Weight Optimization by Using Both Aluminum and Composite Material on the Big Excavator

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Abstract. The aim of this research is the development of a lightweight large excavator. This is due to the need to reduce the system suitable for its movement and to increase the hourly production of the excavator. This lightweight is done on all the main components by adopting aluminum alloy and composite materials. The study, developed in analytically and in numerically way, considers different loading conditions to which the excavator can be subjected during its use. The new solution was developed in order to have almost the same performance for safety coefficient, displacement and so the stiffness and critical buckling load. The excavator in its minimum weight configuration, obtained by applying composite materials for arms and hydraulic cylinders while aluminum alloy for frame, has an operating weight that goes from the value of 577.6 kN to the value of 425.8 kN with a reduction of over 26%. With this result, three important factors are to be underlined: increase in capacity which depends on the geometric configuration of the arms (about +41.5%); a significant reduction in ground pressure allowing the use of the excavator in previously inaccessible places and finally greater ease in transporting the machine.

1. Introduction
The aim of this work is to go and study an innovative solution for the lightweight of a common excavator. It was decided to address the issue of lightweight as the continuous development of the society that requires a constant increase in the performance of the production and transport systems. However, this increase in performance must also be accompanied by a greater attention to the environment, looking at eco-friendliness and eco-sustainability.

For these reasons, a method to be able to have an increase in performance (translatable in our case into a higher hourly production) trying to maintain a low environmental impact (reduction of consumption and of harmful gas emissions) can be found in the lightweight of the components.

In fact, after the works [1-3] in which the methodologies and construction solutions inherent the development of arms and hydraulic cylinders in composite materials were presented to ensure a significant lightweight of the components, this work focuses on design study of a typical excavator frame using a light aluminum alloy [4] compared to the typical construction steel [5, 6].

For these reasons, we will try to identify the optimal material for the construction of the excavator frame by comparing the use of the typical S355 construction steel with a light aluminum alloy [7] and then going to estimate the optimal geometry for the construction [8, 9], it will therefore be possible to
obtain a significantly lighter final structure also thanks to the use of components made of composite material. In addition, we will also study the counterweight and the balance of the machine according to the different construction solutions and the different load conditions.

2. Description of the machine
The excavator used for the following study is the Komatsu PC600 (Figure 1) as it is available for detection of dimensions (Table 1) and for a campaign of experimental tests aimed at determining accelerations during its normal use [10].

Table 1. Main dimensions of excavator

| Dimension | Value [mm] |
|-----------|------------|
| Boom      | 7660       |
| Stick     | 3500       |
| A Overall length | 12810 |
| B Overall width    | 4210 |
| C Overall height (to top of boom) | 4300 |
| D Overall height (to top of cab) | 3290 |
| E Ground clearance | 1365 |
| F Ground clearance | 780 |
| G Tail swing radius | 3800 |
| H Track length on ground | 4600 |
| I Track length | 5690 |
| L Shoe width | 600 |
| M Width of crawler | 3900 |

Figure 1. Excavator Komatsu PC600

An excavator can be divided into three main sections, Figure 2:
1. tracked wagon: allows the movement of the machine;
2. arm group: allows the handling of loads is composed of the arms, the bucket and the hydraulic cylinders;
3. upper structure: composed of the frame on which the boom is fixed, the relative cylinders, the counterweight, the cabin and the engine.

Figure 2. Subdivision of the excavator into three subgroups

3. Frame: structural steel and aluminum alloy
The aim is to study the frame of Figure 3 and therefore optimize it by using a light alloy [11, 12], to do this it is necessary to have the steel frame as a starting base so that you can create the solid model of the same. It was assumed that the original frame was made of S355 [13, 14] construction steel.
Below are some images of the model created and the main dimensions of the S355 construction steel frame.

![Solid model and main dimensions of the frame and undercarriage in S355 [mm]](image)

**Figure 3.** Solid model and main dimensions of the frame and undercarriage in S355 [mm]

For the construction of the light alloy frame, the use of 6060-T5 aluminum alloy (UNI EN 573-3) was assumed, this material presents a good compromise between performance, weldability and costs, the characteristics of the studied materials are shown in Table 2.

| Material       | Density ρ [kg/m³] | Young modulus E [MPa] | Poisson ratio ν | σsn [MPa] | σR [MPa] |
|----------------|-------------------|------------------------|-----------------|-----------|---------|
| S 355 (UNI EN 10025-3) | 780               | 210000                 | 0.28            | 355       | 510     |
| Al 6060 T5 (UNI EN 573-3) | 270               | 69000                  | 0.33            | 120       | 165     |

In order to create the light alloy frame, it was decided to adopt the same safety factor as the design criterion between the two construction solutions both in terms of stresses and displacements in order to have, for the same mechanical behavior, the same structure, but lighter. To do this and to be able to conduct a comparison between the two solutions, it is necessary to establish the load conditions.

### 4. Load Conditions

The main load conditions adopted also for the geometric and structural development of the innovative composite arms are shown below, these load conditions have also been studied under the dynamic profile [15, 16] and also used to compare two different geometric solutions [17].

- Load condition 1 (leveling): in this phase the arms are fully extended with the bucket resting on the ground, the movement sees the approach of the bucket to the body of the excavator as can be seen from Figure 4.
- Load condition 2 (lifting at minimum distance): during this phase the arms are positioned to be able to carry out a lifting action with the bucket positioned as close as possible to the body of the vehicle in question, as can be seen from the Figure 5.

- Load condition 3 (lifting at maximum distance): with this configuration the machine looks like in leveling condition 1 with the only difference that in this case the arms will not have to carry out a dragging action, but lifting and therefore the bucket it will have to perform a movement in a vertical and not a horizontal direction, as can be seen from Figure 6.

The magnitude of the applied forces, in correspondence with the bucket, during the simulations of the loading conditions derives from the load diagram of the machine, the values of these forces are shown in Table 3.

| Load case | F[N]  |
|-----------|-------|
| 1         | 323000|
| 2         | 243500|
| 3         | 93500 |

5. FEM simulation results for S355 frame

Once the constraints and loads [18, 19] relating to each individual load condition were set, finite element numerical analyzes were carried out [20, 21]. The FEM model was created using 4-node brick elements and is made up of approximately 29000 elements and approximately 58000 nodes. The software used
for the finite element analyzes is SolidWorks®. The results obtained from the finite element simulations are shown in Figure 7 as regards the load condition 1, in Figure 8 as regards the load condition 2 and in Figure 9 for regarding load condition 3.

- Load condition 1

![Figure 7](image1.png)

**Figure 7.** Frame S355 load condition 1: (a) stress, (b) displacement

- Load condition 2

![Figure 8](image2.png)

**Figure 8.** Frame S355 load condition 2: (a) stress, (b) displacement
6. Light alloy frame

In order to be able to create the new frame by adopting an alternative material the first step, is to maintain the same geometry as the S355 steel frame, but using the 6060-T5 so as to identify the critical areas of the component. Once the critical areas were identified, iterations were carried out to improve them through thickness increases and modifications in the basic geometries in order to obtain a frame with the same characteristics and the same behavior as the starting one. In this way what has been obtained can be seen in Figure 10 and in Table 4. At this point it is possible to proceed with the simulation at the finite elements whose results are reported in Figures 11-13.

Figure 9. Frame S355 load condition 3: (a) stress, (b) displacement

Figure 10. Frame in 6060-T5
Table 4. Variation in size and weight between frame in S355 and frame in 6060-T5

|       | mm   | S355 | 6060-T5 |
|-------|------|------|---------|
| A     | 460  | 510  |
| B     | 80   | 100  |
| C     | 25   | 40   |
| D     | 1250 | 1150 |
| E     | 30   | 50   |
| F     | 50   | 60   |
| G     | 200  | 240  |
| H     | 50   | 60   |
| Weight [kN] | 122.9 | 54.7 |

- Load condition 1

Figure 11. Frame 6060-T5 load condition 1: (a) stress, (b) displacement

- Load condition 2

Figure 12. Frame 6060-T5 load condition 2: (a) stress, (b) displacement
7. Evaluation of the counterweight

To balance the excavator in the different load conditions, it is necessary to use a counterweight that must be properly sized [22]. To do this, it is necessary to calculate the excavator's center of gravity and weight by considering the arrangement of the different loads and the position of the arms, so as to be able to calculate the overturning moment of the machine. The front part of the tracks, point A of Figure 14, was chosen as the point around which the excavator can overturn in flat ground conditions.

![Figure 14](image)

**Figure 14.** Point of interest for the calculation of the overturning moment (point A)

In order to correctly size the counter-weight it is necessary to use a safety coefficient defined as the ratio between the overturning moment and the stabilizing moment:

$$\eta = \frac{M_s}{M_r}$$

Where the overturning moment $M_r$ is generated by the load present in the bucket, by the weight of the boom and the stick, while the stabilizing moment, which keeps the machine in a safe position, is given by the weight of the load-bearing structure of the excavator and the counterweight (Figure 15). The optimal value is considered equal to 1.1 obtained as the average of the values 1 and 1.2 shown in Table 5.
Figure 15. Forces and distances schematic for counterweight calculation

\[
\begin{align*}
X \cdot a + F1 \cdot b &= \eta(F2 \cdot c + F3 \cdot d + F4 \cdot e) \\
X &= \frac{\eta(F2 \cdot c + F3 \cdot d + F4 \cdot e) - F1 \cdot b}{a}
\end{align*}
\]

Table 5. Counterweight value as a function of the different construction combinations

| Configurations / Weight [kN] | A      | B      | C      | D      | E      |
|-----------------------------|--------|--------|--------|--------|--------|
| F1                          | 360,0  | 266,7  | 360,0  | 360,0  | 266,7  |
| F2                          | 35,3   | 18,6   | 18,6   | 12,4   | 12,4   |
| F3                          | 14,7   | 9,0    | 9,0    | 5,8    | 5,8    |
| F4                          | 93,5   | 93,5   | 93,5   | 93,5   | 93,5   |
| X \eta=1                    | 94,8   | 117,0  | 82,0   | 75,7   | 110,6  |
| X \eta=1.2                  | 140,9  | 160,4  | 125,4  | 117,8  | 152,8  |

Configurations:
A) all part in constructional steel S355;
B) all part in aluminum alloy 6060 T5;
C) frame in constructional steel S355, arms in aluminum alloy 6060 T5;
D) frame in constructional steel S355, arms in composite material;
E) frame in aluminum alloy 6060 T5 arms in composite material.

Table 5 as in table 6 shows the variations in terms of weight of the arms (Table 5) and variation of the counterweight value (Table 6) according to the different construction configurations. In fact, these different configurations have been analyzed on the basis of results obtained from previously works [1-2-3-10], in which the arms and the hydraulic cylinders in composite material (carbon fiber 60% and epoxy resin at 40%) have been studied and developed as shown in Figure 16. In particular, the arms in composite material were designed considering an elliptical truncated cone section instead of a classic rectangular hollow section for both steel and aluminum materials. The ends of the arms and the cylinder connections zones are made of aluminum. For the hydraulic cylinders, both the tube and the rod are made of composite material while the connection ends are made of aluminum.
Figure 16. Different configurations of excavator (a) S355; (b) Al6065-T5; (c) Composite material

Table 6. Variation of the counterweight and the operating weight of the machine according to the different construction solutions

| Configurations/ Weight[kN] | A    | B    | C    | D    | E    |
|----------------------------|------|------|------|------|------|
| Counterweight (F)          | 117.9| 138.7| 103.8| 96.8 | 131.8|
| Operative weight           | 577.9| 483.1| 541.4| 484.1| 425.8|
| Reduction                  | 16.4%| 6.3% | 16.2%| 26.3%|

Configurations:
A) all part in constructional steel S355
B) all part in aluminum alloy 6060 T5, hydraulic cylinders in constructional steel S355
C) frame in constructional steel S355, arms in aluminum alloy 6060 T5, hydraulic cylinders in constructional steel S355;
D) frame in constructional steel S355, arms and hydraulic cylinders in composite material;
E) frame in aluminum alloy 6060 T5 arms and hydraulic cylinders in composite material.

8. Maximum slope rating
We want to study the effect of the overturning moment as a function of the inclination of the ground and the configuration of the excavator in static condition (at the start and end of the movement without considering the inertial effects of the movement). The load conditions shown are 2 (lifting at minimum distance) Figure 5 and 3 (lifting at maximum distance) Figure 6, for both loading conditions the initial and final phase of the movement were considered. The determination of the maximum slope that can be overcome is made by determining the intersection between the curve of the overturning moment and the stabilizing moment as a function of the slope angle of the ground. This parameter is of considerable importance since the machine does not always work on a flat surface and therefore it is necessary to estimate the maximum inclination for safety reasons. The inclination of the ground that can vary from 0 ° to 90 ° is represented by the angle α in the graphs of Figure 18, 19 for condition 2 and Figure 21, 22 for condition 3.

Figure 17. Schematization to calculate the maximum slope to be overcome
- Uphill load condition 2

![Graphs of the maximum gradient that can be overcome under load condition 2: (a) load condition start, (b) load condition end](image)

**Figure 18.** Graphs of the maximum gradient that can be overcome under load condition 2: (a) load condition start, (b) load condition end

- Uphill load condition 3

![Graphs of the maximum gradient that can be overcome under load condition 3: (a) load condition start, (b) load condition end](image)

**Figure 19.** Graphs of the maximum gradient that can be overcome under load condition 3: (a) load condition start, (b) load condition end

The maximum slope before overturning is given by the intersection point of the curves in the graphs.

![Schematization for calculating the maximum slope that can be overcome with the cab rotated 90° respect to the track](image)

**Figure 20.** Schematization for calculating the maximum slope that can be overcome with the cab rotated 90° respect to the track
- Uphill load condition 2

![Graphs](image)

**Figure 21.** Graphs of the maximum gradient that can be overcome under load condition 2: (a) load condition start, (b) load condition end

- Uphill load condition 3

![Graphs](image)

**Figure 22.** Graphs of the maximum gradient that can be overcome under load condition 3: (a) load condition start, (b) load condition end

9. Results

Thanks to the use of innovative materials such as aluminum alloys and in particular carbon fiber composite materials, it has been possible, as can be seen in other works [23, 24], to obtain a considerable reduction in weight [25, 26] in the main components that make up a typical excavator as can be seen from Table 6. In fact, thanks to the use of the aluminum alloy Al 6060 T5 (UNI EN 573-3) and the appropriate construction methods, it was possible to obtain a frame with structural characteristics similar to the steel frame, but with a weight reduction of approximately 56% (Table 4). This technical solution, if combined with the use of arms and hydraulic cylinders made of composite material, determines a reduction in the operating weight of the entire machine greater than 26% (Table 6).

From the graphs shown in Figure 17, 18, 20 and 21 and from those elaborated for the other load conditions, it is found that the intersection of the curves determines the limit angle value of the excavator, before its overturning. Table 7 refers to the overturning values obtained considering the classic construction configuration (all in S355 construction steel), as regards the other configurations or with different combinations of materials, the results are very similar to those in the table, so there is no difference since the counterweight value was chosen precisely to obtain the same performance as the starting machine.
Table 7. Maximum angle of ground inclination before overturning for two load conditions, in the start and end of movement phase

| Load condition | Start | End  |
|----------------|-------|------|
| Load condition 2 | 50    | 37   |
| Load condition 3 | 56    | 51   |

Thanks to the use of innovative solutions and the adoption of unconventional materials essentially composite materials, it has been possible, as seen in table 5 and table 6, to obtain undoubted advantages. First of all it was possible to reduce the force necessary to move the arms because the latter have seen a marked decrease in their weight thanks to the use of composite materials in as can be seen from Table 8, in which, moreover, the increase in the transportable mass is also reported, always obtained through the use of composite materials. Increase in load capacity was calculated for all load conditions and was evaluated both at the beginning of the movement and at the end of it. This value derives from considered the same stresses and deformations as the original configuration.

| Material                  | Weight boom [N] | Weight reduction [%] | Weight stick [N] | Weight reduction [%] | Total weight [N] | Weight transportable [N] | Incremental transportable weight [%] |
|---------------------------|-----------------|----------------------|------------------|----------------------|-----------------|-------------------------|-------------------------------------|
| S355 (UNI EN 10025-3)    | 35316           | -                    | 14715            | -                    | 50031           | 78750                   | -                                   |
| 6063 T6 (UNI EN 573-3)   | 18640           | 47.2                 | 9040             | 38.6                 | 27680           | 90410                   | 102070                             | 14.8                               | 29.6                              |
| Composite Material        | 12450           | 64.8                 | 5850             | 60.2                 | 18300           | 95100                   | 111450                             | 20.8                               | 41.5                              |

Secondly, from Table 6 a really important aspect emerges, in fact, by adopting the configuration: frame in Al 6060-T5, arms in composite material and hydraulic cylinders in composite material, it is possible to obtain a reduction of 26% in the operating weight of the machine. This figure can translate into a lower pressure exerted by the machine on the ground, in fact the pressure generated by the excavator in standard configuration (S355) is equal to 1.03 kg/cm² (taken from the catalog), while thanks to the use of a light alloy frame and above all thanks to the use of composite materials for the construction of the arms and hydraulic cylinders, the pressure value is equal to 0.76 kg/cm² with a reduction of about 26%. The reduction of the pressure exerted by the machine on the ground has undoubted benefits, in fact thanks to a lower pressure the excavator is able to move even in difficult to reach areas in which it is easy to sink (not very compact soils), therefore the adoption of materials innovative as well as guaranteeing benefits related to the reduction of consumption, the possibility of increasing the transportable mass, also guarantees the excavator to be able to move on land or areas not favorable to heavy vehicles.

10. Conclusions
This paper reports a systematic study of lightweight of a large excavator. The research starts from the study of the frame by developing the component also using unconventional materials for this element. The research continues from previous research focused on developing the arms and the cylinders in composite material. The global evaluation of the excavator is also conducted considering the effect of the counterweight whose value is chosen in relation to the configuration of the machine. The results show that adopting unconventional materials for these machines, such as aluminum alloy or composite...
materials, there is a significant reduction in the overall weight of the machine, without compromising the functionality and stability of the machine itself. In summary, therefore, with the adoption of the innovative solution, the stability of the machine is not compromised, but a much lighter excavator is guaranteed. This result can be translated in two different ways, on the one hand one could reduce the power of the propulsion and hydraulic system for the same transportable mass, thus reducing consumption (and consequently pollution) and costs, on the other hand a reduction of the operating weight of the machine with the same hydraulic system can guarantee a greater transportable mass thus leading to an increase in hourly production. A lighter excavator as obvious implies less problems for its transposition in the place where it will operate, however it must be emphasized that a reduction of the weights at stake both by the frame and by the moving parts, such as the arms and hydraulic cylinders, brings also to the undoubted advantage of being able to proceed with faster movements thus increasing the dynamics of the vehicle and consequently ensuring a saving in terms of time for each type of work performed by the excavator. Furthermore, as it has been demonstrated, having a lighter machine guarantees lower pressure on the ground, thus ensuring use even on grounds not suitable for heavy machines.

References
[1] L. Solazzi, A. Assi, and F. Ceresoli. New Design Concept for an Excavator Arms by Using Composite Material. Appl Compos Mater 2017.
[2] L. Solazzi, and A. Buffoli. Telescopic Hydraulic Cylinder Made of Composite Material. Applied Composite Materials 26(4), pp. 1189-1206; 2019.
[3] L. Solazzi. Feasibility study of hydraulic cylinder subject to high pressure made of aluminum alloy and composite material. Composite Structures, 209, pp. 739-746; 2019.
[4] G. Miscia, V. Rotondella, A. Baldini, E. Bertocchi, and L. D’Agostino. Aluminum Structures in Automotive: Experimental and Numerical Investigation for Advanced Crashworthiness. Int. Mech. Eng. Congr. Expo., 2015.
[5] L. Solazzi. Applied Research for Weight Reduction of an Industrial Trailer. FME Trans; 40:57–62, 2012.
[6] R.M. Gouveia, F.J.G. Silva. Designing a new Sustainable Approach to the Change for Lightweight Materials in Structural Components Used in Truck Industry. J Clean Prod, 115–23, 2017.
[7] F. Omar, T. Jimi, and S. Mobini. Lightweight and Sustainable Materials for Automotive Applications. 1st Edito. CRC Press; 2017.
[8] A. Michael, and J. Kara. Materials and Design. 3rd Edito. Butterworth-Heinemann; 2014.
[9] A.F. Michael, and J.R.H. David. Engineering Materials 1 An Introduction to Properties, Applications, and Design. 4th Edito. Butterworth-Heinemann; 2012.
[10] L. Solazzi, A. Assi, and F. Ceresoli. Excavator arms: Numerical, experimental and new concept design. Composite Structures, Vol. 217, pp.60-74; 2019.
[11] A.F. Michael, and J.R.H. David. Engineering Materials 2 An Introduction to Microstructures and Processing. 4th Edito. Butterworth-Heinemann; 2013.
[12] P.K. Mallick. Materials, design and manufacturing for lightweight vehicles. 1st Edito. Woodhead Publishing; 2010.
[13] P. Xiaoping, G. Xingtong, C. Jin, and W. Yabin. Structural analysis and optimized design of working device for backhoe hydraulic excavator. IFToMM World Congress Proceedings; 2015.
[14] Z. Zou, J. Chen, and X. Pang. Lightweight and high-strength optimization design for a fully parametric working attachment of a hydraulic excavator based on limiting theoretical digging capability model. Proceedings of the institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, Vol. 233, pp. 4819-4835; 2019.
[15] L. Solazzi, F. Ceresoli, and M. Cima. Structural analysis on lightweight excavator arms. Proceedings - European Council for Modelling and Simulation, ECMS 33(1), pp. 351-357; 2019.

[16] L. Solazzi, G. Incerti, and C. Petrogalli. Estimation of the dynamic effect in the lifting operations of a boom crane. 28th Eur. Conf. Model. Simul., p. 309–15, 2014.

[17] F. Ceresoli. Excavator with two or three arms: Dynamical behavior and structural implications. FME Transactions, Vol.48, pp.272-280, 2020.

[18] W. Jonathan. Finite Element Methods a Practical Guide. 1st Editio. Springer International Publishing; 2017.

[19] Z. Bofang. The finite Element Method: fundamentals and Applications in Civil, Hydraulic, Mechanical and Aeronautical Engineering. 1st Editio. Wiley; 2018.

[20] Y. Regassa, and H.G. Lemu. Multibody system modelling and simulation: Case study on excavator manipulator. Lecture Notes in Electrical Engineering, Vol. 484, pp.628-635; 2019.

[21] X. Yu, X. Pang, Z. Zou, G. Zhang, Y. Hu, J. Dong, and H. Song. Lightweight and high-strength design of an excavator bucket under uncertain loading. Mathematical Problems in Engineering. Vol. 2019, article number 3190819; 2019.

[22] J.S. Raju, and S. Basavaraju. Structural parameters and working range estimation of excavator backhoe mechanism. International Journal of Recent Technology and Engineering, Vol. 8, pp. 867-872; 2019.

[23] M. Collotta, and L. Solazzi. New design concept of tank made of plastic material for firefighting vehicle. International Journal of Automotive and Mechanical Engineering, Vol. 14, pp.4603-4615; 2017.

[24] L. Solazzi, and R. Scalmana. New Design Concept for a Lifting Platform Made of Composite Material. Appl Compos Mater; 20:615–26, 2013.

[25] U. Hamme, and J. Henkel. New concepts in lightweight structures - Innovative telescopic boom of a mobile cran. Stahlbau, Vol. 82, pp. 246-249; 2013.

[26] K. Skonieczny, M. Delaney, D.S. Wettergreen. and W.L. Red Whittaker. Productive lightweight robotic excavation for the moon and mars. Journal of Aerospace Engineering, Vol.27, article number 04014002; 2014.