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Design and Development of a collapsible wheel for wheelchair-based applications using Aluminum 6061 material

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ABSTRACT

Wheelchair is an important accessory to support patients with disorders in the lower limbs. With the advent of technology, more emphasis is being provided to portability and ease of handling wheelchairs. Reduction of size in wheelchairs, by folding or other means,adds huge utility to its logistics. While research hitherto has mostly concentrated on the improvement in the mobility and automation of the movement of the wheelchair, the present work explores improvement in foldability aspects of the wheels used in wheelchairs. This is achieved by suggesting a collapsible model to the wheel which reduces the diameter of the wheel. Such an approach facilitates reduced storage space for wheelchairs and enhancedease in its portability. A reduction in the diameter of the wheel is compensated by the relative increasing the width of the wheel. The current effort was successful in development of such a wheel which could bear a weight of upto 1500 N, when tested under simulation conditions. The wheel was fabricated using aluminum 6061 alloy and was tested for its robustness. This could further be extended in the development of an electronically controlled wheelchair, so as to aid the betterment of rehabilitation process to the patients with lower limb disorders. This shall also reduce the difficulty involved in portability-related issues of the wheelchairs used.

Keywords: Wheelchair; Automation; Foldability; Collapsible; aluminum 6061

INTRODUCTION

In India, more than 1 lakh people are known to be confined to wheelchairs due to lower limb injuries [1]. Statistics hint that more than half of these individuals are not able to use the wheelchairs due to issues pertaining to carrying them as they travel. This is often attributed to the size and weight of the wheelchairs [2]. While weight has always been a constraint in such rehabilitation-oriented equipment, there have been various improvements oriented towardsits size.Collapsible wheelchairs are known to solve the issue of space and mobility during travel [3].However, the seats can be folded, but not the wheels in general [4].

Lightweight collapsible wheelchairs have exceptionally light casing that is finished with a foldable element [5]. This incorporates the collapsing of the wheelchair seat and segments into a reduced shape that can be put away into the storage compartment of a vehicle, or in to an extra room, for instance [6].The foldable and light casing has turned out to be popular among wheelchair users who wish to have them collapsed for better accommodation, and to reduce the time it takes doing so [7]. Collapsible is synonymous with the word foldable which imply a similarity when they are utilized as an adjective to describe the wheelchair. However, in recent times, foldable wheelchairs are available in the market. [8] Such wheelchairs can be carried during travel and help in the mobility of such patients. [9] But there have been issues with respect to the reduction in the size based on the foldability aspects of these wheelchairs [10]. Several techniques have been developed to fold the wheelchair so as to accommodate them during travel. But the size does not seem to reduce to a great extent due to the constraints related to the wheel. In other words, it is often observed that the wheelchair could be folded only as much as the size of its wheels [11]. The edge of the seat is foldable, including the seat. Often, backrests are made of foldable hassocks or accomplished withcollapsible push bars [12]. Ideally, one would expect the wheel to be foldable as well, which would then result in a more compact design of the wheelchair when folded completely [13]. The capacity of such a wheel would be to overlay or crumple into a smaller and lightweight plan that can be put away with or joined to a collapsible wheelchair. Whenever required, the wheel can unfurl without much of a stretch, lock itself into a spot, as an auxiliary wheel [14].But the wheels of the currently available foldable wheelchairs exhibit a huge constraint in terms of their size. This is due to the fact that, although the wheelchair can be folded to an extent, the wheels of these wheelchairs cannot be folded [15]. Hence, they end up occupying the same space as they used to, when unfolded.

There has been research pertaining to the development of foldable wheel, with a four-segment foldable approach which is not effective in the reduction of the size as well [16]. For instance, the morph wheel design measures 0.60 m across [17].The novelty of the present work lies in the fact that this issue has been addressed by the development of a six-segment based foldable wheel which could solve the current issue with respect to the size occupied by the wheel in a foldable position as well [18].

BACKGROUND

There are numerous variants of wheelchairs existing in the market at present. While some of them are rigid and inflexible, others have been successful in incorporating features which lead to ease of usage, travel-friendly, light-weight, foldable, battery powered as well as usage of smart technologies for the control of wheelchair [19]. These attributes have made it a pleasant experience to use wheelchairs especially for those who cannot manage using cumbersome conventional manual wheelchairs. However, cost and accessibility to technology have always beensignificant constraints especially in developing countries such as India. This has resulted in usage ofconventional rigid wheelchairs more than those with technological innovations. However, in recent times, there have been numerous innovations in the field of wheelchair development with the advent of technology [20].

Aluminum alloys have often been the preferred material for development of wheels due to its higher strength to weight ratio as well as their cost effectiveness for generic applications. They are also known to be corrosion-resistant and fatigue-resistant [21]. However, there exists many alloys which can be used to manufacture wheels, especially for wheelchair based applications. Among them, aluminum 6061 alloy scores over the rest. A brief comparison of a few aluminum based alloys (aluminum 5052, 6061 and 6063 alloys) with respect to their mechanical properties are provided in table 1. [22]

Table 1: Mechanical properties of different aluminum alloys

Mechanical properties	**6061**	**6063**	**5052**
Yield Strength	276 MPa	214 MPa	193 Mpa
Ultimate Strength	310 MPa	241 MPa	228 MPa
Modulus of elasticity	68.9 GPa	68.9 GPa	70.3 GPa
Fatigue Strength	96.5 MPa	68.9 Mpa	117 Mpa
Bearing Yield strength	386 MPa	276 MPa	193 MPa
Hardness (Brinell)	95	73	60
Machinability	Good	Fair	Poor

Based on the information provided in table 1, one could infer that, it is suitable to use aluminum 6061 for the development of wheels, as compared to aluminum 6063 and aluminum 5052 alloys. In terms of the cost as well, AL 6061 is cost effective, as compared to the rest.

There are different types of wheelchairs in the Indian market, ranging from the simplest manual wheelchairs to complicated smart technology-based wheelchairs. A few specifications of different categories of existing wheelchairs are provided in table 2. [23]

Table 2: Different types of wheelchairs existing in Indian market

No	Features	Manual Collapsible	Battery operated	Smart wheelchairs

1	Example	Super Economy Wheel Chair MHL-1009 - Hero	Power Wheelchair Zip Lite - Vissco	KP-31T Blazer Power Wheelchair with LED Lighting System - Karma
2	Weight	46.5kg	40 kg	75-80kg
3	Size - normal	2.26 x 0.64 x 2.39 m	0.965 x 0.62 x 1.06 m	1.20 x 0.60 x 1.44 m
4	Size - Folded	2.26 x 0.36 x 2.39 m	0.70 x 0.37x1.06 m	NA
4	Operation type	Manual	Electric powered	Electric powered with smart technology
5	Cost (In India)	Rs 7000/- ($95)	Rs 50,000/- ($676)	Rs. 2,77,500/- ($3750)

A pictorial representation of the types of wheelchairs (described in table 1) is provided in figure 1to figure 3. Figure 1 depicts a manual collapsible type of a wheelchair (Hero make) in which the seat can be collapsed. But the wheel remains in the same position thereby taking the space, as much as that of the wheel before collapsing. [24]

Figure 1: Manual-collapsible wheelchair - Super Economy Wheel Chair MHL-1009 – Hero

Figure 2 depicts a battery operated wheelchair (Vissco make). This cannot collapse but has a detachable seat and hence can be carried while travelling in cars. [25]

Figure 2: Battery operated wheelchair - Power Wheelchair Zip Lite – Vissco

Figure 3 denotes a smart wheelchair which is software based, but cannot be folded. [26]

Figure 3: Smart wheelchair - KP-31T Blazer Power Wheelchair with LED Lighting System – Karma

One common aspect observed in each of these types of wheelchair is that there is no flexibility in terms of the wheel and all the design and variations are seen in the seats and the mode of operation. However, if one could only try to fold the wheel, then the size of the wheelchair would reduce drastically, when folded. This would then be very easy to carry while travelling as well. [27]

However, there exists an approach to fold the wheel, called the Morph foldable wheel method which have been experimented with wheelchairs. These wheels were originally designed for foldable bicycles and were later incorporated into foldable wheelchairs as well. These wheels measure 0.60 macross. When folded, they measure 0.80 m x 0.32 m, clearly resulting in more than 45% reduction in space requirement. This is shown in figure 4.

Figure 4: Morph foldable wheel

Morph wheels are made of glass filled nylon and are not cost effective. This is a major drawback of this setup, especially in developing countries like that of India. While a simple wheelchair may cost about Rs7000/- ($95) in Indian market, the cost of a single morph wheel itself is about $800 in the US market (roughly about Rs60000/-). [28]So, despite the existence of a foldable technology in the wheel, this is not reachable in terms of the cost. Also in India, this technology is not yet incorporated with wheelchairs and hence, there is an imperative need to develop a cost effective foldable wheelchairs employing foldability of wheels, in the near future.

The present work was successful in developing one such foldable wheel based on an umbrella-like foldable approach, at a highly cost effective manner.

MATERIALS AND METHODS

Design aspects

The current research emphasizes on the design and development of a prototype of a collapsible wheel which could be used as an alternative to the existing wheel for the foldable wheelchairs. At present, wheelchairs are developed, with a rigid wheel setup and foldable seats, in case of a simple manual wheelchair. Although there are a few examples of foldable wheels, such as those of morph wheels, the reduction in size is still a constraint. For instance, a morph folding wheel used for wheelchair reduces in size by nearly 50%., when folded. Hence, the present work emphasized on the development of a novel approach to fold the wheel by dividing the wheel into six segments. Scissor mechanism was introduced for folding the wheel into with regard to ease of storage and portability.

This new design of wheel was developed by using solid rubber tiers as are used in conventional wheelchairs.If these tires wear out, then these could be easily replaced with new tires, as similar to the present wheels. The folding wheel consisted of two-turn, split-spoke design, buttress-threaded and a unique hinging system with quick-action hand grip release. This lets the user to easily unfold the wheel, using a simple twist of the composite handgrip. The folding wheel appeals to both the manufacturers and owners, looking to enhance their deck layout at a fraction of the price of custom variants. A novel approach used to fold the wheel was developed based on a pattern similar to the collapsing of an umbrella allowing the users to benefit from a full-size wheel while saving more than 50% of space when needed.

Materials used

Aluminum 6061 was chosen to be the bestmaterial to develop the prototype of a collapsible wheel, due to its higher strength and relatively low weight for a metal alloy. Aluminum 6061 is a precipitation-hardened aluminum alloy having silicon and magnesium as its major alloying elements. It is known to exhibit good mechanical properties as well as a better weldability among its peers, and is known to be a very commonly extruded alloy. It is more often termed as a general-purpose alloy with an ultimate tensile strength of 124 to 400Mpa. The addition of magnesium and silicon to aluminum 6061 produces a compound of magnesium-silicide, which enables the solution to be heat treated for improved strength. These are widely found throughout the welding and fabrication industry, predominantly in the form of extrusions, and incorporated in many structural components. These alloys cannot be arc-welded without filler material because it is solidification-crack-sensitive. The addition of adequate amounts of filler material during the arc welding process is essential in order to provide dilution of the base material, thereby preventing the hot cracking problem.In the present design, the wheel was fabricated using aluminum flats which were bent in order to have maximum strength. The flanges were developed by cutting and welding the aluminum flats to the designs made. The links were cut into slots and the rim was again welded to it. TIG welding was chosen as it is known to be a better means of welding for aluminum. The center was made by cutting the aluminum pipe for the desired length and welding it with the flats which were then cut into the required size and drilled with holes at suitable positions.M6 bolts with stainless steel locknuts were used to guide the folding wheel mechanism due to their corrosion resistant attributes as well as their cost effectiveness.

RESULTS AND DISCUSSIONS

Various attributes such as the geometrical descriptions of the model, properties of the material, the assembly of the parts, the maximum forces that can be expected on the parts of a structure were first calculated. Since this wheel was designed for the wheelchair based applications, both wheels were designed to bear the entire load on the wheelchair. The applied forces are spread throughout the structure while the resulting stresses, strains and deflections are observed in the entire structure.Aspects such as fatigue, creep, modeling and stress corrosion were found to be negligible, for the wheel, when in normal position. Therefore, the current analysis was limited to the stress and deformation analysis. The stress analysis of collapsible wheel by mathematical method is a tedious job, and it is difficult to determine the maximum stress and its location. So, this analysis was performed applying**Ansys©** software, which is known to be a better computational simulation too. Post simulations, the wheel was assembled. While the entire assembly could not provide accurate results, each of the components of this wheel were analyzed separately with the aid of a CAD software (Solidworks), wherein each of the component was subjected to loading. The results showed that a maximum of 800N could be exerted on the wheel (approx. 80 Kgs). These models were converted to IGES (Initial Graphic Exchange Specifications) formats for further analysis in Ansys. General meshing was performed as well. These results are shown in the succeeding section

Geometric modeling

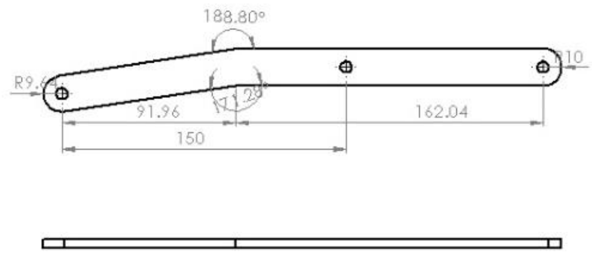

Figure 5: Arms

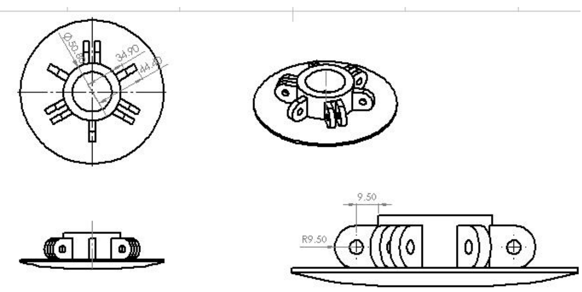

Figure 6: Center hub

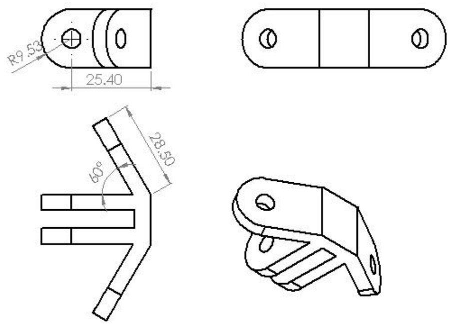

Figure 7: Flange

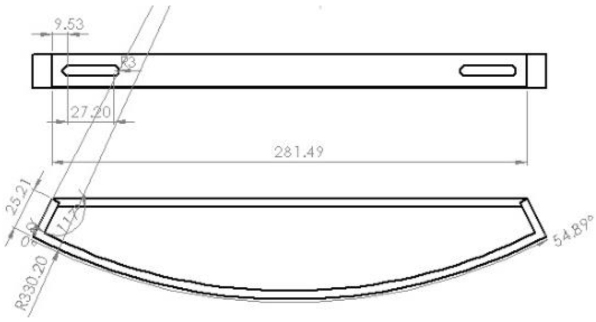

Figure 8: Link

Engineering Analysis

The model was then subjected to a load of 600N and 800N, verified for deformation and stresses using the **Ansys**software and the detailed results of the analysis at different loadings are as follows:

Arm - Model with Loading

Figure 9shows the model of the arm subjected to 800N force, which is equal to around 80kg, in the Ansys workbench.

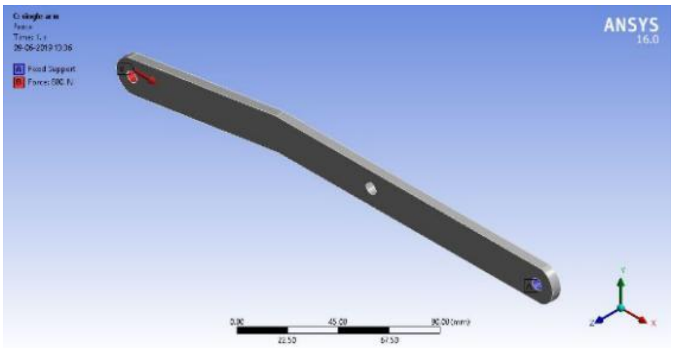

Figure 9: Arm subjected to 800N Load

Links: Model with Loading

Figure10 shows the model of the link subjected to 800N force, which is equal to around 80 kg, in the Ansys workbench. The loading point and the fixed support can be seen at the markers B and A respectively.

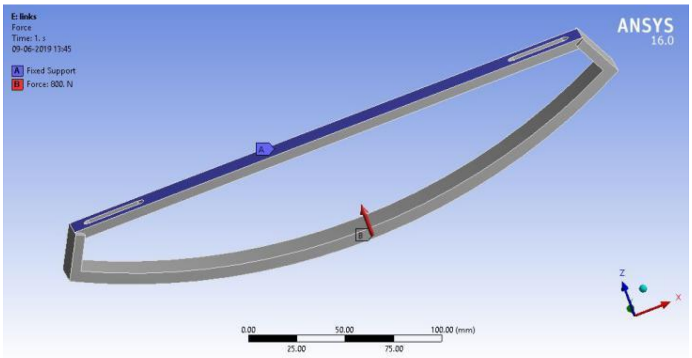

Figure 10: Link subjected to 800N Load

Flange: Model with Loading

Figure11 shows the model of the Flange subjected to 800N force, which is equal to around 80kg, in the Ansys workbench.

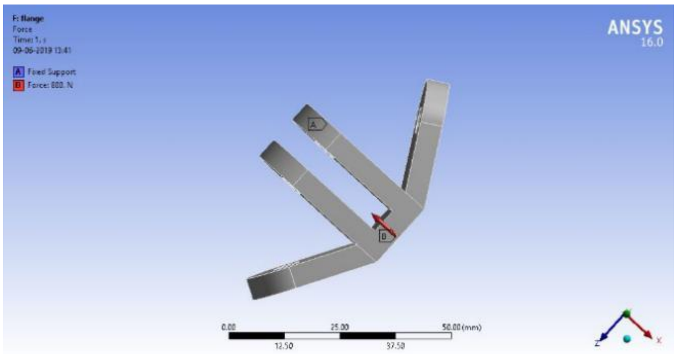

Figure 11: Flange subjected to 800N Load

Stress analysis of the wheel: Model with Loading

Figure 12 shows the model of the wheel subjected to 800N force, which is equal to around 80kg, in the Ansys workbench.

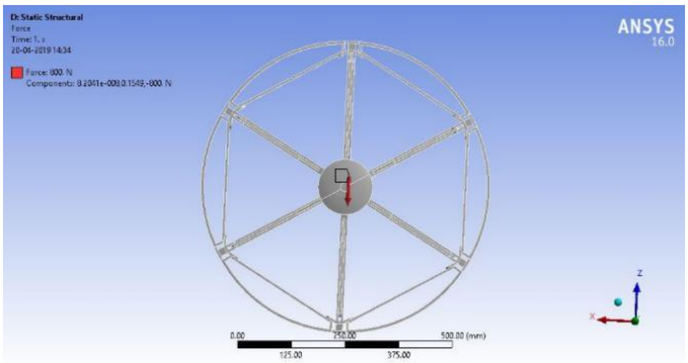

Figure 12: Wheel subjected to 800N Load

Design Review and Evaluation

Arm: Final solutions

The solutions that are obtained from this analysis are the Total deformation (figure 13) and Von-Mises stresses (figure 14).

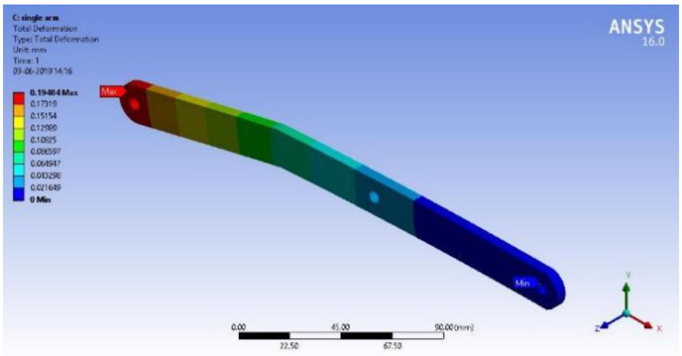

Figure 13: Total Deformation of the Arm

The Total Deformation of the Arm when subjected to the given load is shown in figure 13. The maximum and minimum deformation is shown as well. The maximum deformation was obtained when subjected to the load of 800N i.e., approximately 80 kgwas found to be 1.94 X 10^{-4} m. Also, the maximum value of Von-Mises stress obtained was 80.92MPa. The ultimate strength of the material was 290MPa. Thus, it is evidential that this wheel was safe with factor of safety greater than 2, even after the application of load of 800N.

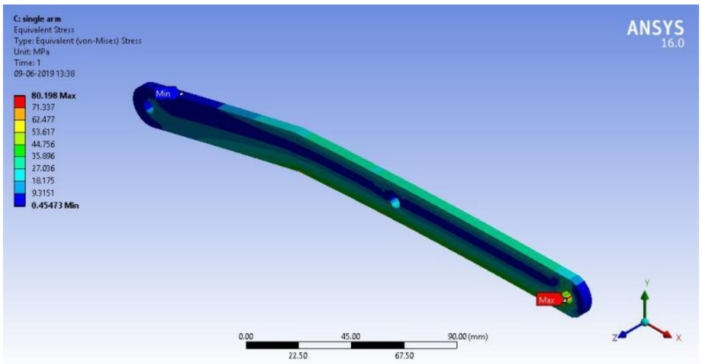

Figure 14: Von-Mises stress on the Arm

Links: Final solutions

Total deformation and Von-Mises stresses solutions obtained for the links are as follows:

The Total Deformation of the Link when subjected to the given load is shown in the figure 15. The maximum and minimum deformation is shown. The maximum deformation was obtained when subjected to the load of 800N i.e., approximately 80 kg is 3.01 X 10^{-5} m.

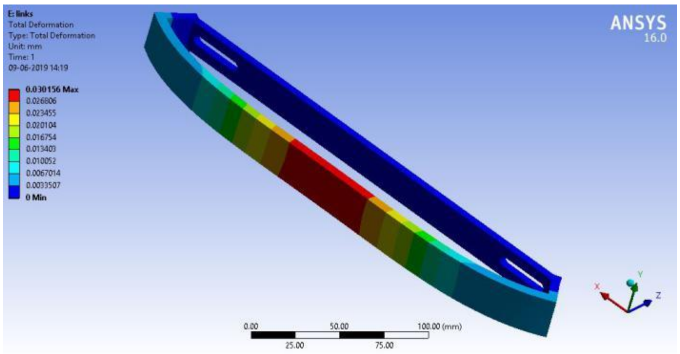

Figure 15: Total Deformation of the Link

In the analysis of the links, as shown in figure 16, the maximum value of Von-Mises stress obtained was 50.94MPa. The ultimate strength of the material was 290MPa. Thus, it was evidential that this wheel is safe with factor of safety greater than 2.

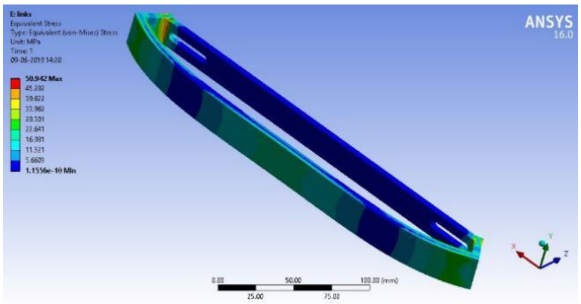

Figure 16: Von-Mises stress on the Link

Flange: Final solutions

The Total Deformation of the Flange when subjected to the given load is shown in the figure 17. The maximum and minimum deformation is shown. The maximum deformation was obtained when subjected to the load of 800N i.e., approximately 80 kg is 1.902 X 10^{-7} m.

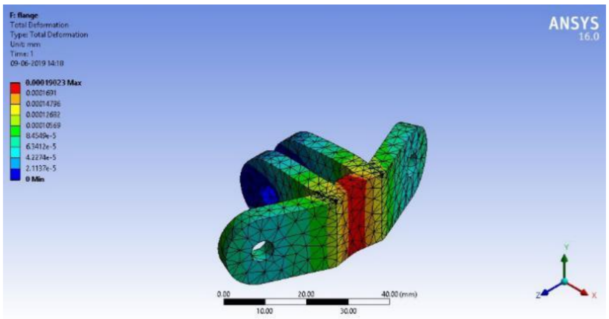

Figure 17: Total Deformation of the Flange

The maximum value of Von-Mises stress obtained was 8.58MPa, as shown in figure 18. The ultimate strength of the material was found to be 290Mpa. The induced stresses were found to be less than the maximum stress of the material. Thus, the design was considered to be safe.

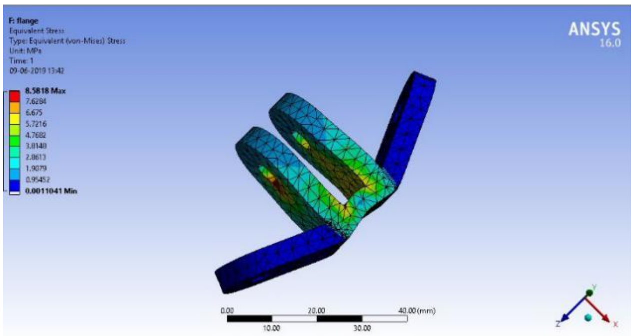

Figure 18: Von-Mises stress on the Flange

The present analysis showed that the components, when subjected to the load of 800N individually, were safe in stress induced and hence, minimum chances of failure. The deformation also being low, these could be practically safe for wheelchair based applications. However, analysis of the entire assembly of the wheel was also done and following results were obtained.

Analysis of complete wheel: Final solutions

The total deformation solution obtained for the entire wheel is tabulated in table 3. A pictorial representation of the same if shown in figure 19.

Table 3: Total Deformation for the entire wheel

Load (in Newton)	Deformation (in meter) x 10^{-5}
75	2.4507

125	4.9014
250	7.3521
375	9.8028
500	14.704
625	17.155
750	19.606
800	22.056

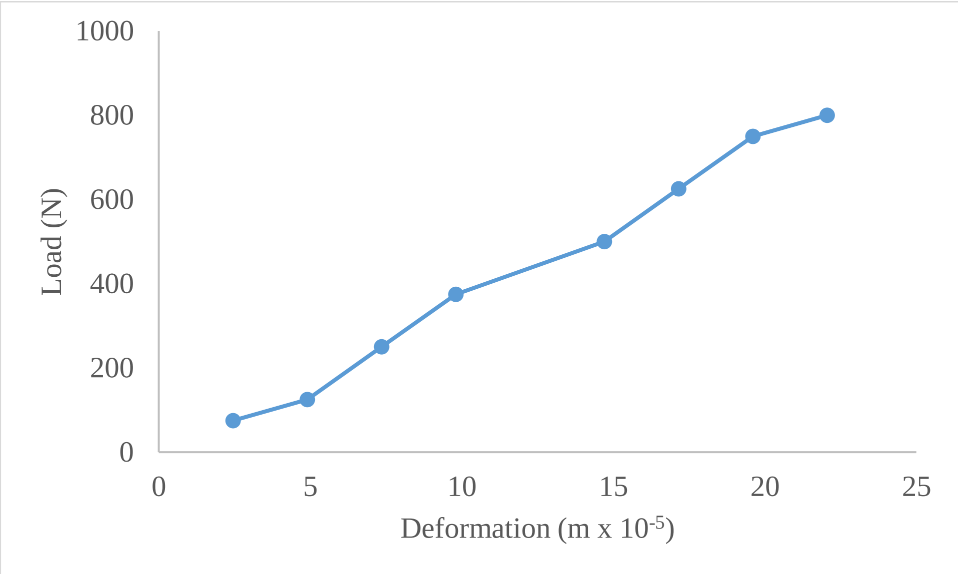

Figure 19: Load v/s deformation for the wheel

The Total Deformation of the wheel when subjected to the given load is shown in Figure20. The maximum and minimum deformation is shown. The maximum deformation was obtained when subjected to the load of 800N i.e., approximately 80kg is 22.05 X 10^{-5} m.

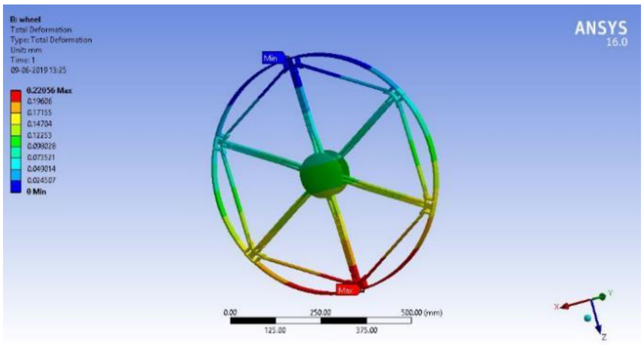

Figure 20: Total deformation of the wheel

The Von-Mises stress based analysis was performed for the entire wheel and the maximum value of Von-Mises stress obtained was 122MPa, as shown in figure 21. The ultimate strength of the material was found to be 290MPa. The induced stresses were found to be lesser than the maximum stress of the material. Hence the design could be considered as safe.

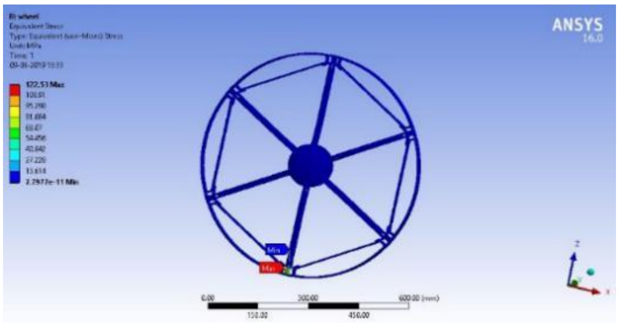

Figure 21: Von-Mises stress of the wheel

The automated drafting, when the wheel is open and folded, for this wheel is given in figure 22 and figure 23, respectively. The final fabricated wheel is depicted in figure 24, in actual position and in figure 25, for folded position.

Figure 22: Automated drafting – wheel expanded

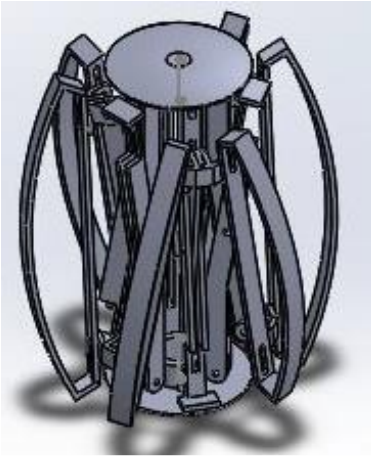

Figure 23: Automated drafting – wheel collapsed

Figure 24: Fabricated wheel – expanded position

Figure 25: Fabricated wheel – collapsed position

Conclusions

In the present work, a foldable wheel was successfully developed based on a six-segment design. Such a wheel could be incorporated into a foldable wheelchair. The diameter of the wheel was observed to be 0.6604 m initially, in the normal position. This reduced to a structure of 0.2032 m (diameter) and 0.254 m (height) when collapsed (circular shape reduced to a cylindrical structure). This model was subjected to a stress analysis using analysis software (Ansys V16.0) on the hub of the wheel where maximum load was applied and the effects were observed. This wheel, made of Aluminum alloy, obtained a Von-Mises stress of 122Mpa and a corresponding deformation of 22.05 X 10^{-5}m for a load of 800N. The ultimate strength of the material was found to be 290MPa with a factor of safety of 3. The results proved that the presently proposed design was safe for the given loading conditions. Since, this wheel was found to beworking safe under a load of 800N, a total of 1600N could be supported with two such wheels.In the case of wheelchairs, i.e., a weight of up to 150kg can be exerted on the wheelchair.In terms of cost effectiveness, for the design of the prototype wheelchair using AL 6061, the overall cost of the materials as well as the processing aspects was nearly Rs.1500/- ($ 20) per wheel. This cost can be further reduced with bulk manufacturing, which could be considered in the near future, after testing the performance of this wheel, in real-time and under dynamic conditions.

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Declaration of interest: None

Conflict of interest: None

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