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DESIGN AND DEVELOPMENT OF A COLLAPSIBLE WHEEL FOR WHEELCHAIR-BASED APPLICATIONS USING ALUMINUM 6061 MATERIAL

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Abstract. The wheelchair is perhaps the most important equipment to support the patients with disorders in the lower limbs. With the advent of technology, more emphasis is being provided to portability and ease of handling wheelchairs. A reduction of size is a huge concern in the case of mobile wheelchairs. While most of the research concentrates on the improvement in the mobility and automation of the movement of the wheelchair, the present work ascertains the improvement in the foldability aspects of wheelchairs concerning the wheels used. This is achieved by introducing the collapsible model to the wheel which reduces the diameter of the wheel. Such an approach facilitates the storage of wheelchairs concerning portability. Such a reduction of the diameter is compensated by relatively increasing the width of the wheel. The current research is successful in the development of such a wheel that could bear a weight of up to 150 Kgs when tested with simulations. This wheel is fabricated using aluminum 6061 alloy and was tested for its robustness. This could further be extended in the development of an electronically controlled wheelchair, based on a collapsible design to aid in the betterment of the rehabilitation process to the patients with lower limb disorders to reduce the difficulty involved for the portability aspects of the wheelchairs used.

Key words: wheelchair, automation, foldability, collapsible, aluminum 6061.

Introduction.

More than 10% of human beings are known to suffer from lower limb injuries and are often confined to wheelchairs[1]. Statistics hint that more than half of these individuals are not able to use the wheelchairs due to the 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 in terms of the size based aspects. Collapsible wheelchairs are known to solve the issue of space and mobility during travel. But the seats are known to be rigid and inflexible. This could be attributed to the fact that the seating of the wheelchairs is supposed to sustain the weight of the patients using the wheelchairs and hence one cannot experiment with the seats in general. Lightweight collapsible wheelchairs have exceptionally light casing that is finished with a foldable element[3]. 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 an extra room for instance. The foldable and light casing has turned out to be famous with wheelchair users who wish to utilize a lightweight wheelchair that can likewise be collapsed for accommodation, and to support the time it takes to perform the daily activities[4]. Collapsible is synonymous with the word Foldable which mean very similar when they are utilized as an adjective to describe the wheelchair. However, Offlate, foldable wheelchairs are available in the market. Such wheelchairs can be carried during travel and help in the mobility of such patients. But there have been issues with respect to the reduction in the size based on the foldability aspects of these wheelchairs[5]. Numerous 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[6]. The edge of the seat is foldable, including the seat. At times, the backrest can be foldable hassocks, or now and again collapsible push bars for parental figure impelled wheelchairs. 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[7]. The capacity of such a wheel would be to overlay or crumple into a little, lightweight plan that can be put away with or joined to a collapsible wheelchair. Whenever required, the wheel can without much of a stretch unfurl, lock into spot, as an auxiliary wheel[8]. 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. 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. for instance, the morph wheel design measures 60 centimeters across and occupies a volume of 22liters[9].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[10].

1. Materials and methods.

Design aspects. The current research emphasized 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. A novel approach was developed to design the wheel by dividing the wheel into six segments. Scissor mechanism was introduced for folding the wheel into a uniform volume, with regard to ease of storage and portability. This wheel, weighing 3,4 kilogram and measuring 80 centimeters, was found to occupy a mere 12 liters of volume when folded against the 22 liters volume which was observed in conventional 4 segment based wheels. This new design of wheel was developed keeping the industrial standards as constraints to fit the quick-release wheel axel and by using solid rubber tiers which are used in conventional wheelchairs. If these tires wear out, then these could be easily replaced with new tyres, 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 about 60 percent of space when needed[11].

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 18 to 58ksi. 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 and 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 where 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 cut into the required size and was drilled with holes at suitable positions[12].

2. 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 wheel chair based applications, two 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. The aspects such as fatigue, creep, modeling and stress corrosion were found to be negligible. 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 with the aid of **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 solidworks, wherein each of the component was subjected to loading. The results showed that a maximum of 800 N could be exerted on the wheel (approx. 80 Kgs). These models were converted to IGES formats for further analysis in Ansys. General meshing was performed as well. These results are shown in the succeeding section

Geometric modeling.

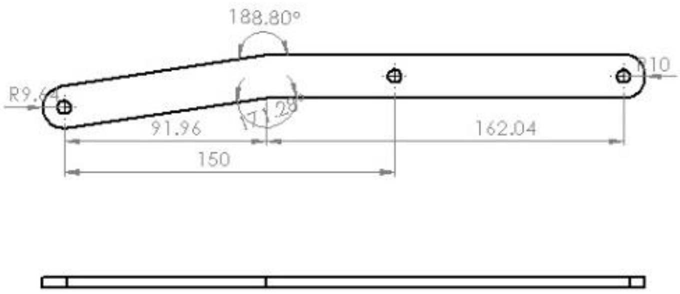

Fig. 1: Arms

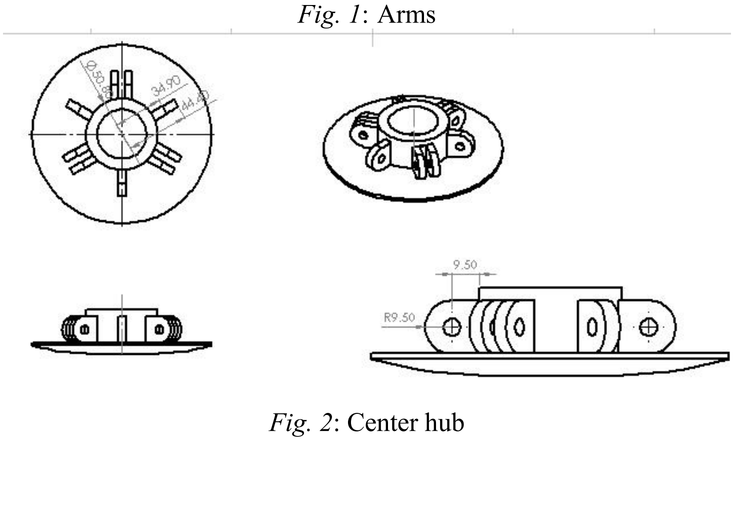

Fig. 2: Center hub

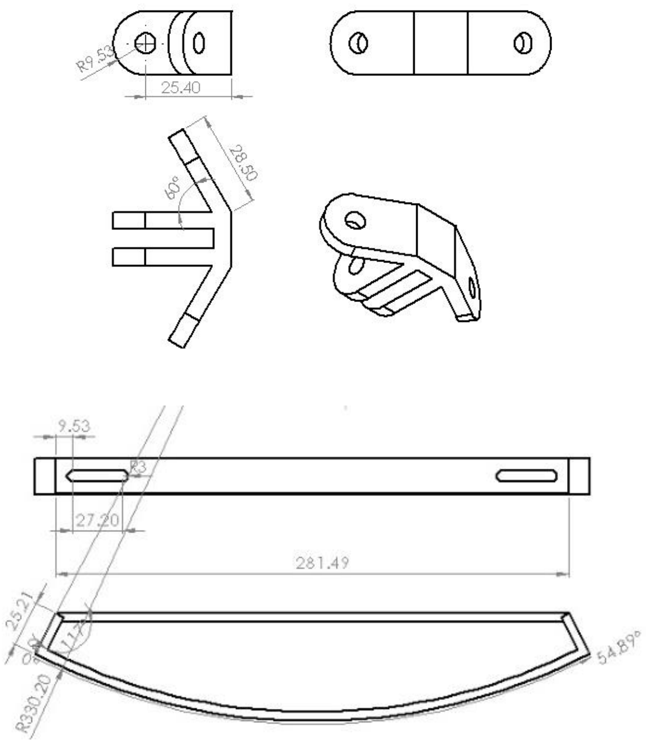

Fig. 3: Flange and Link

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.

Fig. 4 shows the model of the arm subjected to 800N force, which is equal to around 80 kgs, in the Ansys workbench.

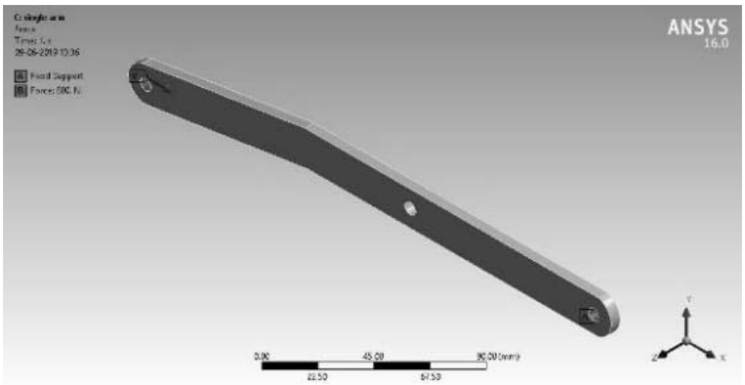

Fig. 4: Arm subjected to 800N Load

Links: Model with Loading.

Fig. 5 shows the model of the link subjected to 800 N force, which is equal to around 80 kgs, in the Ansys workbench. The loading point and the fixed support can be seen at the markers B and A respectively.

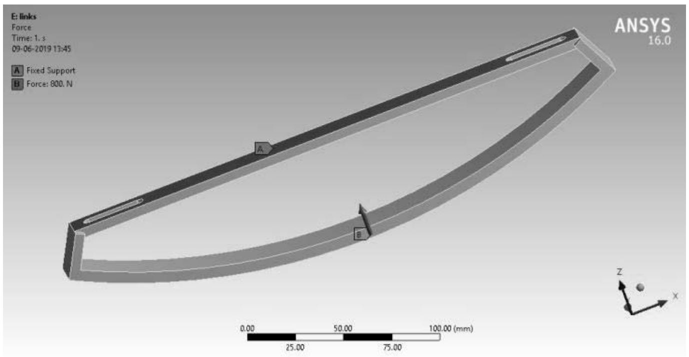

Fig. 5: Link subjected to 800 N Load

Flange: Model with Loading.

Fig. 6 shows the model of the Flange subjected to 800 N force, which is equal to around 80 kgs, in the Ansys workbench.

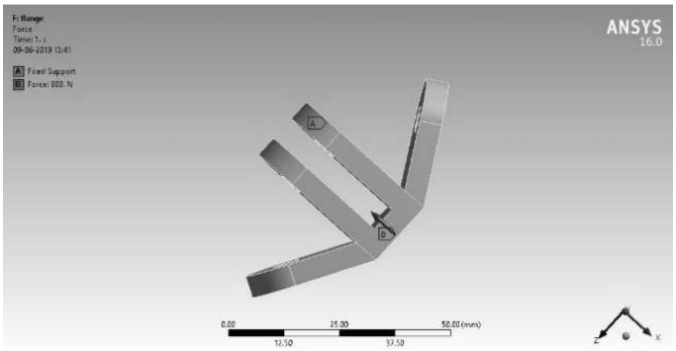

Fig. 6: Flange subjected to 800 N Load

Stress analysis of the wheel: Model with Loading.

Fig. 7 shows the model of the wheel subjected to 800 N force, which is equal to around 80 kgs, in the Ansys workbench.

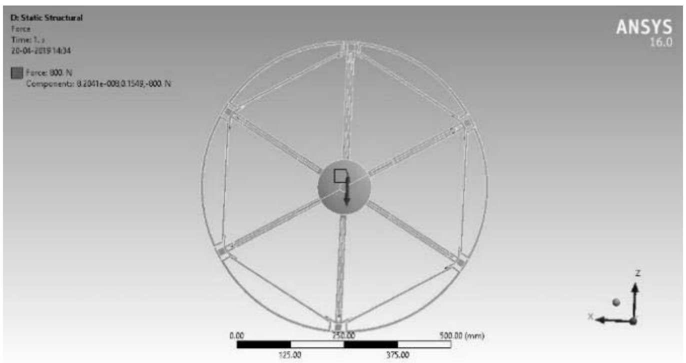

Fig. 7: Wheel subjected to 800N Load

Design Review and Evaluation.

Arm: Final solutions

The solutions that are obtained from this analysis are the Total deformation (fig. 8) and Von-Mises stresses (fig. 9).

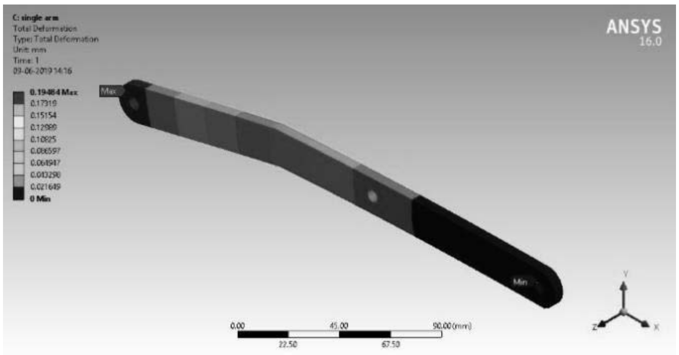

Fig. 8: Total Deformation of the Arm

The Total Deformation of the Arm when subjected to the given load is shown in fig. 8. The maximum and minimum deformation is shown as well. The maximum deformation was obtained when subjected to the load of 800 N i.e., approximately 80 kgs was found to be 1,94e-4 m. Also, the maximum value of Von-Mises stress obtained was 80,92 MPa. The ultimate strength of the material was 290 MPa. Thus, it is evidential that this wheel was safe with Factor of safety greater than 2, even after the application of load of 800 N.

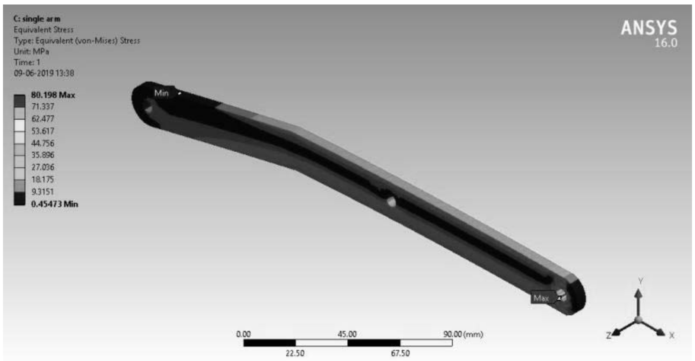

Fig. 9: Von-Mises stress on the Arm

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 fig. 10. The maximum and minimum deformation is shown. The maximum deformation was obtained when subjected to the load of 800 N i.e., approximately 80 kgs is 3,01e-5 m.

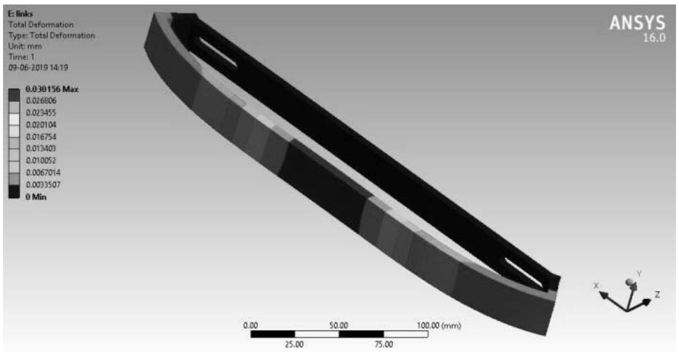

Fig. 10: Total Deformation of the Link

In the analysis of the links, as shown in fig. 11, the maximum value of Von-Mises stress obtained was 50,94 MPa. The ultimate strength of the material was 290 MPa. Thus, it was evidential that this wheel is safe with Factor of safety greater than 2.

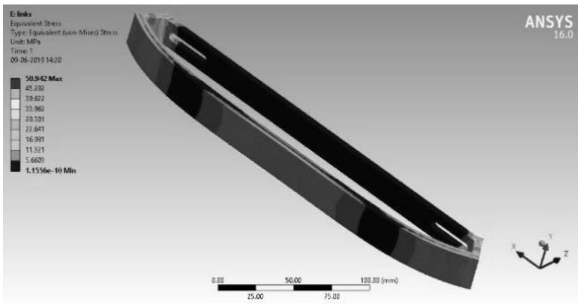

Fig. 11: Von-Mises stress on the Link

Flange: Final solutions.

The Total Deformation of the Flange when subjected to the given load is shown in the fig. 12. The maximum and minimum deformation is shown. The maximum deformation was obtained when subjected to the load of 800 N i.e., approximately 80 kgs is 1,902e-7 m.

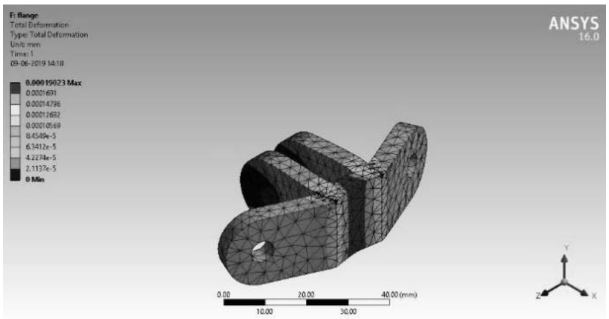

Fig. 12: Total Deformation of the Flange

The maximum value of Von-Mises stress obtained was 8,58 MPa, as shown in fig. 13. The ultimate strength of the material was found to be 290 MPa. The induced stresses were found to be less than the maximum stress of the material. Thus, the design was considered to be safe.

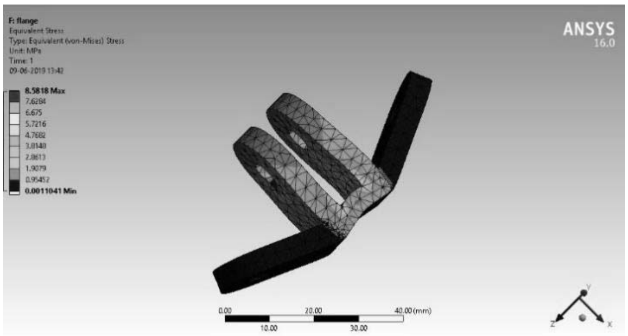

Fig. 13: Von-Mises stress on the Flange

The present analysis showed that the components, when subjected to the load of 800 N 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. A pictorial representation of the same if shown in fig. 14.

Load (in Newton)	Deformation (in meter)
75	0,024507
125	0,049014
250	0,073521
375	0,098028
500	0,14704
625	0,17155
750	0,19606
800	0,22056

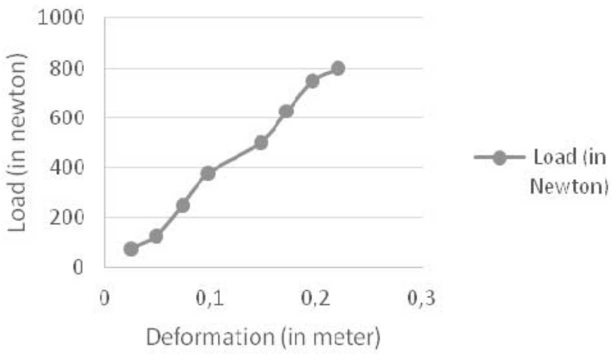

Fig. 14: Load v/s deformation

The Total Deformation of the wheel when subjected to the given load is shown in Fig. 15. The maximum and minimum deformation is shown. The maximum deformation was obtained when subjected to the load of 800N i.e., approximately 80 kgs is 2,205e-4 m.

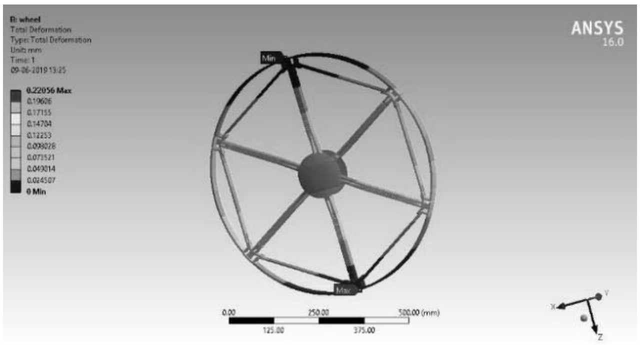

Fig. 15: Total deformation of the wheel

The Von-Mises stress based analysis was performed for the entire wheel and the maximum value of Von-Mises stress obtained was 122 MPa, as shown in fig. 16. The ultimate strength of the material was found to be 290 MPa. The induced stresses were found to be lesser than the maximum stress of the material. Hence the design could be considered as safe.

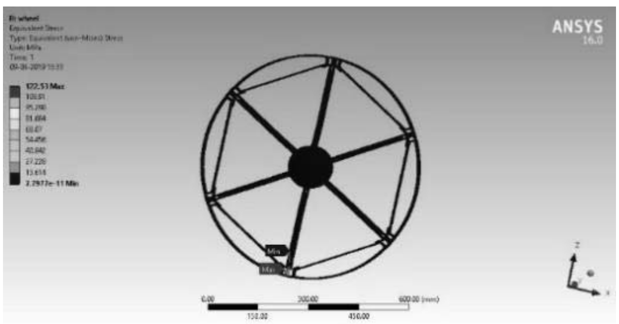

Fig. 16: Von-Mises stress of the wheel

The automated drafting, when the wheel is open and folded, for this wheel is given in fig. 17 and fig. 18, respectively. The final fabricated wheel is depicted in fig. 19, in actual position and in fig. 20, for folded position.

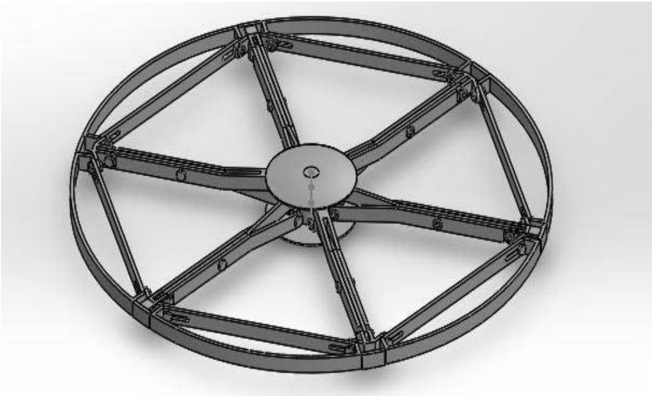

Fig. 17: Automated drafting – wheel expanded

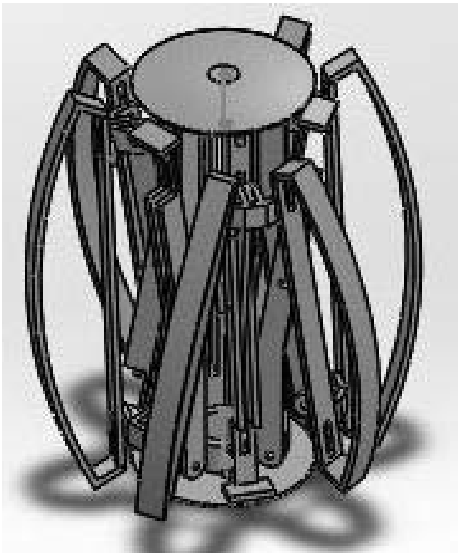

Fig. 18: Automated drafting – wheel collapsed

Fig. 19: Fabricated wheel – expanded position

Fig. 20: Fabricated wheel – collapsed position

Inference.

In the present work, a foldable wheel was successfully developed based on a six-segment design. Such a wheel could be successfully used in foldable wheelchairs. The volume occupied by the currently developed wheel was found to be 1,99X10^6 mm^3 in normal position and 1,2X10^6 mm^3 when in collapsed position. The diameter of the wheel was observed to be 26 inches in normal position and 8 inches in collapsed position and a height of 10 inches when collapsed. 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-misses stress of 122 MPa and the corresponding deformation of 2,205e^{-4} m for a load of 800 N. The ultimate strength of the material was found to be 290 MPa with a safety factor of 3. The results proved that the presently proposed design was safe for the given loading conditions. Since, this wheel was found to be working fine and safe for 800N force, a total of 1600 N could be borne with two such wheels, in the case of wheelchairs, ie, a weight of up to 150 kgs can be exerted on the wheelchair. This work could be extended to the testing of wheelchairs with the presently developed wheels as an extension of the present work.

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РЕЗЮМЕ. Інвалідний візок є чи не найважливішим обладнанням для підтримки пацієнтів із захворюваннями нижніх кінцівок. З появою технологій все більше уваги приділяється портативності та простоті в користуванні з інвалідними візками. Зменшення розміру є величезною проблемою у випадку мобільних інвалідних візків. Хоча більшість досліджень зосереджено на покращенні мобільності та автоматизації руху інвалідного візка, ця робота з'ясовує покращення аспектів згортання інвалідних крісел по відношенню до використовуваних коліс. Це досягається шляхом введення розбірної моделі до колеса, яка зменшує діаметр колеса. Такий підхід полегшує зберігання інвалідних візків з огляду на транспортабельність. Таке зменшення діаметра компенсується відносним збільшенням ширини колеса. Дане дослідження було успішним у розробці такого колеса, яке могло б витримувати вагу до 150 кг при тестуванні за допомогою моделювання. Це колесо було виготовлено з алюмінієвого сплаву 6061 і було перевірено на міцність. Це дослідження може бути в подальшому розширене при розробці інвалідного крісла з електронним керуванням, основаного на розбірній конструкції, щоб допомогти покращити процес реабілітації пацієнтів з розладами нижніх кінцівок і зменшити труднощі, пов'язані з аспектами транспортування.

КЛЮЧОВІ СЛОВА: інвалідний візок, автоматизація, складаність, розбірність, алюміній 6061.

1. *Ellapen T.J., Hammill H.V., Swanepoel M., Strydom G.L.* The health benefits and constraints of exercise therapy for wheelchair users: A clinical commentary // African J. of Disability – 2017. – **6. –** P. 1 – 8.
2. *Viswanathan Pooja, et al.* Smart wheelchairs for assessment and mobility // Robotic Assistive Technologies. – 2017. – P. 145 – 178.
3. *Bertolaccini Guilherme, et al.* A descriptive study on the influence of wheelchair design and movement trajectory on the upper limbs' joint angles // Proc. Int. Conf. on Applied Human Factors and Ergonomics. Springer, Cham, 2017.
4. *Taylor S. J. G., et al.* A lightweight wheelchair propulsion dynamometer for improving user energy efficiency and mobility // Proc. 3rd Int. Conf. on Bio-engineering for Smart Technologies (BioSMART). IEEE, 2019.
5. *Lee Geunho, et al.* Front Caster Capable of Reducing Horizontal Forces on Step Climbing // Proc. Int. Conf. on Big Data Analysis and Deep Learning Applications. Springer, Singapore, 2018.
6. *Flemmer Claire L., Rory C. Flemmer.* A review of manual wheelchairs // Disability and Rehabilitation: Assistive Technology. – 2016. – **11**, N 3. – P. 177 – 187.
7. *Vishnu J., Gopika Vijayan.* Trackball Controlled Novel, Cost Effective Electric Wheelchair // Proc. Int. Conf. on Control, Power, Communication and Computing Technologies (ICCPCCT). IEEE, 2018.
8. *Nakajima Shuro.* Concept of a personal mobility vehicle for daily life // 2016 IEEE Int. Conf. on Robotics and Biomimetics (ROBIO). IEEE, 2016.
9. *Morgan Kerri A., et al.* A motor learning approach to training wheelchair propulsion biomechanics for new manual wheelchair users: A pilot study // The J. of Spinal Cord Medicine. – 2017. – **40**, N 3. – P. 304 – 315.
10. *Mostyn Vladimir, et al.* The synthesis of a segmented stair-climbing wheel // Int. J. of Advanced Robotic Systems. – 2018. – **15**, N 1. – 1729881417749470.
11. *Song Zhibin, Chuanyin Tian, Jian S. Dai.* Mechanism design and analysis of a proposed wheelchair-exoskeleton hybrid robot for assisting human movement // Mechanical Sci. – 2019. – **10**, N 1. – P. 11 – 24.
12. *Gebrosky Benjamin, Jonathan Pearlman, Rory Cooper.* Comparison of high-strength aluminum ultralight wheelchairs using ANSI/RESNA testing standards // Topics in Spinal Cord Injury Rehabilitation. – 2017. – **24**, N 1. – P. 63 – 77.

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