin.

1. Introduction

3D printing techniques are various and address different domains. They became a viable alternative to classic manufacturing especially for small projects or prototypes. In this paper we are focusing on a comparison between two functional models of a robotic arm. One has the 1.0490 DIN [1] as the assigned manufacturing material and the other is using PLA (Polylactic acid) [2]. We aim to show by means of FEA that in case of small loads the PLA-based model can withstand multiple loading cycles. We are proofing the design by taking into consideration two parameters: *the safety factor* and *margin of safety*. Previous work included analyses that verified the structural integrity of spherical PLA based models against compression [3]. We wanted to find out also if 3D printing is accurate enough to consider in small projects or prototypes [4]. This wider research pool helped us formulate conclusions that did encourage us to move on with this new one.

Failure may be predicted using tests, instruments and mathematical models. Designs of all kinds are being implemented using a reliability index which stand on top of a safety factor. There are different opinions regarding the safety factor of a mechanical design. It generally describes the capacity of a system to exceed certain limits thus highlighting how much stronger a mechanical part or assembly is than it was intended to be under a certain load. Subsequently there is another parameter to take into account and that is the margin of safety. We may assess it as a measure of a system's structural capacity. It gives information about the system's excess capacity. If a mechanical part or assembly is subjected to a maximum load, the margin of safety informs us about how many more loads of the same force can it withstand before failing. The two can offer an insight for a specific mechanical part or assembly to be considered safe, overengineered or poorly designed.

G. Bolzon *et al.* have conducted tests which would highlight the behavior of the materials under uniaxial tensile loading. They found out "*that the indentation curves in different states are almost insensitive to the variations of the yield limits of the considered metals while they clearly reflect the change of the ultimate tensile strength*" [5]. This shows a possible failure if aging produces embrittlement or any other sort of treatment (*chemical, temperature dependent, etc.*).



Under a certain load we can obtain results in form of stress or strain. Mathematical equations have been proposed by Yu.G. Matvienko for plane stress and plane strain [6]:

$$SF_{FAD} = 1.44 \cdot SF_Y^{1.34} \quad (1)$$

$$SF_{FAD} = -0.064 + 1.1 \cdot SF_Y \quad (2)$$

Where SF_{FAD} represents the safety factor against fracture and SF_Y the safety factor against plastic collapse.

In case of failure assessment if we are to consider plane strain the two were found to be very similar. In case of plane stress, the author concluded “*that the probabilistic safety factors increase with the decrease of the probability of failure*” [6].

M. Chen *et al.* have presented results about the effect of process repairs taking into consideration the margin of safety. They considered a plastic pre-strain effect, and a thermal aging effect. They found out that the synergistic action of plastic pre-strain and thermal aging effect does not interfere in the evaluation. Failure still appears in plastic domain and “*as work hardening is induced by plastic pre-strain, the safety margin is increased after the repair process for the typical crack in the case study*” [7].

2. Theoretical considerations

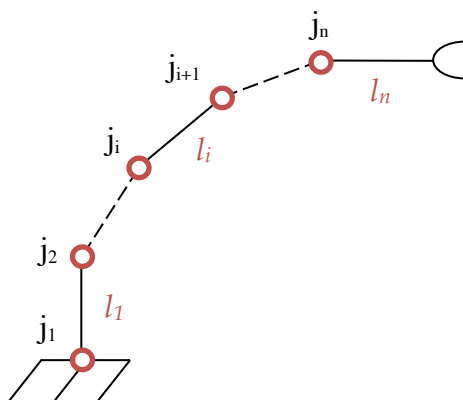


Figure 1. Decomposing a robotic arm into n elements.

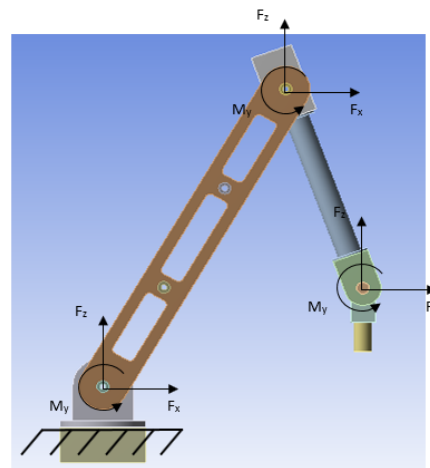


Figure 2. Identification of forces and moments for each joint of the considered robotic arm.

We have taken into account a generic robotic arm model. Mathematically, this model has to be decomposed into single components in order to be properly assessed. The decomposing produces n links: $l_1, l_2, \dots, l_n$ and n joints: $j_1, j_2, \dots, j_n$ (see figure 1). This method allows further decomposing into beam elements and joints. Regarding our model we may have a clear image of the forces that act upon each joint by applying external forces F_x and F_z and the moment M_y in the center of gravity for each joint (see figure 2).

Safety of the entire assembly depends much on its joints. If they fail the entire system would collapse. In this regard, L. Huo and L. Baron proposed a mathematical approach for joint-limits avoidance. They found out that by considering a weighting vector too small “*the redundant displacement may not be sufficient to avoid the joint limits*” and if too high it will produce high velocities in each joint [8].

Another element to be taken into account is the robotic arm’s transmission ratio. Considering joint spaces S.H.H. Zargarbashi *et al.* proposed that it should be expressed as an angle between n -dimensional joint-torque and joint-rate-vectors making it as low as possible. This will act as a protection against overload of the joint-rate and joint-torque vectors [9].

In case of FEA analyses both the weighting vector and the transmission ratio were considered ideal.

3. Setup

By comparing safety factor and margin of safety values obtained under different loads for the same system we can predict how many loads that system will or will not withstand. For the chosen materials we have considered computing the safety factor both for yield and ultimate stress. Since yield will result in a value of the safety factor until the system starts to plastically deform, we have chosen only the evaluation of the safety factor by means of ultimate tensile strength since it gives us a value until failure occurs. Assessing the margin of safety, we may encounter three situations. If zero, the mechanical part or assembly will not accept additional loads before failure. If negative, failure will appear before maximum load is achieved. If one, the mechanical part or assembly will withstand one additional maximum load. We have considered three positions of the robotic arm: *horizontal*, *intermediate* and *vertical* (see figure 3). In each case we have applied a load under the form of a pulling force. Values of 10N, 100N and 1000N were considered. This translates into approximately 1kgf, 10kgf and 100kgf to be lifted by the robotic arm. The type of analysis was set to *Static Structural* and for each one we have set the stress tool to *Maximum Equivalent Stress* with the stress limit type set to *Tensile Ultimate per material*. We have then added the two materials using *Ansys Granta*.

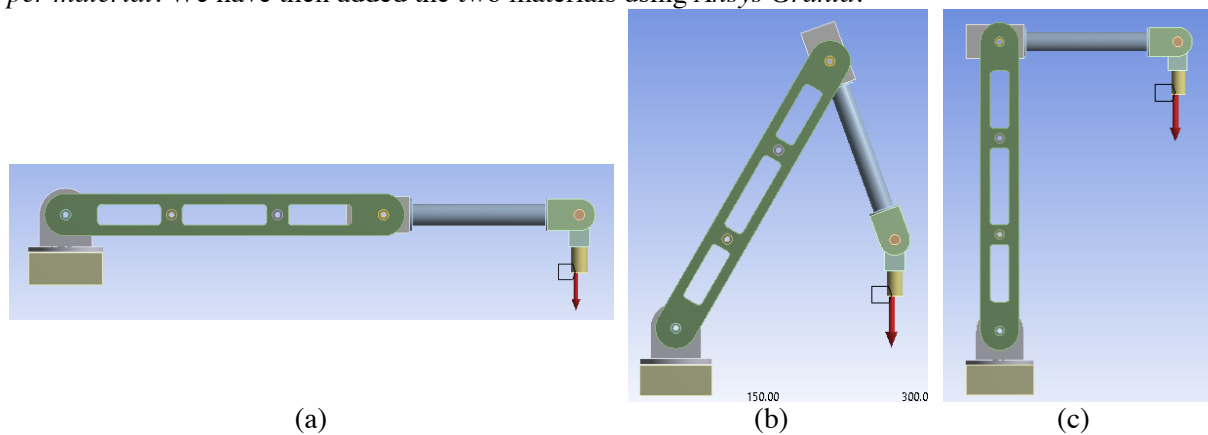


Figure 3. Considered positions of the robotic arm for FEA analyses.

4. Results and discussions

Table 1. Safety factor.

Positions of the robotic arm

	Horizontal				Intermediate				Vertical			
	1.0490 DIN		PLA		1.0490 DIN		PLA		1.0490 DIN		PLA	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
	Force (N)											
10N	1.2383e-004	2.4679	8.8699	15	3.6144e-004	13.858	15	15	15	15	4.2784	15
100N	1.2383e-005	0.2467	0.88697	15	3.6144e-005	1.3859	3.1229	15	14.275	15	0.43188	15
1000N	1.624e-006	2.4532e-002	1.9829e-002	15	3.6144e-006	0.1386	0.3123	15	1.5058	15	3.8802e-002	15

Table 2. Margin of safety.

Positions of the robotic arm

	Horizontal				Intermediate				Vertical			
	1.0490 DIN		PLA		1.0490 DIN		PLA		1.0490 DIN		PLA	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
	Force (N)											
10N	-0.99988	1.4679	7.8699	14	-0.99964	12.858	14	14	14	14	3.2784	14
100N	-0.99999	-0.7533	-0.11303	14	-0.99996	0.38586	2.1229	14	13.275	14	-0.56812	14
1000N	-1	-0.97547	-0.98017	14	-1	-0.8614	-0.6877	14	0.50579	14	-0.9612	14

Results have been plotted for both the safety factor and margin of safety for all considered positions of the robotic arm. We have decided to present where the minimum occurs for both the maximum and minimum values over time. Those values were then introduced in *Table 1* and *Table 2*.

To get a clear view of behaviors for each type of material-based model, graphical representations were obtained by stacking results obtained for all considered force values. This gave us the response of the assembly to an increase loading over time. Combining all positions, we may observe the differences of the assembly's response to a specific load value. By interpreting the charts, we have discovered similar behaviors that led to the conclusion that up to one-point PLA proves to be a valid alternative to its steel peer given the assembly's small dimensions.

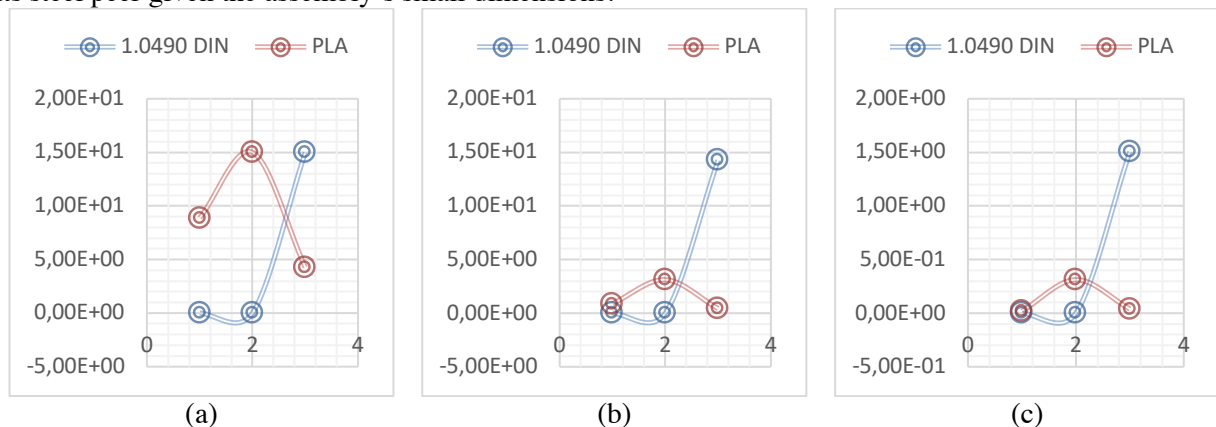


Figure 4. Safety factor comparative charts for both type of materials at minimum values.

We have considered both minimum and maximum values for each load combining results obtained for each position as follows: first the horizontal one, then the intermediate and finally the vertical one. In case of the safety factor, minimums show an interesting evolution. 1.0490 DIN proves as expected very reliable for all loads but reports only 1.5058 in the vertical position at 1000N load. PLA barely makes it over zero with 0.019829 at 1000N load in the horizontal positions (*see figure 4*).

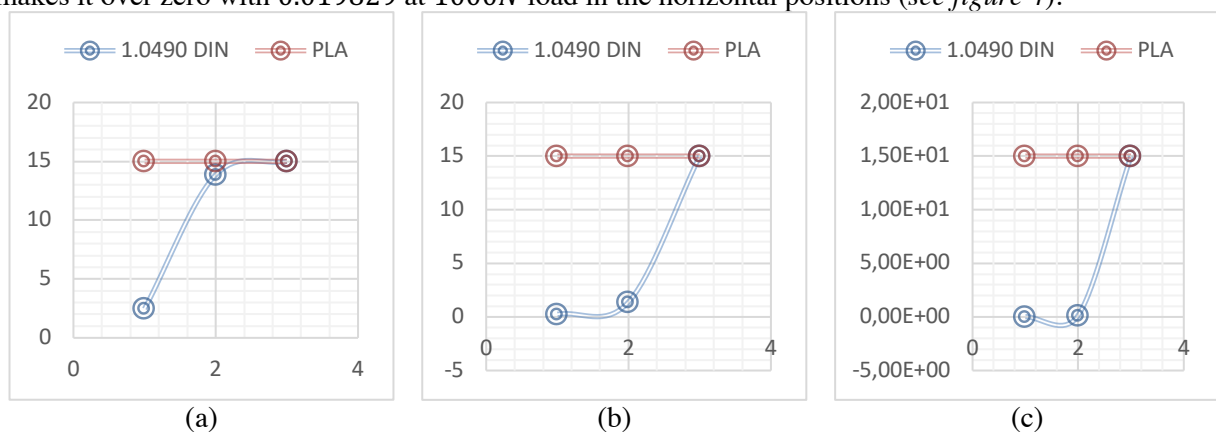


Figure 5. Safety factor comparative charts for both type of materials at maximum values.

Then we have compiled results for the margin of safety's maximum values. The graphical representation from the left corresponds to a 10N load, the middle one to 100N load and the right graphical representation corresponds to 1000N load. Except the 10N load, 1.0490 DIN reports values around 0.2 in the horizontal position as PLA reaches the upper limit. This means that PLA based assembly does not make it under these conditions and further refinement might be necessary. Although maximum reaches the upper limit, the average indicates that PLA proves valid for the 10N load in terms of safety factor requirements (*see figure 5*).

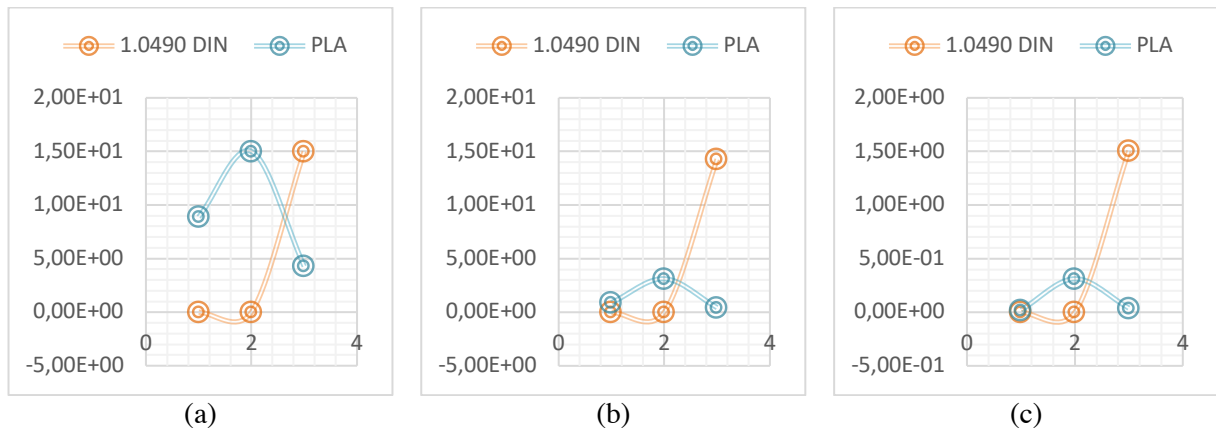


Figure 6. Margin of safety comparative charts for both type of materials at minimum values.

In case of margin of safety, the same working principle was applied. Charts were computed for minimum and maximum results for all loads by combining them for each position of the assembly. As mentioned above values below zero indicate a possible failure before the maximum load is achieved. 1.0490 DIN fails at 1000N load reaching -1 in the horizontal position of the assembly. So, even though the safety factor indicated that maximum load may be achieved this load cannot be sustained for multiple times at 1000N or even 100N for that matter. As well, for the minimums, PLA reports that it will support repetitive loading cycles only for a 10N load (*see figure 6*).

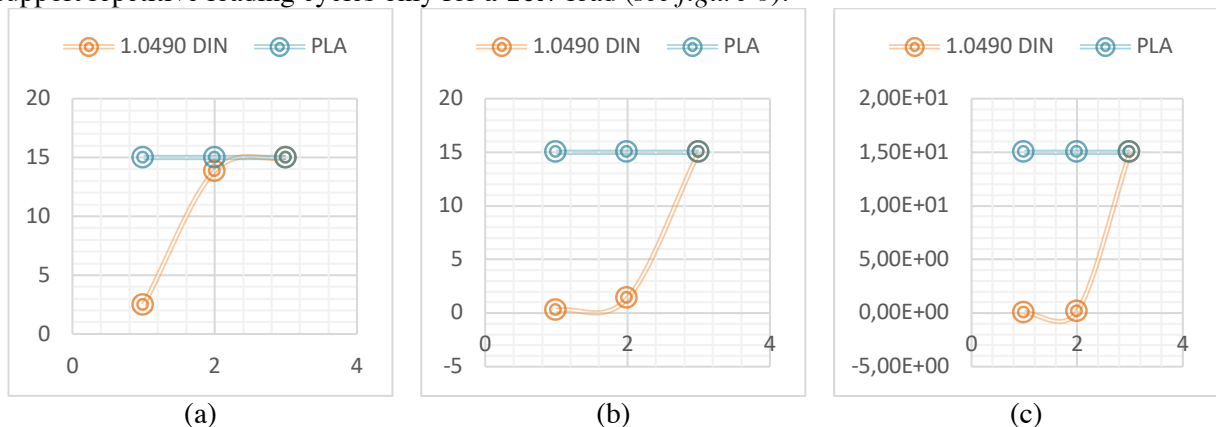


Figure 7. Margin of safety comparative charts for both type of materials at maximum values.

In case of the margin of safety maximums the horizontal position proves to be difficult for the 1.0490 DIN based assembly as it reaches only 1.4679 at 10N load meaning that it will support around 1.5 loading cycles at maximum load. As expected, PLA does not make it by quickly reaching the upper limit. Still, the average reports that the PLA based assembly almost withstands for at least 7 loading cycles. For loads above 10N PLA shows that failure may appear before even one loading cycle at maximum load will get to be finished (*see figure 7*).

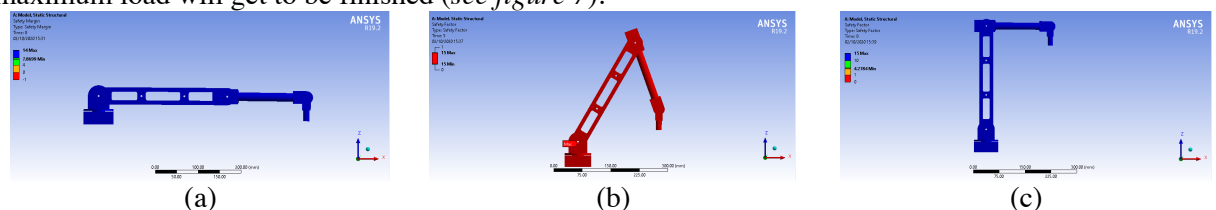


Figure 8. Print screens of PLA based model at 10N load.

Our PLA based model reported failure for one position. In horizontal position PLA based assembly reports 8.8699 for the safety factor and 7.8699 for the margin of safety. In vertical position PLA based assembly scores 4.2784 for the safety factor and 3.2784 for the margin of safety. Intermediate position reports that the assembly will not support a 10N load and paints it in red (*see figure 8*). By repetitive tests we found out that just about half of 10N load will report a “safe” design considering the two parameters.

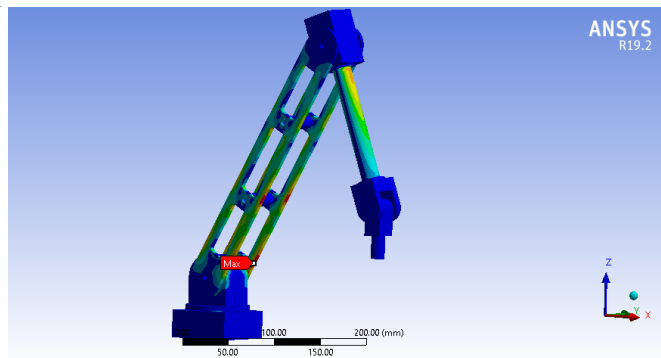


Figure 9. Print screen of PLA based model at 5N load.

The intermediate position proves to be the most demanding one. Because joints are seen as part of the assembly we can spot weak sections of the model and where it is more likely that it would fail. Pulling down with 0.5098581065kgf the beam sections tend to deform all length. That means that this particular design may be greatly improved if we choose for example a single filled middle section instead of two beams connected by bolts between them (*see figure 9*).

5. Conclusions

Does PLA prove a viable alternative against its steel peer in case of small projects or prototypes? In the case of our assembly the answer is *Yes* if small enough loads are used.

The proposed design was imposed by traditional manufacturing techniques where lighter models with the same pulling force are required. But keeping in mind that for smaller projects we need a structurally stronger model that would stand against its steel peers perhaps a fully rigid assembly would be more appropriate. Cylindrical components may prove highly adequate for this type of assembly much like it is the case for the upper arm of the current one.

Nevertheless, our design proved valid both in horizontal and vertical positions with lower loading cycles capacity. The intermediate position poses a threat to our design at maximum load thus making it interesting to conduct a transient structural type of analysis under *Rigid Dynamics* for the same model.

In this paper joints were considered as part of the assembly in order to find out which components of the assembly suffer the most at maximum load. But if joints are to be considered separately on their own, then that would change completely the results. Trying to evaluate the design we chose to overrule them and assess our assembly from the safety factor and margin of safety points of view only.

Future work will also try to take these analyses one step further by imposing a vibratory movement to the selected model thus being able to “see” some of its modal positions and further assess the opportunity of 3D printing for prototypes or small projects.

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