Advanced Composites

Design and Manufacture of a Combined Wheelchair and Tricycle

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Abstract
Focusing on the design of an advanced wheelchair and tricycle, this project investigates devices available to disabled users and looks at the design of a modern, performance option aiming to improve the usability of a tricycle by making it no longer necessary to leave the wheelchair to experience the attributes of a purpose built recumbent tricycle.

The design process is worked through and finite element analysis begun, along with a look into manufacturing options for both workshop and commercial production.
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1. Introduction

This project aims to expand on three previous projects that investigated composite materials, manufacturing processes in the Lab, and the material properties, comparing physical specimens to FEA analysis. All the projects were aiming to work towards the completion of a design for a composite wheelchair with the ability to convert to a performance orientated tricycle for disabled users without the need to get out of the chair.

The first project climaxed in the design of the front triangle section of a composite full suspension mountain bike. A bike frame was chosen due to the more simplistic side of the analysis of a 2-D frame as opposed to a 3-D frame associated with a wheelchair.

The other two projects focused predominantly on the composite material properties and the comparison between physical testing and simulation using Abaqus Finite Element package, as well as the manufacturing of the bike frame from the first project.

This project focuses on the design of the wheelchair and method of transforming it from regular wheelchair into a recumbent tricycle. Additionally the method of manufacture both in the workshop and on a commercial scale will be considered. The project will aim to conclude with a basic Finite Element Analysis (FEA) of the chosen wheelchair frame design.
1.1 Objectives

The projects objectives began with a simple initial goal to design a composite wheelchair that converts to a recumbent tricycle, but expanded as the project progressed:

- Research user group for combined wheelchair and tricycle
- Investigate current tricycle options available for disabled users
- Devise a product specification
- Design a wheelchair to meet the product specification
- Model design using Computer Aided Design (CAD)
- Convert design to a format suitable for FEA
- Work up to FE analysis of wheelchair frame
2. Research

2.1 User Group

2.1.1 Categorisation of Injury

When designing a new product it is important to understand the target user group, particularly with a product designed for a disabled user, as an awareness of abilities and limitations is essential to come up with a suitable design.

An understanding of different types of disability that would require the use of a wheelchair first needed to be gained. Basic research was carried out on the area using medical sources on the internet, as only a level of understanding of what types of disability there are was required and what limitations they result in.

From the Brain and Spine Foundation website, paralysis is the term given to loss of power to move a body part, as a result of injury or disease to the nerves supplying the muscles. When used in its correct context, would imply the complete loss of ability to move and use the effected limbs. There are two main sub types of paralysis that could lead to the need to use a wheelchair, paraplegia and tetraplegia. These both come in different levels of severity dependant on the area of the spine that is injured. Paraplegia refers to paralysis of the lower body, i.e. the legs, and tetraplegia refers to paralysis of the lower body and the upper body with varying degrees of severity.

Paraplegia refers to spinal injuries in the trunk region with the classification T-1 to T-12 (Figure 1). These refer to the region of the spinal cord injured and directly relate to the level of paraplegia. For all levels of the paraplegia there is use of the hands and arms, with trunk movement increasing towards T-12, with those at the latter end of the scale potentially able to walk assisted.

Tetraplegia relates to injuries in the cervical (neck) region, classified C-1 to C-8 (Figure 1). Lower cervical injuries C-7 and C-8 are the only ones that would allow enough arm movement to independently use a manual wheelchair, with functional triceps and increased grip strength.

There are a number of injuries that can lead to the above levels of paralysis, but knowing what levels of paralysis the chair is being aimed at is more important from a design perspective than the injury or disease which led to it. With this in mind, based on the goal of the project, the likely users will be those with C-7 or C-8 tetraplegia and all levels of paraplegia.

1 http://www.spinalinjury.net/
2.1.2 Potential User Interview

As part of the early stages of the project a visit was made to the Southern General Spinal Unit where a Functional Electronic Stimulation (FES) cyclist goes to use the facilities. FES is the use of electronic stimulation of the leg muscles to provide enough stimulation to allow pedalling with the legs for someone who otherwise would have little or no use of their legs. This is an alternative to the use of a hand crank setup where pedalling is done with the arms, or both methods can be used together depending on the tricycle setup.

From the interview with the FES cyclist, it was established what the key areas were to focus on in the design. Independence was found to be one of the most important aspects to the user, and focus on how this could be aided with careful design consideration would be key. This includes the ability to manoeuvre the chair while seated in it effectively, being able to dismantle and lift the chair from out with it such as when getting in and out of a car, and also the conversion from wheelchair to tricycle whilst still in the chair. Design factors to be considered to fulfil this included weight minimisation, dismantling and folding the chair, what adjustments can be made whilst in the chair.

The FES cyclist would use a regular recumbent tricycle (shown in current products sections) which featured a low riding position compared to a wheelchairs seat height, a more laid back seating position, and had the wheels spread further apart and the axle of the rear wheels behind the seating position for increased stability. He also mentioned that the chair would also have to be suitable for everyday use including obstacles such as doorways putting limitations on the overall width of the chair. Design factors to be considered here would be stability, emulating a recumbent riding position, and size limitations.
2.2 Current Products

There are a number of different products available on the market at the moment that could be used by a disabled user for the purpose of a tricycle. The extent to which these are suitable for purpose varies and there must be an awareness of alternative products to ensure a unique design with a potential market that is not already being capitalised on is available.

Current products tended to fall into two categories, designs for fully able users converted or used as is for a disabled user, or designs specifically for a disabled user.

2.2.1 Non-specialised Tricycles

One category of non-specialised tricycles that could be used was recumbent tricycles. It is one of these that the FES cyclist at the spinal unit uses. These come in two forms, either with the 2 wheels at the front or the rear. The benefit of the 2 rear wheel set up (Figure 2) is an ease of accessibility as far as getting in and out of the seat, and it was this configuration that is used by the FES cyclist. These designs tend to be very stable due to the wheelbase (long and wide) and a low recumbent seating position. Disadvantages are that they can be awkward to get in and out of, with controls in the way and a lower seat position than a regular wheelchair.

![Figure 2 – Recumbent Tricycle with 2 rear wheels](http://www.bicycleman.com/recumbents/trikes/hase/hase-KettWiesel-recumbent-trikes.htm)
2.2.2 Disability Specific Tricycles

Berkel is a company which specialise in disability specific tricycles, with a range of products aiming to cater for a variety of needs.

These include the Berkel Bike Classic (Figure 3\(^3\)), which is a front attachment for a standard wheelchair featuring a single wheel powered by a foot pedal and hand crank system. Berkel have a system known as Impulse which is a form of FES allowing the users legs to get a workout and aid the hand cranks. This system attaches on to the front legs of a standard wheelchair, allowing the user to remain in the chair rather than transferring to another device.

![Figure 3 – Berkel Bike Classic](http://www.berkelbike.com/)

The Berkel Bike Pro (Figure 3\(^4\)) is a purpose built hand crank tricycle utilising similar features to the Classic. As a dedicated tricycle, transfer from a regular wheelchair is required; this is assisted by the open access from the side and a seat height similar to a wheelchair. This in turn has the disadvantage of a high centre of gravity which results in instability in corners available on dedicated recumbent tricycles.

![Figure 4 – Berkel Bike Pro](http://www.berkelbike.com/)

\(^{3,4}\) http://www.berkelbike.com/
3. Design

3.1 Design Specification
Using the information gathered in the research a design specification was established to give a guide in the generation of ideas and to keep the design focused. Some aspects of the design were to be more important than others and would get greater focus. The design aims to provide a performance wheelchair that can easily be converted to a tricycle while remaining in the wheelchair by means of a front attachment. The wheelchair should also convert into a more suitable setup for use as a tricycle such as seen in recumbent tricycles. The wheelchair should be suitable, in normal configuration, for everyday use.

3.1.1 Ergonomics: The aspects of ergonomics that need consideration are physiological and anthropometrics. The physiological restrictions on a disabled user will affect their ability to use the chair and any devices associated with it. Anthropometrics will need to be considered to ensure the chair is a suitable size for most users, with suitable adjustments incorporated to allow for different shapes and sizes of users.

3.1.2 Features: Ability to drop chair height while seated. Attach a front pedal unit such as is available from Berkel. Adjust seat back to give a position similar to a recumbent tricycle.

3.1.3 Manufacturing: Manufacturing processes considered in both workshop and for commercial scale. What options are available and which are most suitable.

3.1.4 Materials: As a performance orientated project with a focus on composite materials due to their good strength to weight ratios and ability to tailor their make-up to optimise performance, these should be where appropriate in the design.

3.1.5 Size: The overall wheelchair size will be constrained by the environmental aspects such as doorway widths, and must be able to fold/dismantle the chair to fit into a car.

3.1.6 Safety: British Standards relating to wheel chairs will need to be considered and accounted for. The chair must be able to cope with the static load of the user and also any repeated loadings from its everyday use.

3.1.7 Aesthetics: The aesthetics are not to be a main focus point, but the chair should look appropriate and be appealing.

3.1.8 Cost: Costing to be carried out for workshop prototype and commercial production (material costs) if possible. Use of off the shelf components where suitable.
3.2 Methods for Lowering Height

One of the key features to be incorporated into the design was a method to drop the wheelchair seating position down to one similar to a recumbent tricycle. This was to be done such that the user would be able to lower and raise themselves while in the chair.

In order to make this possible, there needs to be a device installed in the chair to provide assistance in the raising of the seat position. This will need to either be done by storing energy on the lowering process, or by providing additional energy when it comes to raising the seating position.

A number of possible devices were considered for this task and their advantages and disadvantages considered:

3.2.1 Spring: (Figure 5) As spring is a simple device that can will store energy in a variety of ways such as tension, compression and torsion, depending on the type of spring and the way in which it is loaded. By using a spring in its unloaded state when the seat is in the highest position, when lowered down it will store energy which can be later used to aid the raising procedure. If a spring is to be used, a mechanism will need to be devised to make the most of the spring.

![Figure 5 – Torsion Spring](http://www.engineeringtalk.com/guides/torsion-spring.html)

3.2.2 Hydraulic: The use of hydraulics would be effective in raising and lowering the seating position, although the associated equipment required to make it work would over complicate the wheelchair design, as well as taking up valuable space and weight.

3.2.3 Compressed Gas: (Figure 6) This method involves using a compressed gas such as CO2 as found in inflatable lifejackets, and tyre inflators. This could be used in conjunction with a gas spring (Figure 7) similar to what is used in a swivel chair, with the gas cartridges refilling the cylinder and extending the gas spring without having to remove weight as you would have to with a swivel chair. With this option, each cartridge would have a limited number of uses requiring regular replacement.

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5 http://www.engineeringtalk.com/guides/torsion-spring.html

6 http://www.klr650.com/CO2%20Tire%20Pump.htm

Figure 6 – CO₂ Cartridges

Figure 7 – Gas spring from swivel chair

3.2.4 Winch: (Figure 8) Using a winch to raise and lower the seating position is an obvious option and would be the simplest to carry out. The issue with using a winch is mainly its size and weight, two aspects that would be detrimental to the performance of the wheelchair.

Figure 8 - Winch

From the above options for the raising and lowering the seating position, the option of a form of spring powered mechanism was chosen as most suitable. This was due to the simplicity it would bring to the design, along with reliability. From the various types of springs and ways of implementing them, a torsion spring system was considered the best option and the reasons for this will be considered in more detail in the mechanisms section.

http://www.boatwinch.org/boat-lift-winch/
3.3 Concept Development
The wheelchair design was developed with focus on the key issues addressed in the design specification, taking a basic, minimalist frame as a starting point and developing the key features to make it a unique and innovative design around it.

3.3.1 Software
The wheelchair design was done using SolidWorks Computer Aided Design (CAD) software. SolidWorks is a powerful CAD package allowing easy, but concise models to be created in such a way that the user is encouraged to properly constrain their creations ensuring there are minimal issues later in the design process. It allows complete assemblies to be created with options to create animations, useful when demonstrating how a product functions. Further, technical drawings are quick and easy to create from parts and assemblies.

3.3.2 Initial Design
The frame was initially designed as one piece, incorporation a foot rest, mounts for the front wheels and mounting points for the seat (Figure 9). The main frame sections were based around simple cylinders with a view ahead to the manufacturing processes and keeping the design as simple as possible. The basic frame was used to start building up the mechanism for lowering the seating position, the amount of drop to be seen and any interference between components to be seen.

![Figure 9 – Initial Frame Design](image)

The first part of the mechanism to devise is the motion of the drop. The first goal was to provide a height drop, but secondly from looking at the recumbent tricycles, the ability to extend the wheel base for stability would also be desirable. To achieve a change in both height and length simultaneously the ideal choice was a swing arm whereby the wheels are brought from directly below the frame to behind and closer to the frame.
3.3.3 Creating the drop motion
Initially the swing arms were made quite short to understand the motion, and before the height drop aimed for was determined. A small level of drop can be seen in the frame in Figure 10, but not to the extent that would make an effective difference.

![Figure 10 – Short pivot arm raised and lowered](image)

To gain a greater change in height, the length of the swing arms was increased and using a CAD drawing (Figure 11), the drop height of the seat could be determined along with the angle of motion the arm will have to swing through. The CAD drawing created shows the position of the rear wheel at various points in the swing centred around the arm pivot point on the frame. The level of drop was to provide a new seat height similar to that of a recumbent tricycle as well as providing an equal amount of movement horizontally as vertically increasing wheelbase length by a similar amount to the height decrease.

A swing angle of 85° from 5° off the vertical gives a drop of just over 160mm, providing a sufficient change in height.
With the movement for the height drop established, the method for actuating it had to be designed. The use of torsion springs had already been decided upon, but alone would not be enough to provide the raising motion. The proposed user is expected to have a level of upper body and arm strength which could be used to aid in the motion.

By extending the swing arms out the opposite direction, they can act as levers from which the user can contribute to the motion. The length of the arms had to be long enough to bring the handles clear of the wheels. The greater length also provides a greater amount of leverage. Shown in Figure 12 below:
To improve the position of the handles for the swing arms, the lever arms were bent to provide a more appropriate angle for use, providing a movement from full extended arms to approximately 90° as opposed to bring the levers right under the shoulders where optimal strength is not available (Figure 13).

![Figure 13 – Bent swing arm for easier use](image)

### 3.3.4 Frame Refinement

As can be seen from the development of the swing arm, the frame has changed in several respects. The most obvious change is that the foot rest has been made a separate component; this was to allow it to be positioned optimally for different leg lengths using a simple hole and clip method with different position holes on the main frame. The footrest and clip can be seen in Figure 14.

![Figure 14 – Foot rest and mounting clip](image)
Further changes were made highlighted below (Figure 15):

Lugs added to aid initial assemblies with front attachment in SolidWorks

Front well arms changed to simpler form and ends to allow for front wheels to pivot up

**Figure 15 – Stage 2 Frame with mounts for pivot front wheels**

It was recognised that the front wheels would become in the way when the front tricycle section is attached and would need to be removed or stored somehow out of the way. The first solution to this problem was to use a pivot allowing the wheels to swing up and back. An idea that seemed simple, but to get the wells to swing up in reality was not so simple and an alternative solution was sought.

The next consideration was to move the front wheels up and down in line with the front wheel legs. A sprocket and straight gear system was designed to allow this movement, looked at in more detail in section 3.4 Design Features.

The frame was completed with the addition of mounting points for the seat (A), pivot axle (B), and brackets (C) for the locking of the pivot arms in their up and down positions, shown in Figure 16.

**Figure 16 – Final main frame design**
3.3.5 Wheelchair seat
With the frame and dropping mechanisms designed, the final part of the wheelchair to be designed was the seat (Figure 17). In the CAD this was the frame upon which cushioning would be added along with the adjustable angle back.

![Figure 17 – Wheelchair adjustable seat](image)

The seat has several key features:

1. Back angle adjustment via increment arms on inside of side panels
2. Front pivot on base
3. Rear angle selection on base
4. Side panels to protect user from wheels and hold them in the chair

The back angle adjustment can be done from within the chair by simply leaning forward, lifting the arms and moving the back to the desired position.

Note: Another option for back rest adjustment found, but too late to integrate into design, worth consideration in future; a ratchet system (Figure 18⁹) found on kayak back rests and snowboard bindings. This would allow the back rest to be brought forward without taking all the weight off it, and is a much more secure and slick design.

![Figure 18 – Ratchet adjuster for back rest](image)

⁹ [http://www.norfolk-canoes.co.uk/accessories.htm](http://www.norfolk-canoes.co.uk/accessories.htm)
The seat base angle relative to the frame can be adjusted out with the chair using the angle selection arm at the rear of the base, this is an option that will be chosen by the user as their optimal and left, with minor angle adjustments possible of the overall chair using the front wheel height.

3.3.6 Raise/lower procedure
In order to give an idea of what the chair would be like in tricycle mode, a simple front section was designed with just a wheel and attachments to the main frame, as at this stage the intention would be to just use a standard Berkel front end.

With the front end attached, the motions of the chair can be seen along with the steps for conversion to tricycle:

Step 1: Attach front section, Figure 19

Step 2: Lift front wheels (method shown in 3.4 Design Features), Figure 19

Figure 19 – Complete wheelchair with front attachment, Front wheel lift
Step 3: Lower rear wheels using lever arms, Figure 20

Figure 20 – Lowering back end down, showing range of movement
3.3.7 Complete Chair Render
The final chair was rendered in its assembled state to give an impression of how it would look manufacture in predominantly carbon composite, shown in Figure 21.

Figure 21 – Complete Wheelchair Render
3.4 Design Features

3.4.1 Rear end Drop
This is the most standout feature of the design, and so it is important to get it right. The basics of the design have already been described in section 3.3, and so this section will go into more detail of how it works.

![Torsion spring, showing mount for pivot axle](image1)

It was decided to use two torsion springs to create a balanced force between both sides of the chair. These are mounted on an axle that passes through the pivot point for the swing arms on both sides of the chair and through the frame as well. The springs are mounted on the inside of the frame, attaching to the axle via a metal ring with grub screws to hold its position. The springs are then fixed directly into the side of the frame, with opposite direction springs so the rotation that increases torsion is the same for both. One of the spring is shown mounted in Figure 22 and rendered in Figure 23.

![Torsion spring render](image2)
3.4.2 Spring Calculation
The correct size of the spring was calculated using an iterative process starting with the load the spring must take, a rough diameter and the spring material. From this the diameter, wire diameter, and number of coils was calculated. The springs were assumed to take 60% of the load, with the user having to account for the other 40%, this was based on a user mass of 80kg, although due to the design of the spring set up, the spring could be preloaded to account for a larger range of masses. This is done using the attachment for the spring to the pivot axes, rotating the fitting and fixing in place using the grub screws.

The size of spring required was calculated using an iterative process based around taking an estimated initial spring diameter and wire diameter, and then knowing the force it must apply and the range of movement, the spring can be selected.

- The range of movement, \( \theta \), is the angle the swing arm pivots through in radians, 1.48rad
- Two springs, each giving a force of 235.44N based on taking 60% of effort
- Initial spring diameter of 35mm, initial wire diameter of 3mm
- Material selected, ASTM A228, Music Wire

From these initial specifications, through iteration, a suitably sized spring was found with yield strength in the conditions greater than the maximum stress the spring will endure to ensure no failure would occur. The Ultimate Tensile Strength (UTS) for the initial specification was taken from Table 1\(^{10}\).

\(^{10}\) Harrison, P (2010), Lecture notes, Design of Springs Torsion
The yield strength is then found using the value for yield stress relating to chosen material. The spring wire diameter is then updated using the equation for maximum stress:

\[ \sigma_{\text{max}} = K_i \frac{32Fr}{\pi d^3} \]

The ‘d’ value found is then rounded up to the nearest wire diameter available to ensure it is over specified rather than under specified. A new UTS is found from the table, to find the new yield strength. It is checked that this value is greater than \( \sigma_{\text{max}} \).

The number of coils, unloaded length and loaded length of the spring, and minimum inside diameter were then calculated:

- Spring Diameter = 35mm
- Spring wire thickness = 3.5mm
- Number of coils, N = 29.5
- Unloaded length = 107mm
- Loaded length = 112mm
- Minimum inside diameter = 30mm
3.4.3 Front Wheel Lift

The front wheel lift was an issue that became apparent as the design progressed, and went through several iterations, described in section 3.3. The final chosen design was a vertical lift system allowing each front wheel to be moved independently.

Using a gear and a notched cylinder, the front wheel can be raised by hand from within the chair. See Figure 24

Step 1: Pull winged handle out sideways

Step 2: Rotate to raise or lower leg

Step 3: Push handle back in to lock front wheel in place

Using ball bearings sprung on the inside of the handle to provide resistance to hold it in place when pushed in or pulled out and a small lip to prevent it being pulled off.

By making small adjustments with the front wheel height without the front attachment, minor adjustments can be made to the overall wheelchair angle.

The front wheel lift system provides a maximum range of 65mm, enough to lift the wheels clear of the ground with the seat in the lowered position and front pedal section attached.

Figure 24 – Front wheel lift mechanism
4. Finite Element Analysis

Finite Element Analysis (FEA) was the next stage of the project, although most of the time had been spent on completing the design. FEA was the obvious next step, as with a completed design it is important to understand what it will endure during its use. By using FEA any problems with the design, such as weak points, unwanted flexing, as well as potential areas for problems during manufacture can be sought out. The design can then be altered and analysed again, before costly time and resources are put to manufacturing what could potentially be a product containing many problems.

The FEA package used was Abaqus/CAE Student Edition 6.9. This version has limitations on the maximum number of nodes (1000), but this was in excess of what would be required and provided all the components required for the analysis.

4.1 Understanding Abaqus

Before analysis could be started on the wheelchair, experience with the software had to be gained as with SolidWorks. This was done be using the Abaqus supplied tutorials that built the analysis process up in stages. Knowledge gained from working through the tutorials along support materials were used to complete the analysis.
4.2 Three Point Bend Test

Physical test were first carried out using the material Twintex. Twintex is a twill woven (Figure 25\textsuperscript{11}) composite fabric consisting of E-glass fibres and Polypropylene (PP) fibres. The PP fibres are a thermoplastic and will melt when heated; this allows them to form the composites matrix, with the E-glass fibres remaining solid. This makes Twintex an easy material to work with as unlike using creating other composites it does not require specific mixes of resins, or specialised processes to manufacture components from.

![Twill Weave](http://www.finemeshmetals.co.uk/wovenwire.htm)

Figure 25 – Twill Weave

Along with Weikeong Teng and Niall Morton, tests were carried out on specimens on Twintex formed using vacuum bagging. The formed sample was made up of 3 layers of Twintex set at specific angles.

- Top layer fibres at 0° and 90°
- Mid layer fibres at 45° and -45°
- Bottom layer fibres at 0° and 90°

Weikeong and Niall were focusing on the comparison of the real test pieces and the FEA, the focus here was to use the 3 point bend test as a starting point on which to build up towards further stages of analysis for the wheelchair frame.

The sample was tested using the method set out in BS EN 2746:1998 for determining the flexural properties of glass fibre reinforced plastics. The standard sets out the test equipment, specimen size, test procedure and results to be presented.

Using the standard, 4 specimens were cut from the sample. These were rectangular of size 3mm x 15mm x 60mm, with a test span of 48mm. The apparatus was set up to the standards specification, although a larger loading nose had to be used as one of the specified size was not available, but for the point of the tests to provide a rough comparison, this should not be overly critical.

\textsuperscript{11} http://www.finemeshmetals.co.uk/wovenwire.htm
The specimens were tested with the loading nose moving at a speed of 1.5mm/min.

Measurements of loading force and displacement were recorded at regular intervals and are displayed in Figure 26.

**Twintex 3 point bend test**

![Twintex 3 point bend test diagram](image)

*Figure 26 – Twintex 3-point bend test, Force vs Displacement*

From the above results, the mean force at point of failure was calculated to be 378N with a vertical displacement of 2.76mm.
4.3 Abaqus Analysis of 3 Point Bend Test

4.3.1 Material Properties

In order to get a useful comparison between the physical tests and the FEA, the material properties of Twintex need to be known. These are not readily available to the level required for FEA, but the material make up of Twintex is known with 35% E-glass\(^{12}\) to 65% PP.

The approximation is made that each layer is uni-directional, and then using Halpin-Tsai, an empirical method of expressing a composites properties based upon its constituent matrix and fibre materials including the ratio and their geometry.

The equations are used to find the composite’s modulus, \(M\) (i.e. \(E_2, G_{12},\) or \(\nu_{23}\)) from the fibre’s modulus, \(M_f\), and matrix’s modulus, \(M_m\). Where ‘\(f\)’ is the fibre volume fraction and \(\xi\) relates to the geometry of the fibres.

\[
\frac{M}{M_m} = \frac{1 + \xi f}{1 - nf}
\]

\[
n = \left(\frac{M_f}{M_m}\right) + 1
\]

Based on Halpin-Tsai and the following properties E-glass (fibre)\(^{13}\) and PP (Matrix)\(^{14}\):

Table 2 – Composite material properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume fraction of fibres, (f)</td>
<td>0.35</td>
</tr>
<tr>
<td>Young's modulus fibres, (E_f)</td>
<td>7.24E+10 Pa</td>
</tr>
<tr>
<td>Young's modulus matrix, (E_m)</td>
<td>1.12E+09 Pa</td>
</tr>
<tr>
<td>Poisson's ratio fibres, (\nu_f)</td>
<td>0.2</td>
</tr>
<tr>
<td>Poisson's ratio matrix, (\nu_m)</td>
<td>0.3</td>
</tr>
<tr>
<td>Shear Modulus of Fibres, (G_f)</td>
<td>3.00E+10 Pa</td>
</tr>
<tr>
<td>Shear Modulus of Matrix, (G_m)</td>
<td>5.38E+08 Pa</td>
</tr>
</tbody>
</table>


\(^{13}\)http://www.matweb.com/search/DataSheet.aspx?MatGUID=d9c18d47c49147a2a7c8b0bb1743e812&ckck=1

\(^{14}\)http://www.matweb.com/search/DataSheet.aspx?MatGUID=1202140c34e8443b273862e245f0e&ckck=1
The material properties for a uni-directional lamina layer of E-glass and PP is:

**Table 3 – Uni-directional lamina properties**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{11}$</td>
<td>2.61E+10</td>
<td>Pa</td>
</tr>
<tr>
<td>$E_{22}$</td>
<td>2.81E+09</td>
<td>Pa</td>
</tr>
<tr>
<td>$G_{12}$</td>
<td>1.09E+09</td>
<td>Pa</td>
</tr>
<tr>
<td>$G_{13}$</td>
<td>1.09E+09</td>
<td>Pa</td>
</tr>
<tr>
<td>$G_{23}$</td>
<td>1.08E+09</td>
<td>Pa</td>
</tr>
<tr>
<td>$v_{12}$</td>
<td>0.265</td>
<td></td>
</tr>
</tbody>
</table>

These properties were then used in the Abaqus analysis to represent the properties of Twintex.
4.3.2 Abaqus Analysis

The 3 point bend test was then created in Abaqus. This was done using 3-D shell elements as this would allow the material to be easily assigned and varied without having to re-draw the model, additionally shell elements would later need to be used for the analysis of the wheelchair frame.

The model was created as half the 3-point bend test done in the lab, due to the symmetry in the process. This was to simplify the model and speed up the analysis process (Figure 27).

![Figure 27 – 3-point bend test, half model](image)

The model was initially specified as steel, an isotropic material, to test the analysis by keeping the process as simple as possible. The material properties were an elastic material with Young’s modulus of 200GPa and Poisson’s ratio 0.3.

This provided a successful analysis, and so the material was changed to a composite similar to that used in the physical test.

The basic composite layup tool available in Abaqus does not allow for woven materials such as the Twintex used in the physical test, therefore the material was simplified to a non-woven layup, but with the layers reflecting the angles of the woven layup. The material was selected as a lamina and given the properties calculated using Halpin-Tsai (Figure 28).
Figure 28 – Creating lamina properties

Figure 29 shows the layup used in the Abaqus analysis:

![Figure 29 – Creating composite layup](image)

The analysis was run using Boundary Conditions to change the displacement of the centre of the part, while constraining the supported point as it would have been in the physical test. The displacement of the edge representing the mid-span of the specimen was set to 2.76mm, the mean displacement at failure found in the physical tests, with the intention to find the force along the mid-span at this displacement to validate the results.

The model was seeded such that each square in the mesh would be 3mm by 3mm. This was based on the investigation by Weikeong\textsuperscript{15} into the effect of the mesh density with this determined to be the best balance between accuracy and efficiency.

Figure 30 shows the result of the analysis, showing the contours of the displacement in the 3-direction (vertical displacement).

\textsuperscript{15} Weikeong Teng, Comparison of Composite material with Finite Element Analysis 2010
As can be seen in the figure above, the specimen deflects as it did in the physical test, although not to the point of breaking, this is where the physical test was useful, knowing the displacement at which failure occurred, allows it to be used in the FEA as the end point for the analysis as it is known up to that point that the specimen behaves linearly.

The resultant forces were also of interest as they can be compared directly to the physical test. Figure 31 shows the resultant forces in the 3 (vertical direction).

The result forces at the nodal points were output to a report. By summing the resultant forces at each of the nodes (Figure 32) along the edge representing the mid-point of the test specimen, it was found that the total resultant force was 359.9N. This value sits within the range of values measured at the point of failure of the test specimen confirming the accuracy of the FEA simulation.
4.4 Abaqus Analysis of Simple Tube

A simple tube was created in SolidWorks and imported into Abaqus (method described in Section 4.4). The material orientation for a flat plate is simple as the surfaces face one direction, but for a cylinder with a curved surface, the normal to the surface varies. It is for this reason that the material orientations need to be defined separately.

The cylinder when imported was segmented into two halves. The aim when creating the material orientations was to have the normals at all points perpendicular to the surface of the cylinder outwards. The 2-directions all pointing the same direction along the length of the cylinder and the 1-direction pointing at a tangent to the cylinder surface all in the same direction of rotation around the cylinder.

When plotting the material orientations on the cylinder, Abaqus necessitated that the orientation be plotted separately for each half of the cylinder. By assigning datum axis appropriately all the normals were plotted perpendicular to the cylinder, 2-axis all ran along the tube length, and 1-axis at a tangent to the surface. Despite this, the orientations on each half for 1- and 2-axis were reversed. Figure 33 shows the material orientations on the cylinder.

![Figure 33 – Cylinder material orientations](image)

The orientations could create problems during analysis; unfortunately there was not time to proceed further with the Abaqus analysis.
4.5 Abaqus Analysis of Simplified Frame

To carry out a direct analysis on the full wheelchair frame would not be easy and could result in many errors along the way. To begin with an analysis of a simpler frame would be more likely to lead to success and make spotting errors or possible problems a lot easier. To this end the frame was simplified in Abaqus first and converted to a shell to make applying material properties to it easier.

The foot rest was attached to the main frame and detailed components removed before the solid object was changed to a surface model (Figure 34).

![Figure 34 – Simplification of frame](image)

![Figure 35 – Section cut showing frame as shell](image)

To analysis the frame in Abaqus, it must be imported from SolidWorks. To do this the CAD model must be saved as an appropriate file format recognised by abaqus. Two options are available, IGES file and ACIS file.

IGES stands for Initial Graphics Exchange Specification, and is designed to be a neutral format for transferring a design between dissimilar software packages [http://ts.nist.gov/standards/iges/].
ACIS is a 3D modeller based on object orientated C++ architecture and is designed as an open format particularly suited to applications that require flexibility so that various modelling features can be used. This makes it a useful format for exporting and importing between different software packages using 3-D modelling.

Figure 36 shows the simplified frame imported into Abaqus using IGES format. The format can be seen to display issues with complex geometries such as tight angles and interfaces between dissimilar shapes in the model. This could pose issues when later analysis is run.

Importing into Abaqus using ACIS format (Figure 37) raises no issues, and so would likely make the more appropriate basis for further analysis in Abaqus.
5. Manufacturing

Manufacturing is a key area to investigate for any product. For the wheelchair manufacturing must be looked at in two contexts; workshop manufacture and commercial manufacture. The workshop manufacture will focus on limited production and prototyping, whereas the commercial manufacturing section will investigate the most viable options for producing the wheelchairs for sale.

5.1 Workshop Manufacture

Workshop manufacturing has to be suited to the processes and machinery already available in the University. The bike frame from Alan Easdale’s project uses two male moulds, each half the bike frame. This allows the frame to be built in two halves by layering the composite on the individual moulds and then using vacuum bagging or vacuum infusion to cure the composite depending on the material chosen. The two halves are then trimmed and fixed together with the aid of skeleton pieces. This works well with a bike frame, due to the 2-D nature of it, but is unlikely to translate well to the 3-D form of the wheelchair frame. This is due to the difficulty of splitting the frame into parts that can be moulded with a single piece mould and easily released after curing. Based on the process for creating the bike moulds, this would be a time consuming process milling the board to the mould shape, followed by the priming of the surface before it can be used.

One manufacturing option for the workshop would be to use a single use process similar to the idea of investment casting where a single use mould is made and destroyed after use when releasing the casting. For composite forming a male mould could be made from polystyrene, most likely in multiple pieces to simplify the process of creating the moulds and to allow smaller machinery to be used to create the moulds. The composite can then be layered around the assembled mould. Due to the size and shape of the mould, vacuum bagging or infusion would not be easy to carry out, and a wet layup followed by a tight wrap would be easiest to mould the frame.

Alternatively, if a reusable process is desired, recommendation would be to split the frame into multiple parts. There are a number of long straight tube sections to the frame, these could be moulded around a metal pipe, either individually, or as one long piece and cut to the individual lengths. The other parts and then much smaller than the whole frame and could be produced in a two-part mould similar to the bike mould, with smaller diameter extensions to either end to allow them to be inserted into the tube sections. The whole frame once slotted together could then be wrapped in additional layers of composite material to ensure extra strength. Each of these options would have different resulting properties and potential weak spots, and this would have to be considered with any further simulation as to which manufacturing process is chosen.
5.2 Commercial Manufacture

Composite manufacturing has progressed significantly in recent years, becoming more accessible in the commercial market what was once the reserve of the aerospace industry. For the manufacturing of a wheelchair frame, the bicycle industry offers some viable options.

For producing a one-piece, high quality frame there is one stand out process. This involves using an air-bladder. The air-bladder is custom made to the shape of the frame with no stand out seems. The layup is then made over the inflated air bladder before being put in a female mould to cure. Once cured, the mould is released, and the bladder is deflated and removed from the inside of the frame, ready to be re-used.

This produces an accurate frame, with a high quality internal and external finish, ensuring the thickness at key points are as intended, and giving a sleek one-piece frame.

Giant Bicycles are using their own version of this process for their top end carbon fibre road and mountain bike frames, with great result.\textsuperscript{16}

This process would involve a high set-up cost due to the specialised equipment, but should a regular production be required, in the long term would be a more viable option than those suggested for workshop production.

\textsuperscript{16} http://archive.giant-bicycles.com/uk/050.000.000/050.005.000.asp
6. Conclusions
During the course of the project, most objectives were achieved, with a completed design for the wheelchair and a suitable method for converting it into a tricycle that is both modern and simple. Work has been started on the Finite Element Analysis, and this combined with work from previous projects should allow a full analysis to be conducted in few steps.

Further, suggestions have been proposed for the most suitable manufacturing processes and should allow a prototype to be produced in the workshop from which comparison can be made between FEA and physical testing.

7. Future Work
This project is now at the stage where it is ready to start producing prototypes. The next steps would be:

- Decide on the workshop production process and construct a prototype
- Continue Abaqus analysis with frame, utilising work of Weikeong Teng and Niall Morton
- Run further practical tests, particularly with cylinder sections to build up a model of how these sections might behave in the frame
- Consider layup orientations and how to optimise them on the wheelchair frame
References


[15] Weikeong Teng, Comparison of Composite material with Finite Element Analysis 2010


[21] SolidWorks Tutorials
Appendices:

A - Spring Calculations
The iterative spring calculations process was carried out using an Excel Spreadsheet with the values in it shown below. Values highlighted in red were inputs, with all other values calculated in the spreadsheet.

Table 4 – Spring calculation Excel table

<table>
<thead>
<tr>
<th>User Mass</th>
<th>80  kg</th>
<th>Initial Spring Diameter</th>
<th>0.035 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>784.8 N</td>
<td>r</td>
<td>0.0175 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M = F*r</td>
<td>4.1202 Nm</td>
</tr>
<tr>
<td>Spring takes 60%</td>
<td>470.88 N</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Two Springs:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Force one spring</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>takes</td>
<td>235.44 N</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>θ</td>
<td>1.48  rad</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T = θ<em>2</em>pi*r</td>
<td>0.16273 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>k = M /θ</td>
<td>2.78392 Nm/rev</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of coils, N</td>
<td>29.518</td>
<td>New d</td>
<td>0.003033 0.0035</td>
</tr>
<tr>
<td>Body Length</td>
<td>0.107</td>
<td>New outs</td>
<td>1.75E+09</td>
</tr>
<tr>
<td>Loaded Length</td>
<td>0.112</td>
<td>New yield</td>
<td>1.52E+09 10</td>
</tr>
<tr>
<td>Min Inside Diameter</td>
<td>0.030</td>
<td>New C</td>
<td>1.083333</td>
</tr>
<tr>
<td></td>
<td></td>
<td>New ki</td>
<td>1.06E+09</td>
</tr>
<tr>
<td></td>
<td></td>
<td>σmax</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>σyield must be greater than σmax</td>
<td></td>
</tr>
</tbody>
</table>
**B - Halpin-Tsai Twintex**

An Excel Spreadsheet was used to perform the Halpin-Tsai calculations. Red values were inputs, with all other values calculated in the spreadsheet. The Spreadsheet could be used for other combinations of materials replacing the red values with those relating to the new materials.

**Table 5 – Halpin-Tsai Excel Table**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume fraction of fibres, f</td>
<td>0.35</td>
</tr>
<tr>
<td>Young’s modulus fibres, Ef</td>
<td>$7.24 \times 10^7$ Pa</td>
</tr>
<tr>
<td>Young’s modulus matrix, Em</td>
<td>$1.12 \times 10^7$ Pa</td>
</tr>
<tr>
<td>Poisson’s ratio fibres, vf</td>
<td>0.2</td>
</tr>
<tr>
<td>Poisson’s ratio matrix, vm</td>
<td>0.3</td>
</tr>
<tr>
<td>Shear Modulus of Fibres, Gf</td>
<td>$3.00 \times 10^7$ Pa</td>
</tr>
<tr>
<td>Shear Modulus of Matrix, Gm</td>
<td>$5.38 \times 10^6$ Pa</td>
</tr>
<tr>
<td>$E_{11}$</td>
<td>$2.61 \times 10^7$ Pa</td>
</tr>
<tr>
<td>$E_{22}$</td>
<td>$2.81 \times 10^7$ Pa</td>
</tr>
<tr>
<td>$G_{12}$</td>
<td>$1.09 \times 10^6$ Pa</td>
</tr>
<tr>
<td>$G_{13}$</td>
<td>$1.09 \times 10^6$ Pa</td>
</tr>
<tr>
<td>$G_{23}$</td>
<td>$1.08 \times 10^6$ Pa</td>
</tr>
<tr>
<td>$v_{12}$</td>
<td>0.265</td>
</tr>
<tr>
<td>Young’s modulus longitudinal direction, $E_1$</td>
<td>$2.61 \times 10^7$ Pa</td>
</tr>
<tr>
<td>Poisson’s ratio ratios, $v_{12}$</td>
<td>0.265</td>
</tr>
</tbody>
</table>
C - Animation
As part of the design process, the animation function of the CAD package was used to give a visual representation of the wheelchairs mechanisms in action for presentations. The animations are created in the assembly part of the package, using the motion study tool. The key functions used are described.

The most complex animation was the front legs, where rotary motion was required simultaneously with linear motion. The rotary motion was achieved by applying a rotary motor to the winged handle. The speed and direction of rotation is then set.

![Figure 38 – Rotary motor in animation](image)

The linear motion of the leg was set by manually setting the position at the start of the handles rotation and end of the rotation.

The Calculate button is then used to put all the steps together, the animation can then be exported in the chosen format.

![Figure 39 – Recording animation](image)
D - Convert to Surface in SolidWorks
Most designs are created as a 3-D solid in CAD as it is usually the most intuitive method, but this is not always the most useful format, as this would define the designs material thicknesses preventing flexibility at later stages such as FEA.

Converting the design to a surface model is useful as it will allow different material properties to be applied in FEA and alterations to be easily made. To convert a solid model to a surface model in SolidWorks the surface tools need to be found by going to View > Toolbars > Surfaces.

![Figure 40 – Finding surface tools](image)

This will cause the surface toolbar to now be displayed. The most useful tool for converting to a surface model is the offset surface tool, highlighted below.

![Figure 41 – Offset surface tool](image)
The tool requires all parts to be selected to transfer the whole model to a surface model, making sure any hidden surfaces are also selected. To get an offset model identical in form to the solid model, set the offset distance to 0mm, creating a surface on that of the solid model.

The final stage is hide the solid body by right-clicking Solid Bodies in the Tree and selecting hide, the part should now be a complete surface model.
E - Exporting from SolidWorks for Abaqus

Exporting from SolidWorks is done using SaveAs and selecting the desired format from the Save as Type drop down menu (IGES or ACIS). The model can then be imported into Abaqus/CAE using Import from the File menu.

Figure 44 – Exporting in suitable format
Figure 45 – Complete chair orthographic drawing with key dimensions
Figure 46 – Complete chair exploded diagram