Task: MM-1 Structural Improvements to Manual Wheelchairs

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Rationale

The purpose of this project was to design and develop a novel wheelchair with a unique combination of features. This wheelchair design was intended to address a market need for a wheelchair capable of folding compactly for stowage (e.g., overhead compartments during commercial air travel), accessing narrow passageways and other areas requiring a compact profile and footprint, and providing a high degree of maneuverability. Our intent was to design an "Enhanced Access Wheelchair" to achieve these capabilities without sacrificing the performance characteristics essential for everyday use (Figure 24). We also attempted to determine the feasibility of incorporating fiber reinforced material technology.

Figure 24 - Enhanced Access Wheelchair.

Goals

The goals of this project, as originally proposed, were to design, fabricate and evaluate an aesthetically pleasing, general-purpose wheelchair that could be easily stowed, manipulated and maneuvered through narrow corridors. The conceptual design was proposed to meet this objective by providing several important features:

- Compact folding frame;
- Light weight (using composite materials);
- Three position (anti-tip, rear support and folded) auxiliary wheels; and
- Attractively shaped solid side frame members that allow for subtle incorporation of mechanisms like brakes, releases and structural members.

Three prototype wheelchairs were designed, fabricated and tested in the course of this project. The final design incorporated side frame members made from inexpensive, molded thermoset materials. Other frame components were eventually machined individually from aluminum stock due to difficulties with machined composite parts. It was (and is) our expectation that these parts could be manufactured more efficiently in production models. The dimensions of the folded frame are 5.5 inches wide by 21 inches deep by 12 inches tall with the footrest mounts and main wheels removed and not including the back rest. The wheelchair is shown folded in Figures 25 and 26. Auxiliary wheels are included to allow passage through openings as narrow as 18 inches (overall width is defined explicitly by the seat width) when the main wheels are removed (Figure 27). The development effort has focused on the incorporation of these novel features and manufacturing processes. Weight reduction will be an objective for subsequent design iteration.

An important secondary goal of this project was to demonstrate alternative materials and manufacturing techniques for the production of wheelchairs. Our experience with this option is summarized in the following section of this report.

Figure 25. - Side view of folded wheelchair.

Methods

A CAD design for the prototype wheelchair was executed using CADKEY. This design was exported to a more sophisticated CAD system at Westinghouse Corp. Science and Technology Center where the design was further refined. A structural analysis using ANSYS, a finite element analysis program, was conducted to determine the necessary material strengths for the different parts. Stress analyses were performed on individual components and for an articulated model of the prospective prototype. Upon completion of the design and computer simulation phases, the project proceeded to the development of the physical prototype. Thermoset materials were considered as a low-cost production option for wheelchair structures.

Inexpensive, molded thermoset materials offer several advantages for use as low cost wheelchair structures. Two major disadvantages are manufacturers' lack of experience with thermoset molding and the high initial cost of molds. Both of these problems were considered in this project.

The structural elements of the wheelchair were designed as compression molded, glass filled polyester components. One reason for this selection is the very low cost of this material. It is used commonly in industry for electrically insulated structural parts. Since it is an engineered plastic, an entire range of material strengths, weights and costs are available. This allows for trade-off between weight and cost in the design and manufacture of wheelchairs. The basic design and geometry of this wheelchair was defined substantially by the novel folding mechanism of the chair and by common structural requirements for wheelchairs.

A few iterations of weight reduction analysis were done on the parts to save some material. Considerably more refinement is possible. The chair was modeled as plate elements and loaded with a 200 kg dummy at 3 g's. Consideration was given to both the maximum von Mises stress and the maximum deflection. Acceptable deflection was based only on assumed aesthetic perceptions for the prototype development. The stress limit was determined from isotropic treatment of the maximum allowable tensile stress.

Figure 26 - Folded (front).

The high cost of mold fabrication precluded mold development for parts other than the side frame. Parts were initially machined from sheet stock. This decision was made with the knowledge that machined composite parts typically have structural strengths on the order of 40% less than comparable molded parts. This loss of strength is well documented and results from surface cracks and defects left from milling the smooth, fiber free surfaces. The use of machined composite parts proved not to be a viable solution in subsequent testing. The parts (other than the side panels) were subsequently machined from aluminum sheet and bar stock.

Figure 27 - Side view with main wheels removed.

The molding technology chosen for this project is based on spray metal tooling. This technique for mold making takes about a month and costs less than $8,000. This process is rather new and has seldom been used on compression molded parts of this size. Only 20 to 150 parts would be expected from this tool. By contrast, standard mold construction (using steel) for comparable sized parts would require 4 to 6 months to complete at a cost on the order of $70,000. These steel molds could be used to produce 500,000 to 5,000,000 parts. Standard aluminum molds are less expensive ($45,000), quicker to machine (approximately 3 months), and would be suitable for producing 5,000 to 25,000 parts. The project provided an opportunity to consider the efficacy of compression molded parts at modest cost.

The mold was fabricated over the course of 8 weeks and was received at Penn Compression near Pittsburgh, PA. The mold was made from a wood model of the final part, which was placed in an inert bed up to the mold parting line. An electric spray head was used to sputter-coat thin layers of a zinc-aluminum alloy onto the pattern. Zinc-aluminum wire is fed into the spray head and electrically melted. Repeated layers of sprayed metal were applied until a shell was created from 1/8 to 1/4 inch thick. This shell was backed with an aluminum-filled epoxy to provide strength and stiffness and placed into a cold rolled steel frame about 1/2 inch thick. This process was repeated to form the other half of the mold. Unfortunately, the mold was incorrectly developed as a conventional injection mold, rather than as a compression mold. For injection molding the mold is parted at the midline with two symmetrical (in this instance) halves that are held in opposition while material is injected. In contrast, a compression mold has a “force” component and a “cavity” component as the two “halves.” Without a force and cavity, it was difficult to assure that sufficient material would be incorporated into the mold to fill the part. After six attempts the proper charge of bulk molded material to fill the part was determined. After the third piece was molded, the ejector system failed and the molder was forced to pry subsequent pieces out of the mold using hand tools. This was difficult, as the mold must be stabilized at 350 degrees before the molding process can begin. The failure required a modification of the mold. It became necessary to machine away extra material. This ultimately weakened the parts.

Figure 28 - Narrow access.

The molded side-frame had four "through holes," including a 1" diameter main axle hole and three 1/4 inch diameter holes to stop the auxiliary wheel in its various positions. Of the parts produced, five did not fill completely and several others were broken while being ejected from the tool. In the end, six acceptable parts were made, allowing for the assembly of three prototypes.

Prototype assembly

Fabrication of an initial prototype resulted in the discovery of weaknesses in the original design. As a result of the initial fabrication phase, a substantial number of the components were redesigned with the goal of increasing the structural integrity of the wheelchair frame. The modified designs were used to fabricate two additional prototypes, which were evaluated using applicable ISO standard test procedures. The modified version is shown in Figure 29 and 30.

Figure 29 - Assembled Prototype.

ISO Test Evaluation of the prototype

The first of the modified prototypes was tested according to ISO 7176-8 (Wheelchairs - Part 8: Requirements and test methods for static, impact and fatigue strength). The chair passed all static and impact strength tests with the exception of armrest upward weight bearing. The armrest upward force test is not applicable to our design since the armrests were designed to release with upward force. The chair successfully completed 200,000 cycles on the two-drum fatigue strength test without failure, but failed after 2055 cycles of the curb drop test. This failure was a fracture of the side frame where the footrest and front caster wheels are attached. Prior to the testing, we observed cracks in the frame resulting from a poor fit between the molded side frame and the footrest/caster wheel mount. It will be necessary to address this area of structural weakness in the design of future prototypes using molded components.

Consumer Evaluation of the Prototype

Initial evaluation was provided by an experienced wheelchair user and resulted in several comments and suggestions:

- The concept of the design is attractive. The ability to remove the rear wheels and use 8 inch auxiliary wheels to roll down an airplane aisle or in a small rest room would be useful. (Figure 28)
- The ability of the chair to fold and break-down into small components makes it attractive for storing in overhead compartments of aircraft or in compact automobiles.
- The folding mechanism is awkward and cumbersome. The wheelchair can become difficult to fold if the central pin loses alignment with the cross-braces. The dovetail joints bind and are prone to jamming from dust and dirt.
- The wheelchair is much too heavy. The materials need to be changed and the overall design lightened.
- The wheelchair is too tall and the leg rests are positioned too far forward.
- The auxiliary wheels do not perform adequately as anti-tip devices and are cumbersome to use.
- The wheelchair and center of gravity are not adequately adjustable.
- The backrest folding mechanism is bulky and does not provide adequate lateral stiffness.

- The chair has multiple pinch points that need to be eliminated
- The wheelchair provides a proof-of-concept and would require additional refinement prior to being acceptable to consumers.

Figure 30 - Front view of assembly

Several of these problems have already been addressed. For example, the seat was redesigned to eliminate the possibility of pinching while it is being opened. The backrest support brackets were redesigned since this initial evaluation was made. Amelioration of all other shortcomings is being considered. The design will require further iteration to become viable for commercial development.

Outcomes Summary

Our initial impression of the prototype relative to its performance is positive. The solid seat together with the cross braces and side frame members form a support structure that feels significantly more rigid than typical "X" cross brace frame, folding wheelchairs. Even with the large main wheels removed for narrow access, the wheelchair was sturdy and stable. In informal trials in our laboratory, varying users have found the chair's performance to exceed their expectations for a folding frame wheelchair. A formal beta test program will be developed as the next stage of development. Although the concept of a compactly folding wheelchair that allows access to narrow corridors and is rigid and durable enough for everyday use is now several years old, there is still considerable need for such a product by many wheelchair users. As a result, we feel that the market potential for a wheelchair with these features is still significant. This initial funding provided the basis to take the most critical step in the research and development process: from conceptual design to full-scale working prototype. There are still several important engineering problems to solve before the eventual development of a commercial product; however, we have successfully demonstrated the feasibility of producing the wheelchair for enhanced access. Although it was not our primary objective, we have also shown the possibility of using parts manufactured with inexpensive techniques and materials.

<u>External Evaluation</u>

A more thorough demonstration and evaluation was conducted by the RERC on Technology Transfer at SUNY Buffalo. The Enhanced Access Wheelchair was evaluated by three focus groups of 30 consumers who had used a manual wheelchair for a minimum of five years. Some general results from comparisons with existing commercial products were particularly encouraging:

1. 55% of the consumer participants preferred the prototype to existing products.
2. Consumers were willing to pay up to $200 more for the features incorporated in the Enhanced Access Prototype.
3. Consumers increased the additional amount they would pay for the prototype features to $370 (mean) after viewing the features of a competing, production model wheelchair.
4. Among features valued by the consumers were the folding mechanism, the folded size, and the 3-position deployment of the auxiliary wheels, the "solid" seat, and the aesthetics of the side-frame. Disadvantages identified included the imprecision and "awkwardness" of the mechanisms, the overall weight, and the lack of tie-down points. Suggestions were generally on ways to improve the mechanisms and decrease

the weight. One of the strongest preferences for the prototype over production folding chairs was the folding mechanism. It was perceived to be more stable and to allowed more compact folding.

Recommendations for Future Development

The project has progressed to the point of successful demonstration of several valuable features of a manual wheelchair. We believe that the evaluation information is sufficiently positive to warrant further development. Initial plans for a second generation prototype have been completed. We believe that it will be necessary to produce a metal frame model to gain the interest of current manufacturers. If we can obtain additional funding for this project we shall proceed with development of an all metal prototype in which we shall refine the mechanisms and reduce the weight of the wheelchair as suggested by the consumer panels.

Publications and Technical Reports

Brienza, DM, CE Brubaker (1996) Design and Development of a Wheelchair for Enhanced Access, *RESNA Proceedings*, 16:250-252.

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