Summary

The case at hand involves a wheelchair that is manufactured by Enduro Titanium of Connecticut (see Figure 1). This particular wheelchair was provided to Group YVM by Adaptive Design Services of Northampton in order to come up with a solution to prevent the constant failure of a particular L-Brace that connects the backrest of the wheelchair to the seat cushion.

The L-shaped bracket that connects the wheelchair backrest and seat cushion failed at the point where the triangular rib intersects the bottom half of the L-brace (see Figure 2). The analysis of the L-brace was broken down into the determination of significant forces acting on the member; hand calculations of the stress with a focus on the “critical area;” finite element analysis using Pro-Mechanica; calculation of Fatigue stress and fatigue life; and comparing and contrasting the hand-calculated stress values versus the computer derived stress values.
After speaking with the specialists at Adaptive Design Services of Northampton, it was established that the cause of failure of the L-brace occurred from considerable backward thrust motions on the backrest of the wheelchair. These backward thrusts are a result from the man who uses this particular wheelchair. The man is a significantly strong individual that is prone to having seizures that produce convulsive muscle spasms. When the man exerts enough of a force backwards, the L-Brace that connects the seat to the backrest of the chair fails. A quick observation of the operating environment at hand revealed that the continuous thrusting motion over a period of time could cause significant fatigue stresses at the “critical area” in question (see Figure 2).

Introduction

A failed L-brace support from a wheelchair has been analyzed. The focal point of this investigation was the “critical area” of failure, the point at which the triangular rib meets the bottom half of the L-brace (See Figure 2).

The purpose of the L-brace is to allow the backrest to collapse onto the seat when not in use (see Figure 3) and to lock the backrest in an upright position within a range of 95-105 degrees when the wheelchair is in use (see Figure 4). The L-brace is the primary support unit that stabilizes the wheelchair in the upright position.

Figure 3: Photograph of wheelchair in collapsed position
Failure of the L-brace can have devastating results. Most likely, the handicapped individual will be caught off guard and hurled backwards as the brace finally gives. This failure can possibly lead to great physical harm of the person in the chair. In addition to the physical harm caused, the ineffectiveness of the L-Brace can cause other damages to the assembly of the wheelchair. These may include, but are not limited to, bending of the attached extruded shafts and damage to the backrest and seat.

Through analysis of the original part’s failure, it is conclusively evident that a redesign is necessary. The first step in determining a redesign is deciding which approach to follow. The perspective of the redesign kept in mind the possibility that the extruded shafts would fail if the L-Brace did not. After careful analysis it was determined that the extruded shafts would not fail since they are currently a safe design and would still be able to withstand loads applied by the individual in the wheelchair. Therefore, increasing the maximum allowable stress of the L-Brace would be the most rational direction to follow in the redesign. Thusly, the redesign involves thickening the width of the triangular rib to match the thickness of the part. This solution not only decreases the stress concentration at the critical point of failure, but also keeps manufacturing costs the same since the overall part thickness has not changed.

It can be undoubtedly seen that the goal of the redesign is cost and safety orientated. With this in mind redesign proposals were analyzed following the original method: determining significant forces acting on the member, hand calculations of the stresses with a focus on the critical area, finite element analysis using Pro-Mechanica, Fatigue stress and fatigue life calculations and comparing and contrasting the hand-calculated stress values versus the computer derived stress values.
Objectives

The goal of this project is to comprehensively analyze the L-Brace structure for the primary forces and stresses that cause the structure to fail. Modeling of the failure conditions is necessary in determining redesign solutions. Both the original L-Brace and redesign will follow a format of analysis, which includes hand calculations, determining maximum stresses, fatigue stresses and finite element analysis using Pro-Mechanica.

Procedure

The procedure followed in the analysis of the L-Brace is as follows:

Forces and Stresses

First the forces were determined from the help of Adaptive Design Services (ADS). ADS informed us that the weight of the man using the chair was approximately 220 lbs. and that it would be fairly accurate to assume that he exerts about double his weight into a backward thrust of 440 lbs. However, since there are two L-Braces, this force can be divided in half between the two braces. In effect, each brace is therefore acted upon by 220 lbs. Using a simplified model of the L-Brace (see Figure 5), an approach for calculating the stresses was formulated from the force application. The red region below is constrained from moving in all directions because the only movement that is important is the movement between the vertical and horizontal members. Therefore, keeping the horizontal member stationary while moving the vertical member provides a close model that allows us to calculate the forces and moments.

![Figure 5](image)

Red region is constrained from moving in any direction
Finite Element Analysis

Having determined the applicable forces and figuring out the most realistic representation of forces for the software, the load conditions and constraints were entered into Pro-Mechanica. In order to illustrate the load conditions occurring, the load of the backwards thrust was entered in as a distributed force because a snug fit exists between the L-Brace and extruded shafts.

Results

Results were reached both from hand calculations and computer analysis. Both sets of values were analyzed and compared. Also the results of the redesign were compared to that of the original design.

Conclusions

Conclusions were made after detailed comparisons of both the original and redesign. Keeping with the established goals of this project, a decision was made on whether to keep the original design or move forward with the redesign.

Analysis

After careful analysis and inquiry to ADS and Enduro Titanium, it was made clear that the probable causes of the L-Brace’s failure are fatigue stresses due to everyday operation of the wheelchair and stresses due to the application of the 440-pound force on the seatback. Though both the seat cushion tube and the seat back tube move relative to the ground, the only movement that is of importance to the L-Brace is how the beams move relative to one another. As a result, we can assume that the seat cushion beam is fixed in place, and that the only movement will be the seat back tube rotating clockwise about the pin-hinge (see Figure 6). This movement is due to the subject pushing against the back of the wheelchair with an approximate force of 440 lbs (1957 N), which was explained in the previous section. As a result, there will be a high stress concentration at the location where the triangular rib intersects the bottom half of the L-Brace, which is where the part failed.

Figure 6

![Figure 6](image)
As shown in the figure above, the red region, which is where the L-Brace is in contact with the seat cushion beam, is constrained in only the x-direction. This constraint is due to the tight fit of the brace to the seat cushion tube, which prevents the brace from moving side to side. The blue region, which is where the L-Brace is bolted onto the seat cushion tube, is constrained in all three directions. This constraint is because the bolts and pin-hinge prevent the brace from moving at all.

**Hand Calculations**

The point of failure in question, the location where the triangular rib meets the lower portion of the L-Brace had to be separated from the entire part. This was done due to the complex geometry of the part. By separating the triangular rib from the part, the stresses can be calculated by treating the rib like a cantilevered beam (see Figure 7c).

Since the rib is attached to the horizontal and vertical members of the L-Brace, the forces acting on the rib can be modeled as variable distributed loads (see Figure 7a). Since the L-Brace is in static loading, the reactive load can be calculated (F). Once force F is calculated, the rib can be treated as a cantilevered beam, with side B as the beam and side A as the wall (see Figure 7b).

**Figure 7**

![Figure 7a](image1.png)  
**Wall (A)**  
**Beam (B)**  

![Figure 7b](image2.png)  
**Moment at critical region = 475 N-m.**  

![Figure 7c](image3.png)
Force Calculation of Original Design – Bending Moment Stresses

Resultant of distributed load on wall B = 12,118 N

M at critical region = 475 N-m

h = 0.0825 m

b = 0.003 m

c = h/2

I = bh^3/12

\[ \sigma_{\text{MAX}} = \frac{Mc}{I} \]

\[ \sigma_{\text{MAX}} = 139.5 \text{ MPa} \]

Fatigue Calculation of Original Design – Stresses and Cycle Life

M = 475 N-m

\[ \sigma_{\text{MAX}} = 139.5 \text{ MPa} \]

From Appendix2, the Tensile strength of 13% glass reinforced Zytel is 103 MPa

\[ S_u = 103 \text{ MPa} \quad S'_n = 0.5(S_u) = 51.5 \text{ MPa} \]

\[ S_n = S'_n(C_L)(C_G)(C_S) \quad C_L = 1, \ C_G = 1, \ C_S = 0.7 \]

The value for C_S was approximated since there were no accessible tables to calculate it from.

\[ S_n = 51.5(1)(1)(0.7) = 36.05 \text{ MPa} \]

There is an alternating force as the man pushes and releases on the seatback. This force is an alternating force of 440 pounds (1957.2 N) that is divided between the two L-Braces. Therefore, each L-Brace experiences an alternating force of 220 pounds.

I disregarded a concentration factor (K_f) because there was no way to calculate a K_f for the geometric change at the location of the intersection of the triangular rib and the horizontal bar.

\[ 10^3\text{-Cycle Strength} = 0.9S_u = 0.9(103) = 92.7 \text{ MPa} \]
We now draw the constant-life fatigue diagram for the L-Brace

Equation of line AB is \( y = (-0.35)x + 36.05 \)

Looking at the constant-life fatigue diagram, the stresses (139.5 MPa) that the L-Brace is subjected to is much greater than the stress at the \( 10^3 \) life cycle. Therefore, we conclude that the L-Brace fails due to static loading and not fatigue stresses over its life of operation. Knowing this, attention is then turned to the hand calculations and the FEA results.

**Finite Element Analysis**

For our Finite Element Analysis, some simplifications were made in order to reduce the complexity of the analysis. These included suppressing insignificant ribs, rounds, and chamfers, as well as replacing the moment with a comparable increase in the distributed load. The suppressing of the insignificant features is allowable because they do not drastically alter the results of the stress analysis. As stated early in the Analysis section, two constraints were applied to the L-Brace. Though in actuality the bolts and the base beam acted as forces on the L-Brace, for modeling purposes in Pro-Mechanica
these forces were treated as constraints. This is a realistic approach since the bolts and the beam only act as reactant forces due to the backward thrust force of the man. As constraints, they will also act as reactant forces in Finite Element Analysis, thus creating a realistic representation of the actual scenario.

The only simplification that may cause a notable discrepancy in the stress calculation is the elimination of the round between the triangular rib and the bottom half of the L-Brace. Although the stress concentration will vary slightly due to this simplification, it is impractical to manually determine this difference quantitatively.

As was stated earlier, the only force acting on the L-Brace is the man’s backward thrust. This force was calculated to be 1957 N, and the point where this force is being applied is 0.66m away from the pivot point. In order to account for the moment created by the backward force, the variable distributed load (see Figure 8) that was applied to the L-brace was increased. Despite the fact that this greatly increased the shear forces that were acting on the L-Brace, it was more important to accurately represent the moment caused by the backwards thrust since this part will fail due to the stress caused by the bending moment rather than the shear forces.

Appendix 4 reveals that the stress concentrations and the maximum principal stress occur at the joint of the rib and the horizontal member. This location concurs with the location of fracture on the original piece and also with the suspected “critical area” of the hand calculations. Summarized below is a comparison of hand calculation and FEA results. As can be seen from the two values, the results from the FEA are larger by 4%. This difference is due to the inclusion of the stress concentrations at the critical region by Pro-Mechanica. Also, the calculated stresses at the critical region are higher than the yield strength of the material.
Table 1

<table>
<thead>
<tr>
<th>Method</th>
<th>$\sigma_{\text{max at rib}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hand Calculations</td>
<td>139.5 MPa</td>
</tr>
<tr>
<td>FEA (Max Principal)</td>
<td>145 MPa</td>
</tr>
</tbody>
</table>

Redesign

The primary focus of the redesign was centered on preventing the brace from failing. Failure occurred from static loading, not from fatigue. The chosen redesign solution is increasing the thickness of the rib from 0.003m to 0.0045m (See Figure 9). Also, to assure a reasonable safety factor, the material was changed from 13% glass reinforced Zytel with a tensile strength of 103 MPa, to a 33% glass reinforced Zytel with a tensile strength of 143 MPa.

Figure 9

![Original Design](image1.png) ![Redesign with thicker rib](image2.png)

FEA and Hand Calculations for Redesign

Appendix 5 displays the redesign Finite Element Analysis. The redesign was loaded and constrained the same as the original design, and it can be seen that the stress is experienced at the same location, but at a decreased value. For the hand calculation, the same methods and equations were used as the original model. However, with an increase in the thickness of the rib, the “b” value increased from 0.003m to 0.0045m. Summarized below are the values obtained from the FEA analysis and the hand calculations. The results from the FEA are larger by 6.4% because Pro-Mechanica takes into account the
stress concentrations at the critical region. Note that the stress at the critical region is now less than the yield strength of the material.

Table 2

<table>
<thead>
<tr>
<th>Method</th>
<th>$\sigma_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hand Calculations</td>
<td>93.1 Mpa</td>
</tr>
<tr>
<td>FEA (Max Principal)</td>
<td>99.1 Mpa</td>
</tr>
</tbody>
</table>

Fatigue Calculations of Redesign – Stresses and Cycle Life

According to hand calculations, $\sigma_{\text{max}} = 93.1$ MPa

From Appendix 3, the tensile strength of 33% glass reinforced Zytel is 143 MPa.

$S_u = 143$ MPa $\quad S'_u = 0.5(S_u) = 71.5$ MPa

$S_n = S'_u(C_L)(C_G)(C_S) \quad C_L = 1, C_G = 1, C_S = 0.7$

The value for $C_S$ was approximated since there were no accessible tables to calculate it from

$S_n = 71.5(1)(1)(0.7) = 50.05$ MPa

There is an alternating force as the man pushes and releases on the seatback. This force is an alternating force of 440 pounds (1957 N) that is divided between the two L-Braces. Therefore, each L-Brace experiences an alternating force of 220 pounds.

A concentration factor ($K_f$) was disregarded because there was no way to calculate a $K_f$ for the geometric change at the location of the intersection of the triangular rib and the horizontal bar.

$10^3$-Cycle Strength = $0.9S_u = 0.9(143) = 128.7$ MPa

\[ S_{10^3} = 128.7 \text{ MPa} \]

\[ S_{10^6} = 50.05 \text{ MPa} \]

We now draw the constant-life fatigue diagram for the L-Brace
Equation of line AB is $y = -0.353x + 50.5$

Looking at the constant-life fatigue diagram, the stresses (93.1 MPa) that the L-Brace is subjected to is much lower than the stress at the $10^3$ life cycle but higher than the stress at the $10^6$ life cycle. Therefore, the redesigned L-Brace would eventually fail due to fatigue; however, the number of backward thrusts that the individual produces is highly unlikely to ever reach the cycle necessary for failure.

**Conclusions**

At the onset of this project, it was assumed that fatigue was the likely cause of failure. After careful inquiry into the situation at hand, it was revealed that the failure of the L-Brace was due to static loading rather than fatigue stresses. The maximum principal stress at the critical location is also greater than the tensile strength of the material.

In the redesign, the failure will be due to fatigue stresses over the operation cycle of the wheelchair. However, as noted above, the individual using the chair will probably never be able to produce enough backward thrust motions to ever reach the cycles needed for failure of the brace. Also, the maximum principal stress at the critical location is much less than the tensile strength of the new material. Below is a table comparing the attributes of the original L-Brace and the redesigned L-Brace. A safety factor of 1.6 can be incorporated into the redesigned L-Brace since the calculated maximum stress is 93.1 MPa and the tensile strength is 143 MPa.
For our purposes and limitations, the forces and constraints acting on the L-Brace were simplified into a less complex model that could be evaluated using the current knowledge and software. The analysis shows that the redesigned L-Brace, if undertaken, is a viable replacement for the current one. The redesigned brace is stronger and would be able to withstand the repeated loads applied to it without failing. Group YVM recommends the redesign; however, it is advisable that further research and tests should be conducted before any redesign changes are implemented.