MECH 6V49.002

ADDITIVE MANUFACTURING

DR. WEI LI

(SPRING 2022)

PROJECT 1 REPORT

TOPIC:

ON-SITE REPAIR APPLICATION OF ADDITIVE MANUFACTURING

GROUP MEMBERS:

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1. Abstract

The project is based on the on-site repair of a bracket being used for a pump using additive manufacturing. The bracket is loaded with forces on the sides of the component holder and has been fixed at the 6 holes using bolts. Analysis is first done on a defect-free model to observe the results at the given loading conditions, followed by analysis on a defective model that has a crack formed due to high stress concentration with the same conditions. After comparing the results, a repair operation of the crack using additive manufacturing is simulated and the bracket is analyzed with the original loading conditions, to check for feasibility of using AM repairs as compared to replacing the component completely or using traditional manufacturing repairs.

2. Introduction of Wire AM

Wire AM is a type of Directed Energy Deposition (DED) method of additive manufacturing where a wire feed is used as opposed to powder. The reason for that is that the wire can be put through an arc welding plasma to melt it, and form beads. What makes wire AM an ideal process for on-site repairs is that variable bead size can be achieved through control software for repair operations on parts with complex design, without additional tooling or machining.

3. Methodology description

a) Geometry variants

Analysis was carried out for three different geometric variants of the bracket. The first simulation involved a bracket without any defect, the second geometry is a bracket with defect and the third geometry involved a bracket after repairing the defect site using additive manufacturing FEM simulation.

b) Materials selection and its properties

The materials used for this simulation are Structural steel, Titanium alloy, and polyethylene. A comparison study is done between the three materials to evaluate the material selection for this application.

Material Properties:

Structural Steel-

Ultimate Tensile Strength: 460 MPa

Elastic Modulus: 200 GPa

Melting Temperature: 1350°C

Titanium Alloy-

Ultimate Tensile Strength: 1070 MPa

Elastic Modulus: 114 GPa

Melting Temperature: 1660°C

Polyethylene-

Ultimate Tensile Strength: 30 MPa

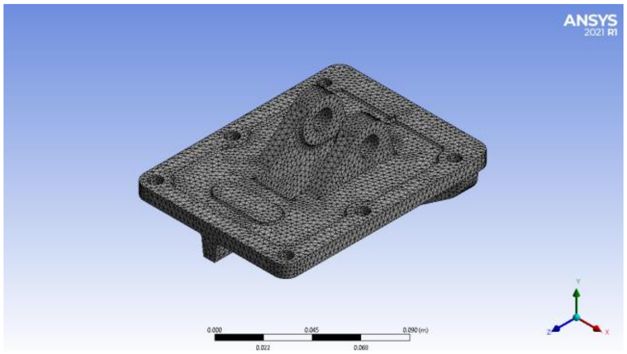
Elastic Modulus: 1 GPa

Melting Temperature: 115°C

c) <u>Meshing parameters considered</u>

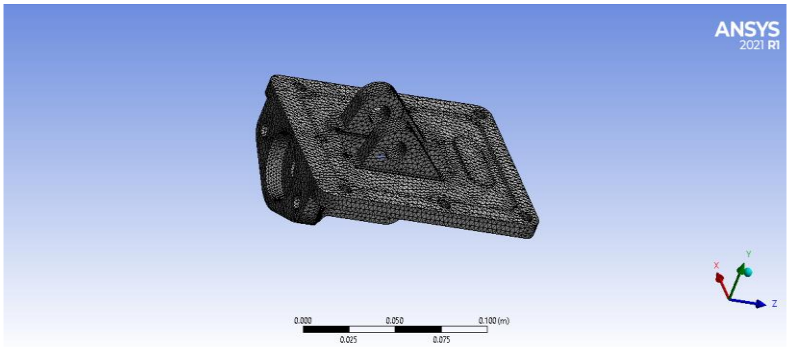
i. Static structural analysis for bracket without Defect

An adaptive sizing mesh was used for this analysis with a resolution of 7 for three different materials



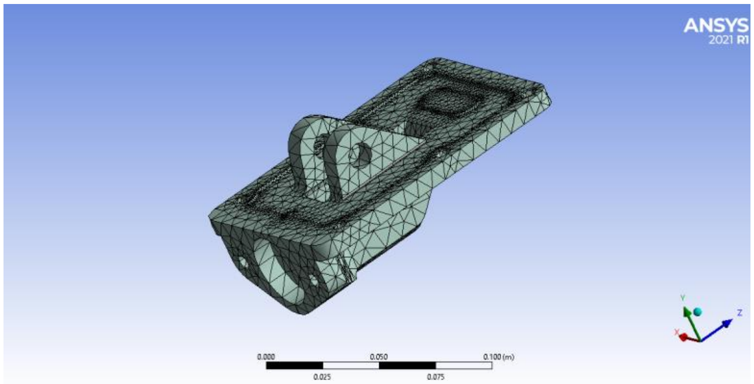
ii. Static structural analysis for bracket with defect

An adaptive sizing mesh was used to produce a fine mesh of resolution 7 for all different materials



iii. Transient Thermal for bracket with repair

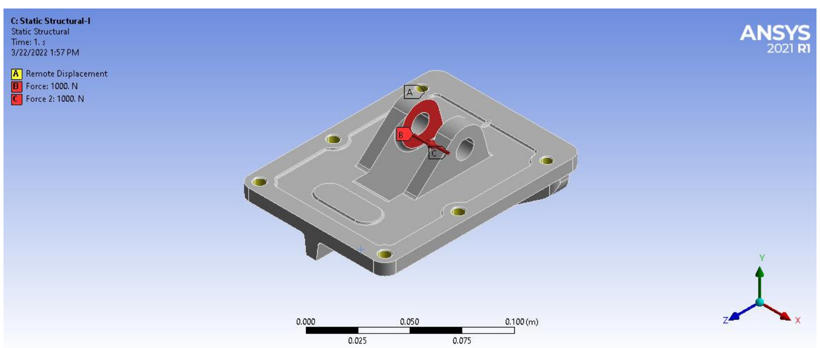
An automatically generated mesh was used for this application as we wanted to reduce the number of elements in the additively manufactured site. The repair site was filled using 11 elements for the three different materials. In this way the, the element birth and death was simulated easily.



d) Loads and boundary conditions considered

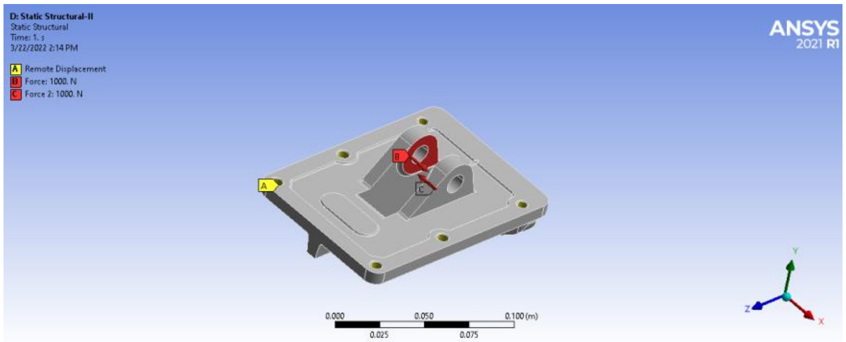
i. Static Structural analysis for bracket without defect

A remote displacement boundary condition with zero displacement was applied at all 6 bolting locations. A force load of 1000N was applied at each face of the component holding site as shown in fig. The force was chosen based on the ultimate tensile strength of the different materials and a high safety factor value was achieved.



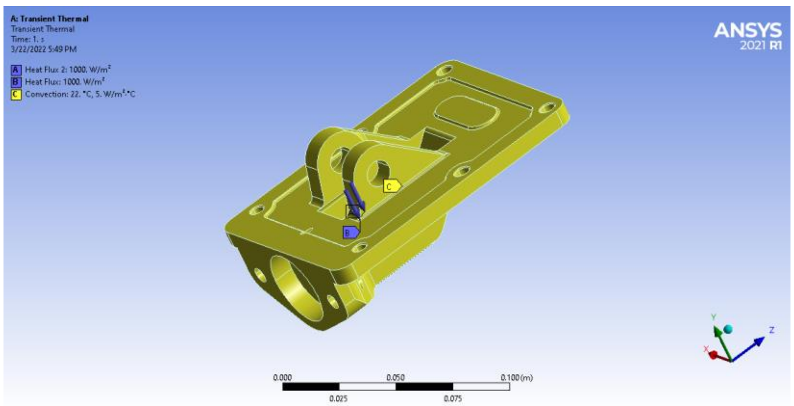
ii. Static Structural Analysis for bracket with defect

A remote displacement boundary condition with zero displacement was applied at all 6 bolting locations. A force load of 1000N was applied at each face of the component holding site as shown in fig. The force was chosen based on the ultimate tensile strength of the different materials and a high safety factor value was achieved.



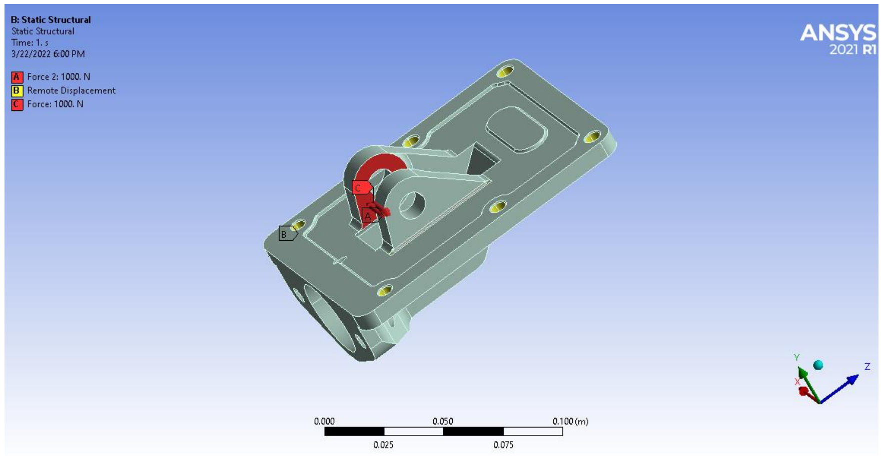
iii. **Transient thermal analysis for bracket with repair**

A thermal load heat flux of $1\times 10^{-3}\ W/mm^3$ was used to simulate the heat load while performing the wire additive manufacturing process for Structural steel and titanium alloy due its high melting point. Polyethylene on the other hand was given a thermal load of $1\times 10^{-6}\ W/mm^3$ to account for its low melting point. A Convection load with a film coefficient of $1\times 10^{-6}\ W/mm^3$ was applied over the whole surface to simulate the convection heat transfer taking place while additively manufacturing the repair site.



iv. **Static Structural analysis for bracket with repair**

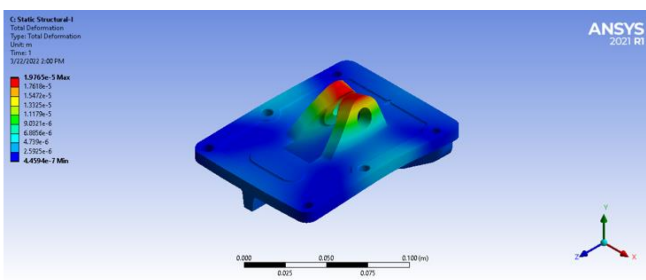
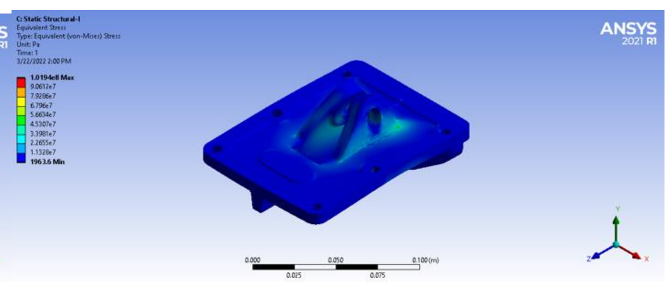
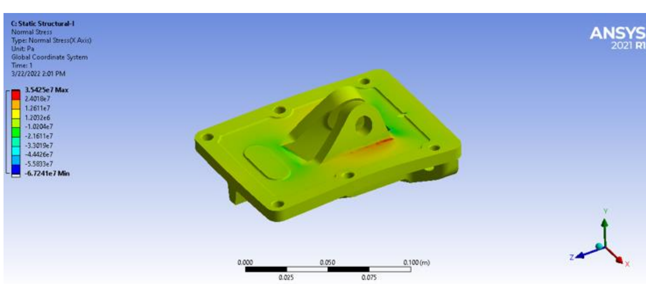
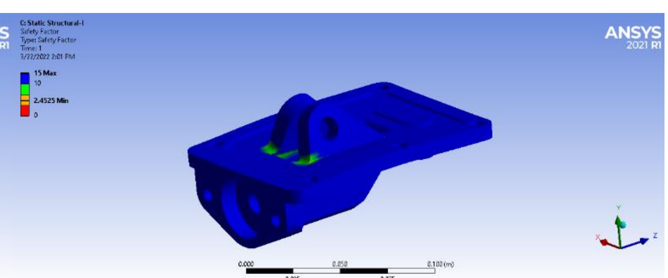
A force load of 1000 on each face of the component holding site was applied with a direction shown in Fig. A fixed remote displacement boundary condition was applied at all the bolting sites within the component. Moreover, all the loads and boundary conditions from the transient thermal simulation was transfer to account for stress while additively manufacturing the repair site.



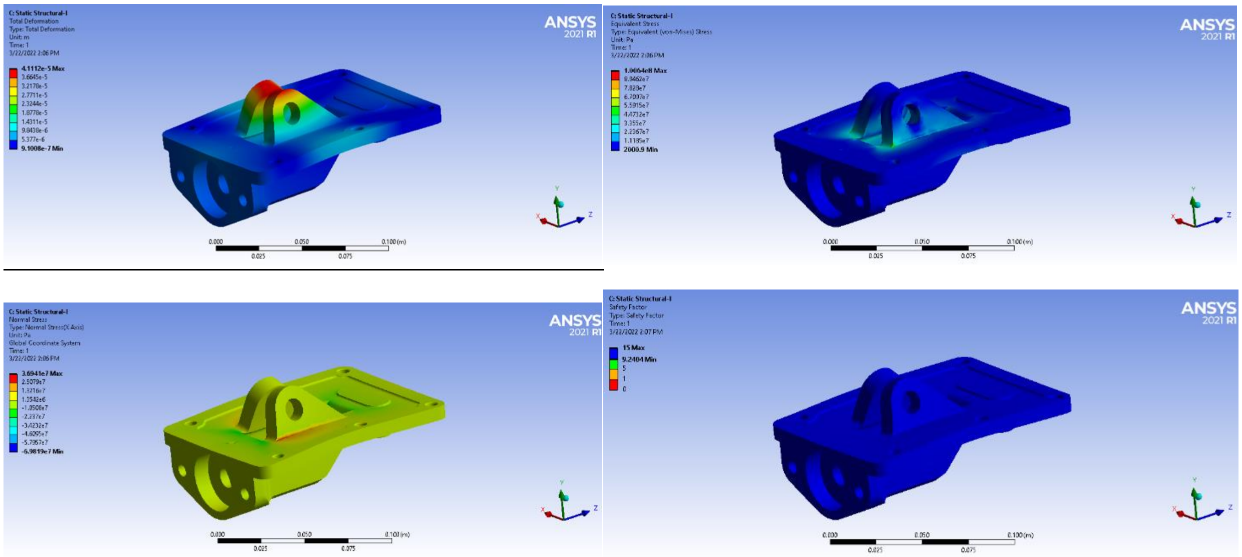
4. <u>Results (Contour plots)</u>

i. Static structural analysis for bracket without defect

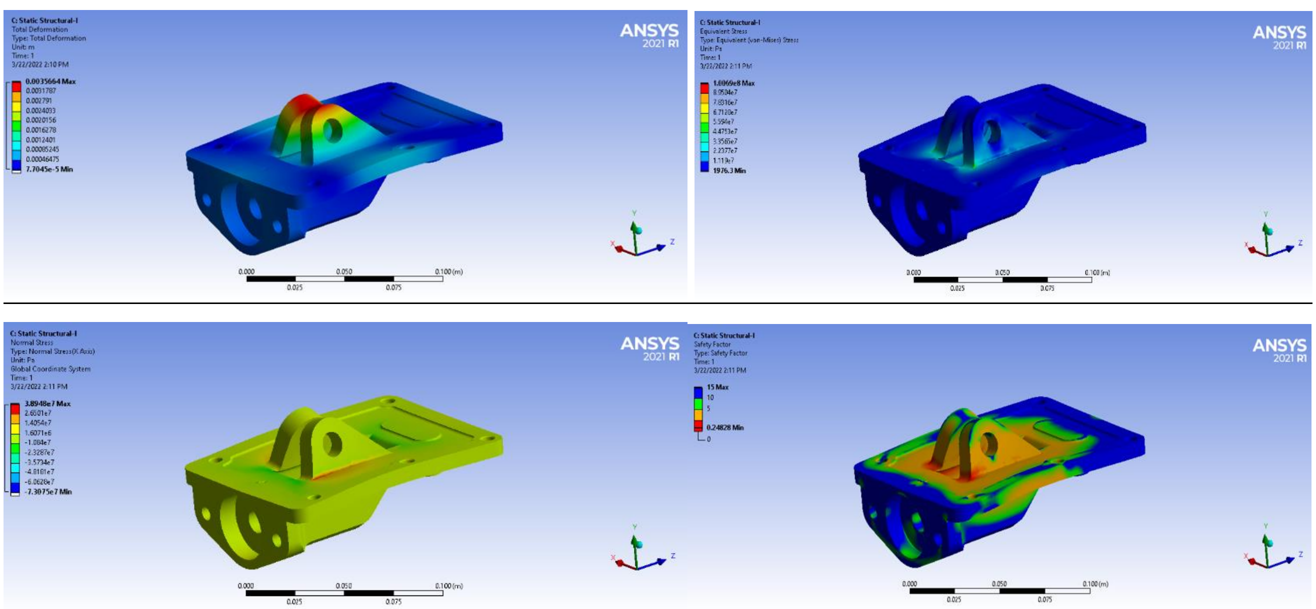
<u>Structural Steel</u>- (Order of images: Deformation, Von mises Stress, Normal Stress, Factor of safety)

Titanium Alloy-

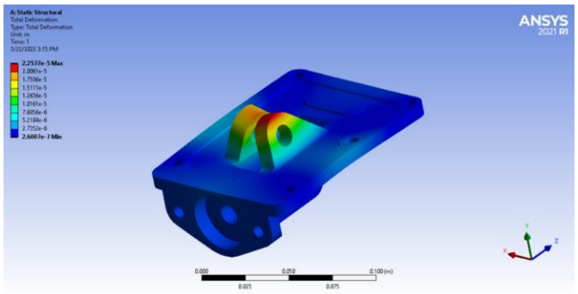


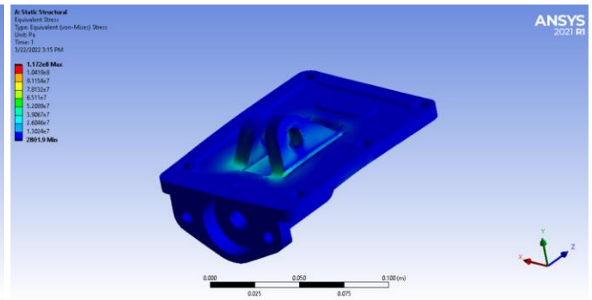
Polyethylene-

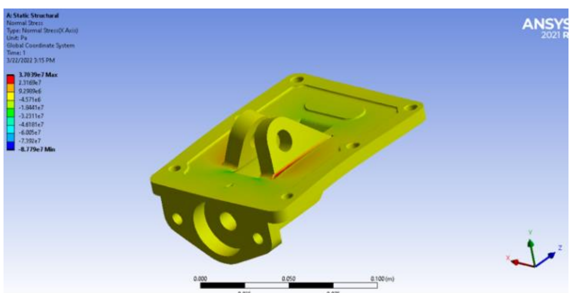


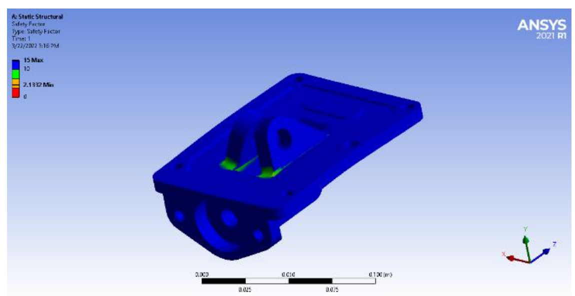
ii. **Static Structural Analysis for bracket with defect**

<u>Structural Steel</u>- (Order of images: Deformation, Von mises Stress, Normal Stress, Factor of safety)

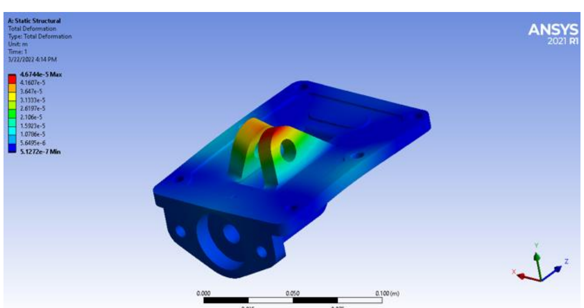


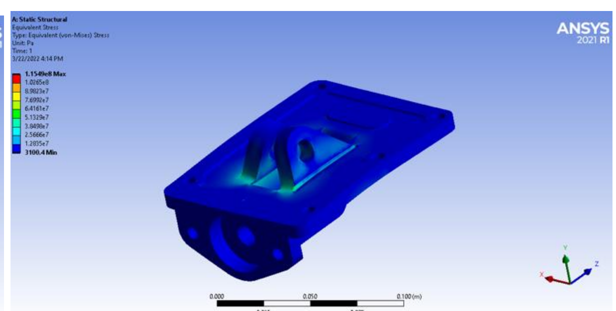


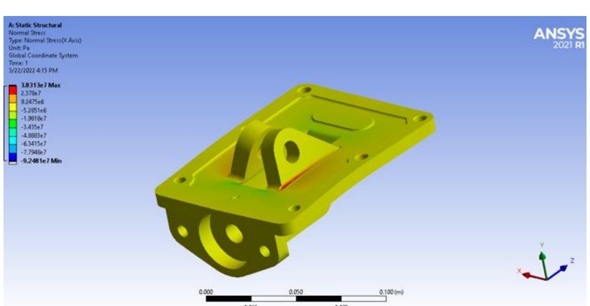


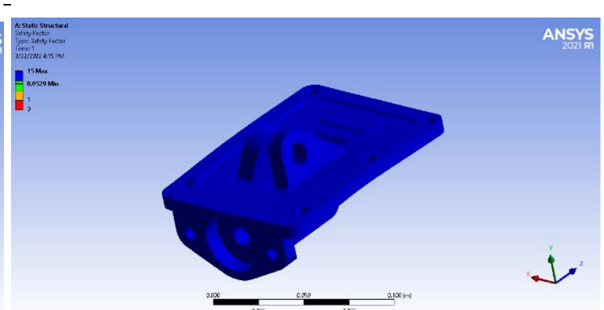


<u>Titanium Alloy</u>

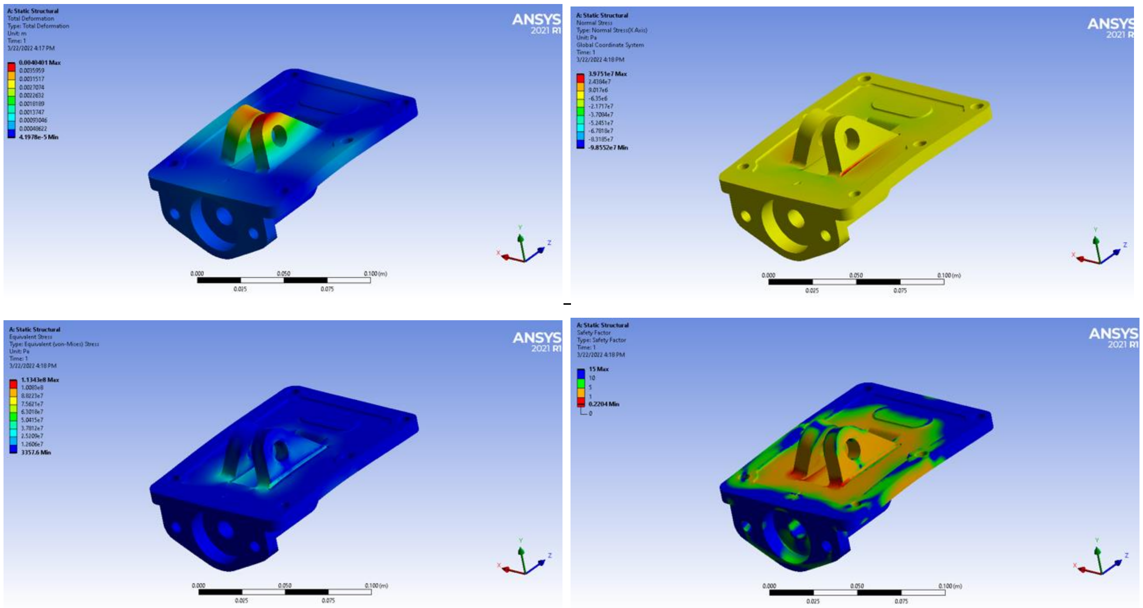






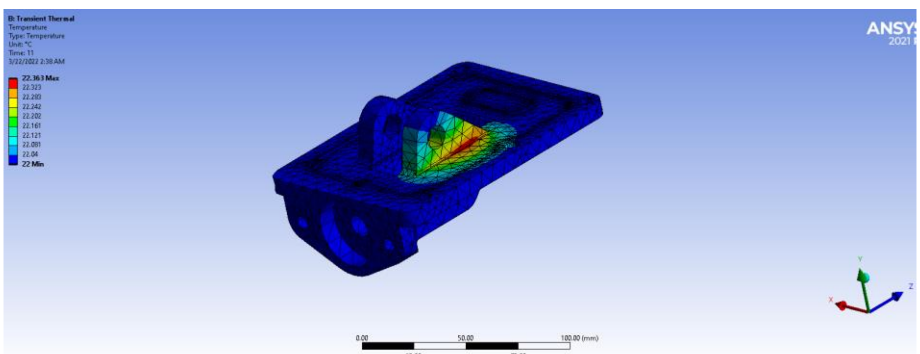


Polyethylene

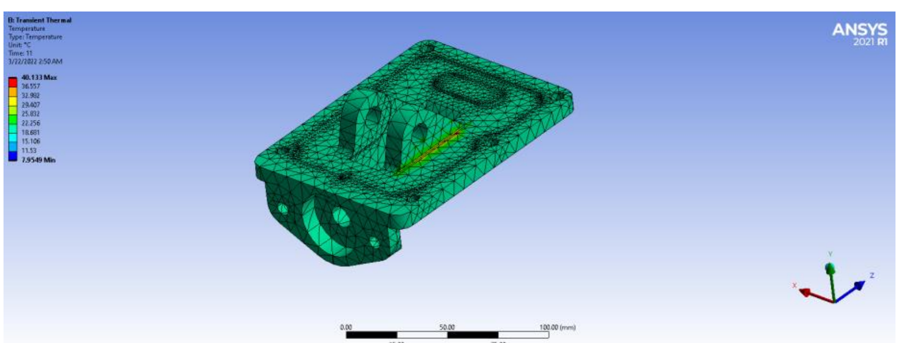


iii. Transient Thermal for bracket with repair

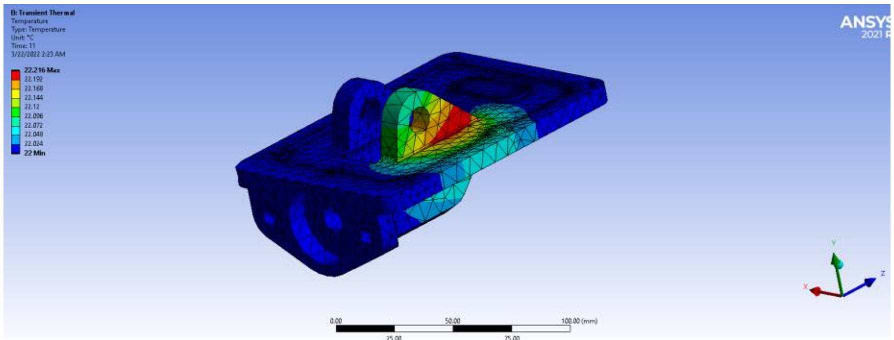
Temperature Contours



Structural Steel



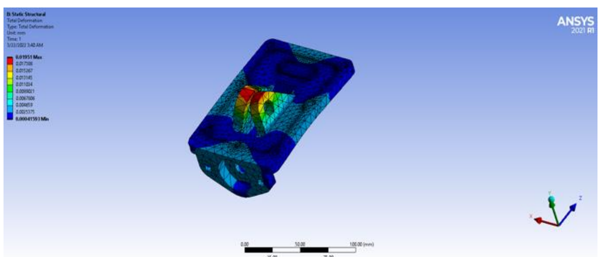
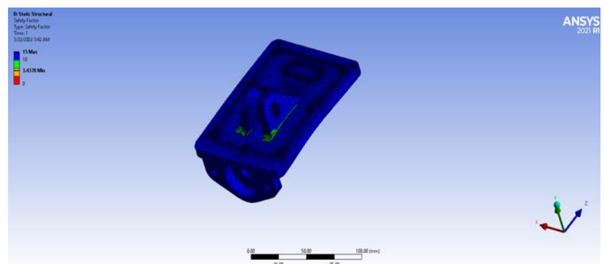
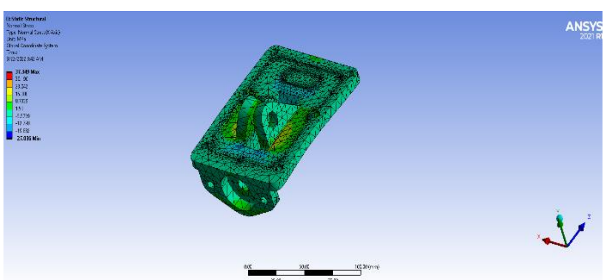
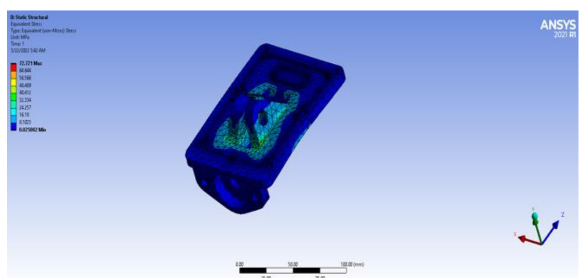
Polyethylene



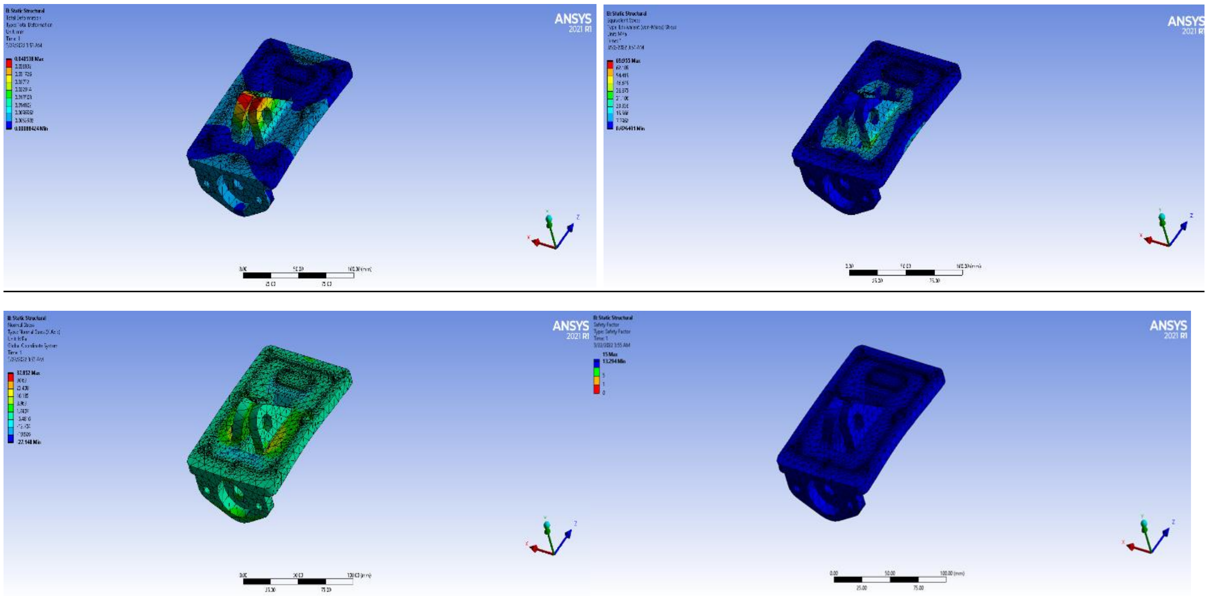
Titanium Alloy

iv. **Static Structural for bracket with repair**

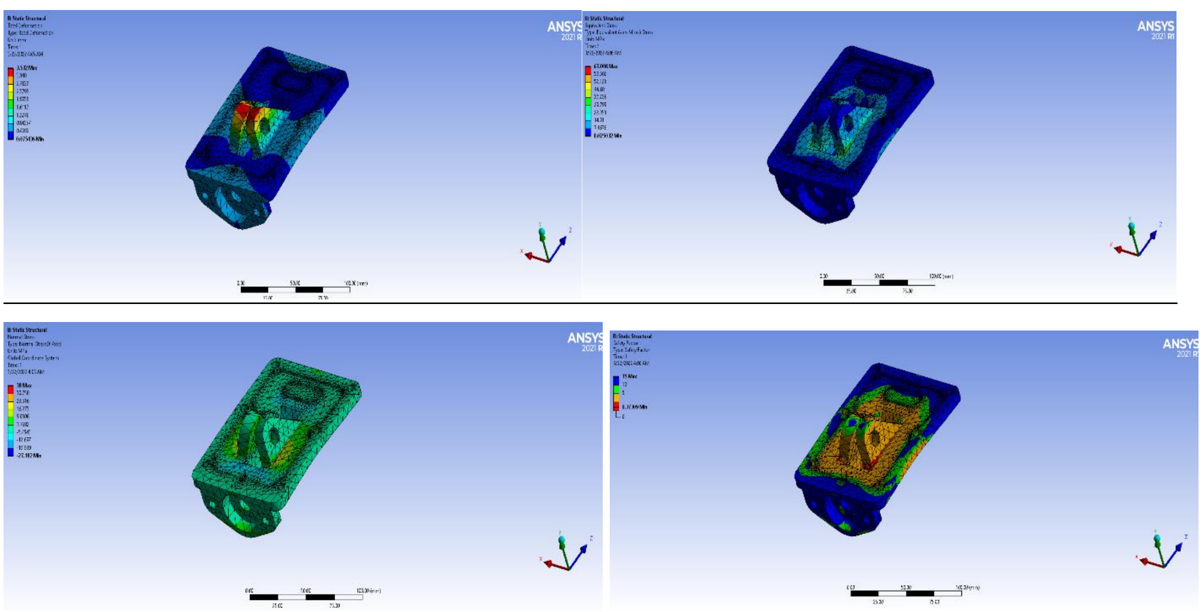
<u>Structural Steel</u>**-** (Order of images: Deformation, Von mises Stress, Normal Stress, Factor of safety)

Titanium Alloy-



Polyethylene-



5. Results

In the following table are the results for different cases of simulation, materials and mechanical properties

Analysis	Material	Deformation (m)	Von mises (N/m^2)	Normal Stress (N/m^2)	Safety Factor
Static structural without defect	Structural steel	1.9765 e-5	9.01 e7	3.542e7	2.4525
	Titanium alloy	4.112e-5	1.0064 e8	3.69 e7	9.2
	Polyethylene	0.0035664	1.0069 e8	3.89 e7	0.248
Static structural with defect	Structural steel	2.53 e-5	1.172 e8	3.7039 e7	2.1332
	Titanium alloy	4.6744 e-5	1.1549 e8	3.8313 e7	8.0529
	Polyethylene	0.004040	1.1343 e8	3.975 e7	0.2204
Static Structural after defect	Structural steel	**1.95 e-5**	7.272 e7	3.73e7	**3.4378**
	Titanium alloy	**4.05 e-5**	6.995 e7	3.78e7	**13.294**
	Polyethylene	**3.532 e-3**	6.7 e7	3.8e7	**0.37309**

Static structural analysis was carried out for three cases- bracket without defect, with defect and repair. Results for deformation, stress, factor of safety and normal stress were calculated using Ansys and tabulated in the table above. Essentially, after performing structural analysis for the bracket without defect we identified the stress concentration areas were failure is most likely to happen. Next, the defective model was analyzed and then repaired using Direct energy deposition additive manufacturing technique. From results, we can conclude that the additively repaired model improved its mechanical properties such as von mises stress, normal stress, and strain. Moreover, Comparing the factor of safety for the different models, we can conclude that the repaired model has a higher factor of safety which makes additively manufacturing a highly efficient technique compared to other conventional manufacturing technique which involves a lot of time and cost.

Three different materials were used in this simulation and after comparing the results we can observe that structural steel has the lowest stress concentration and deformation owing to its materials properties but titanium alloy had the highest minimum factor of safety owing to its high ultimate tensile stress.

Polyethylene on the other hand had the lowest factor of safety due to which it cannot be used in modelling such an application.

Observing the temperature contours from the transient thermal analysis, we can observe that titanium alloy material has the lowest thermal stresses owing to its high specific heat capacity whereas polyethylene was exposed to high thermal stresses and temperature distributions within the body.

Given below are the parametric table of various design points pertaining to different forces applied on the bracket

Bracket without defect

Table of Design Points

	A	B	C	D	E	F	G
1	Name	P1 - Force Magnitude	P2 - Force 2 Magnitude	P3 - Safety Factor Minimum	P4 - Equivalent Stress Maximum	P9 - Total Deformation Maximum	P10 - Normal Stress Maximum
2	Units	N	N		MPa	m	Pa
3	DP 0 (Current)	1000	1000	2.9497	84.753	1.9836E-05	3.3015E+07
4	DP 1	2000	2000	1.4749	169.51	3.9671E-05	6.603E+07
5	DP 2	2000	1000	1.7275	144.72	4.0483E-05	6.7413E+07
6	DP 3	1000	2000	2.004	124.75	4.0497E-05	6.3391E+07
7	DP 4	3000	3000	0.98325	254.26	5.9506E-05	9.9045E+07
*							

Bracket with defect

Table of Design Points

	A	B	C	D	E	F	G
1	Name	P5 - Force Magnitude	P6 - Force 2 Magnitude	P1 - Total Deformation Maximum	P2 - Equivalent Stress Maximum	P3 - Normal Stress Maximum	P4 - Safety Factor Minimum
2	Units	N	N	m	Pa	Pa	
3	DP 0 (Current)	1000	1000	2.2537E-05	1.172E+08	3.7039E+07	2.1332
4	DP 1	1000	2000	4.1579E-05	1.5472E+08	7.5079E+07	1.6158
5	DP 2	2000	1000	4.7373E-05	1.9704E+08	6.9687E+07	1.2688
6	DP 3	2000	2000	4.5073E-05	2.3439E+08	7.4077E+07	1.0666
7	DP 4	3000	3000	6.761E-05	3.5159E+08	1.1112E+08	0.71106
*							

Looking at the tables above, we can observe that there exists a maximum force that can applied to the model in order to maintain a fair factor of safety. The parametric evaluation of the different forces applied gives us a good idea on the selection of loads for the model. A force of 1000N on both faces was seen to produce a maximum factor of safety making this the maximum force that can be applied.

6. **Conceptual questions**

a) Convergence of the results is achieved by mesh refinement. When the mesh is unrefined, the results are not accurate. Thus, convergence studies are required when creating FEA models to ensure accuracy of results. When the mesh density is high and the results are approaching convergence, further increase in mesh density does not affect the result much.

b) The basic equation that we need to solve to get the temperature out of heat flux loading conditions is known as the Fourier's law and is given as follows.

$$\dot{q_x} = -\lambda \frac{dT}{dx}$$

where, $\dot{q_x}$ = heat flux (W/m^2) vector in the positive x-direction

$\frac{dT}{dx}$ = (negative) temperature gradient (K/m) in the direction of heat flow

λ = Thermal Conductivity of the material (W/mK)

(Journal reference: Fourier. J. (1955) The Analytical Theory of Heat, Dover Publications, New York.)

c) The main advantages of AM repair operations are that they can be implemented on-site as opposed to relying on old supply chain and traditional manufacturing such as casting, forging and billet machining for repaired parts. Furthermore, they are customizable to suit all manufacturing requirements and part geometries without compromise to quality, safety, efficiency and strength, alongside minimal to none material wastage.

d) Safety Factor is defined as the ratio of Ultimate Load (Strength) to Allowable Load (Stress). The range of 1-5 is chosen for the safety factor keeping in mind that the ultimate load can be five times that of the allowable stress, making it significantly less prone to failure. The allowable stress is always less than the ultimate failure stress. Hence, the factor of safety is always greater than 1, and cannot be less than 1 as the structure will surely fail in that case.

e) As inferred from the simulation results for various materials mentioned above, the use of AM repairs increases the ultimate load (strength) as compared to the allowable load (stress), and is generally less costly and quicker than traditional manufacturing repairs. Hence, it is a viable option for all kinds of materials such as metals, plastics, ceramics, etc.

f) The melting of feed material (powder/wire) is dependent on the solidus and liquidus temperature of the material. For melting the feed material, its maximum possible temperature needs to be within the range of solidus and liquidus temperatures. Since every material has its own solidus and liquidus temperatures, a specific heat flux needs to be applied using a heat source such as laser or plasma arc in an AM process depending on the material to melt it for deposition. Similarly, due to metals, plastics and ceramics having different strengths, they cannot withstand the same amount of loading. Hence, different heat loads and structural loads need to be applied if the materials for the bracket vary.

7. References

a) https://whatispiping.com/factor-of-safety/#:~:text=Factor%20of%20safety%3DUltimate%20Load,is%20always%20greater%20than%201.

b) https://www.sciencedirect.com/science/article/pii/S2238785421014356

c) https://www.thermopedia.com/content/781/

d) https://link.springer.com/article/10.1007/s00170-021-08265-y

e) https://aml3d.com/technology/

f) https://www.sciencedirect.com/science/article/pii/S2590123021001316

g) https://www.sciencedirect.com/science/article/pii/S0264127521000241

h) https://www.sciencedirect.com/topics/pharmacology-toxicology-and-pharmaceutical-science/titanium#:~:text=As%20shown%20in%20Table%203.1,alloys%20(Mitsuo%2C%201998).