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Evaluation of Materials Used in the Bracing of a Single-Story Portal Framed Agricultural Building.

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i. ABSTRACT

Advancements in material technology has resulted in successful paradigm shifts within numerous industry sectors (Malihi & Shee, 2017) such as those widely experienced by aerospace and automotive industries. However, they can also require costly investment to new infrastructure, assets, methodology or operational change such as adjustment to manufacturing methods or retraining employees (Pistorius, 2017; U.S. Congress, 1985). These reasons along with a risk averse approach within the construction industry appears to have resulted in no fundamental changes regarding constructional materials used.

This report establishes if there are any viable options for alternative materials for bracing in steel portal frame buildings. Utilising a specific case study building manufactured by Shufflebottom Ltd, the existing bracing is analysed allowing for validation of potential substitute materials in terms of key criteria outlined by the business objectives. Critical appraisal was established using numerous methods including a variety of mathematical calculations, Granta Design material intelligence™ Cambridge Engineering Selector (CES), Solidworks™, Finite Element Analysis (FEA) and an adaptation of Pugh's decision-making matrix. The factor of safety (FOS) and utilisation ratio (UR) are also discussed as well as a more optimised steel brace design.

The main conclusion reports on two viable substitute bracing materials ABS and Al-alloy, however these would require further evaluation and verification from real-world testing. Filling compounds and additives could be investigated to further improve specific properties of a chosen material. Greater consideration into the utilisation ratio should be explored. It was found that the risk averse attitude of the construction industry, along with its lack of innovation and resistance to change mean that it is unlikely that any changes will be incorporated unless there is a drastic change in attitude (Pistorius, 2017).

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iii. AUTHOR'S DECLARATION

I hereby declare that this dissertation is the result of my own work and includes nothing which is the outcome of work done in collaboration except where specifically indicated in the text. Published and unpublished work has been duly cited. The report contains 20,978 words.

Richard Hinds

University of Wales Trinity St David, Swansea, April 22nd 2018

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vii. NOMENCLATURE

Upper Case Symbols

A	Cross sectional surface area
E	Young's modulus
G	Giga
I	Moment of inertia
J	Joules
M	Mega
N	Newtons
Pa	Pascal
R_t	Transition slenderness ratio
SR	Slenderness ratio
V	Volume
W	Watts

Lower Case Symbols

d_i	Inner diameter
d_o	Outer diameter
e	Exponents of 10
g	Gram
k	Kilo
m	Metres
mm	Millimetres
r	Radius of gyration

ρ Density

Symbols

S_y Material yield strength

μ Micro

$^{\circ}\text{C}$ Degrees Celsius

Abbreviations

ABS Acrylonitrile butadiene styrene

Al Aluminium

BS British Standard

CA Cellulose Polymers

CAE Computer aided engineering

CHS Circular hollow section

CO₂ Carbon dioxide

EU European Union

FEA Finite element analysis

FOS Factor of safety

FRP Fibre reinforced plastic

GBP Great British Pound

HAZ Heat affected zones

I Ionomer

ISO International Standardisation Organisation

LCA Life-cycle assessment

LGV Long goods vehicle

MCDM Multi criteria decision matrix

MiG	Metal inert gas
MOT	Ministry of Transport
MPG	Miles per gallon
OHSAS	Occupational Health and Safety Assessment Series
PA	Polyamides
PC	Polycarbonate
PE	Polyethylene
PET	Polyethylene-terephthalate
PHA	Polyhydroxyalkanoates
PHB	Polyhydroxybutyrate
PMMA	Polymethylmethacrylate
POM	Polyoxymethylene
PP	Polypropylene
PS	Polystyrene
QFD	Quality function deployment
REACH	Registration, Evaluation, Authorisation & restriction of Chemicals
RIBDA	Rural and Industrial Design and Building Association
RoSPA	Royal Society for the Prevention of Accidents
RIDDOR	Reporting of Injuries, Diseases and Dangerous Occurrences Regulations
tpPUR	Polyurethane
tpPVC	Polyvinylchloride
WEEE	Waste Electrical and Electronic Equipment recycling
UB	Universal beam

Software packages

Granta Design material intelligence™ Cambridge Engineering Selector (CES)

Microsoft Excel™

Microsoft Word™

Solidworks™

Trimble Tekla CSC Fastrak™

1. INTRODUCTION

This dissertation represents the work undertaken to identify viable alternative materials which could be substituted in place of structural steel for the bracing in portal steel frame buildings at Shufflebottom Ltd. The following introduction provides a summary of the context and rationale, aims and objectives, and an introduction to the case study development and structure.

1.1 SHUFFLEBOTTOM LTD – THE HISTORY

Shufflebottom Ltd, established in 1977, is one of the UK's largest independent manufacturers of industrial and agricultural steel-frame buildings. Situated on a seven-acre site in Cross-Hands, Llanelli Shufflebottom Ltd have had numerous large contracts with businesses such as Tesco, Ffos Lass and the Air Ambulance for Wales. Shufflebottom Ltd were the first British manufacturer of steel-framed farm buildings to receive the European CE mark and proud to be one of the few manufacturers who form their own cladding. The team are trained to British standard in welding BS EN 287-1 and welding procedures BS EN 15614-1. Shufflebottom Ltd is registered under the International Organization for Standardization (ISO) standard 9001, 14001 and Occupational Health and Safety Assessment Series (OHSAS) 18008. They have accreditations with RIBDA, are qualified in Construction Plant Competence Scheme, Construction Design and Management (CDM) regulations and have a RoSPA 2012 Gold Award for occupational health and safety.

1.2 RESEARCH AIMS AND OBJECTIVES

Aims

- Establish loadings for design of bracing.
- Identify potential alternative materials for bracing.
- Evaluate alternative materials against key criteria aligned to Shufflebottom Ltd business objectives and make recommendations.

Objectives

There are seven key objectives to be delivered through the project:

1. Identify key criteria required.
2. Analyse current bracing material properties.

3. Identify potential alternative bracing materials, validating their suitability using mathematical equations and relevant software.
4. Identify and use a process to compare current and alternative bracing materials.
5. Evaluate alternative bracing materials and identify viable alternatives, if any.
6. Provide key conclusions, identify limitations and make recommendations including future direction.
7. Independent and collaborative work with the team as Shufflebottom Ltd

1.3 MATERIAL SUBSTITUTION – A BRIEF BACKGROUND

Numerous industries have benefited from paradigm shifts with advancements in material technology. A paradigm shift can be defined as a radical change in theory (Malihi & Shee, 2017). The automotive industry has seen tremendous benefits with weight reduction and reduced corrosion of vehicles, whilst yielding higher performance for less cost. Future progression indicates the potential of chassis being made from composite materials (Szeteiova, 2010; Plastics Make it Possible, 2017). The aerospace industry, with the Airbus A380 has utilised twenty five percent more composite which in turn has led to a sixty percent increase in passengers and a forty percent reduction in fuel usage (Staszewski, et al., 2009).

The construction industry however, appears to have a risk averse approach as no fundamental changes regarding materials has been seen. Acknowledging that material substitution is not a straight forward process requiring multi-criteria decision-making (MCDM) to which many factors affect the decision making (Bakhoun & Brown, 2015).

1.4 NON-PRIME LOAD BEARING BRACING

The main components of a steel portal frame structure are columns and rafters. Columns, to which there are two opposite one another, are secured to the ground and elevated vertically. These are chosen to resist bending moments. Rafters are sections which span to make the roof usually pitched and connected to the columns. These members are selected for resistance of bending and axial loads. Additional components improve connections between members and greater resistance to bending moments in the form of haunches. These members complete a single portal frame and an example can be seen in Figure 1 (Salter, et al., 2004).

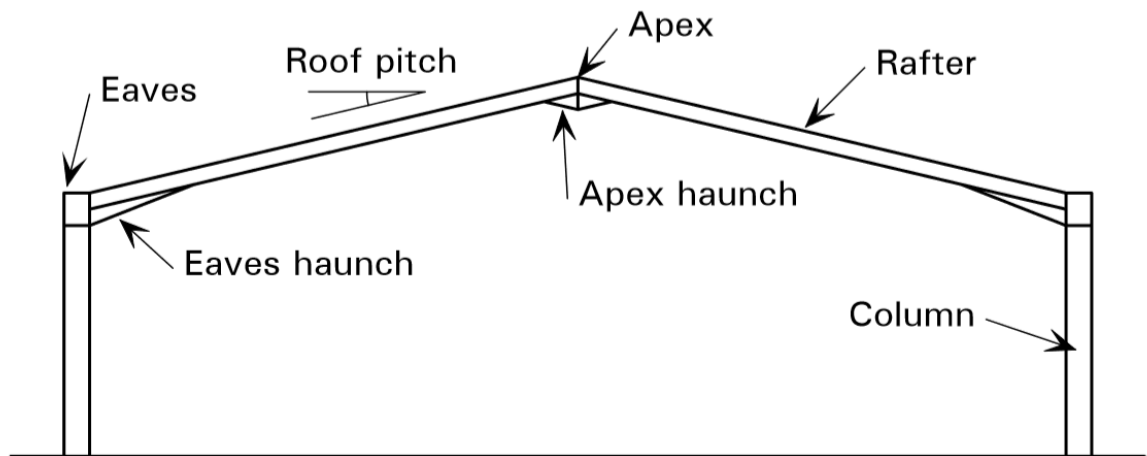


Figure 1: Single-span symmetrical portal frame.

(Salter, et al., 2004)

Buildings consisting of multiple portal frames require connecting in the form of bracing which provides lateral stability (Figure 2). Benefits of bracing are to transmit forces from wind and construction to the ground, further facilitating construction and providing rigidity to the end structure. Shufflebottom Ltd predominantly use circular hollow sections in brace construction with either end having fabricated attachments known as cleats to secure onto opposing cleats on the portal frames. Other less common types of support between portal frames have been in the form of concrete walls between the columns, eradicating the need for longitudinal bracing. In multi-story designs the use of angle or flat sections to form a cross pattern in tension have been utilised. The confines of this report considered roof, end truss and longitudinal braces only.

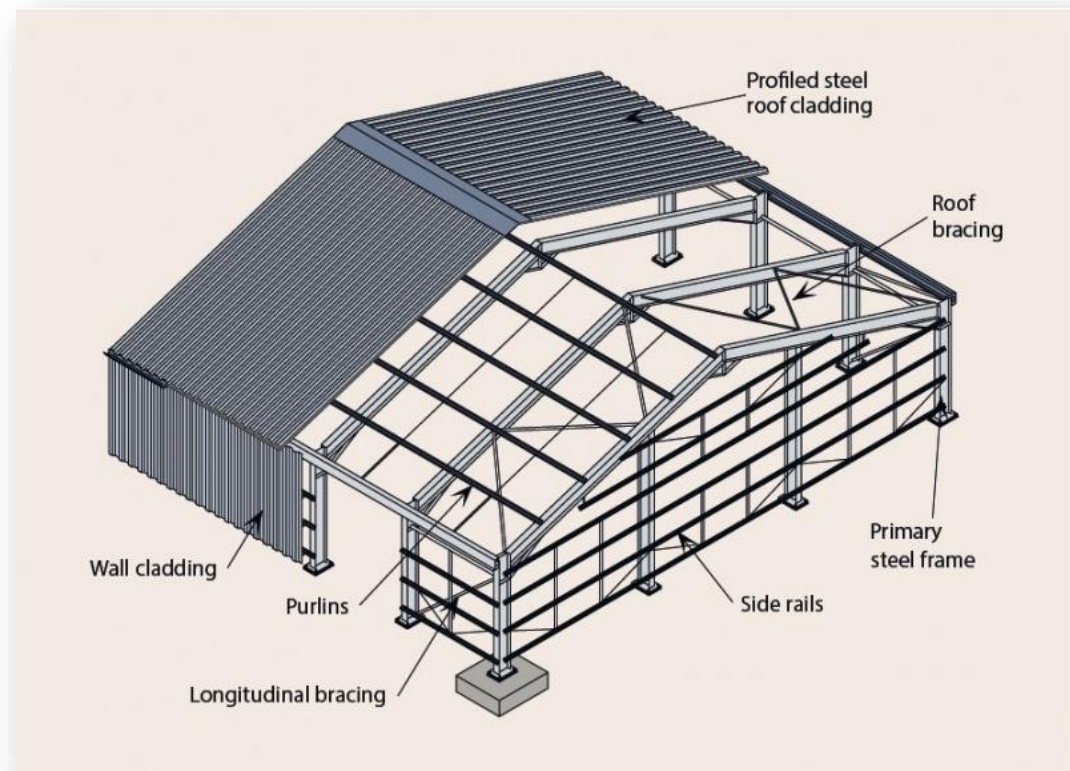


Figure 2: Principal components of a portal frame building.

(Steel Construction, 2013)

1.5 SHUFFLEBOTTOM LTD SAFETY IMPLICATION AND AWARENESS.

In 2015 Shufflebottom Ltd contracted Advance Door Engineering Ltd to install roller shutter doors into a building at Mustang Marine in Pembroke Dock. During installation a telescopic handler machine became obstructed on fencing when ascending. The stored energy was overcome causing the machine to jolt resulting in the two operators being thrown from the safety cage. Tragically, one operator was not secured to the designated location point of the safety basket causing him to fall from height and sustain fatal injuries. Shufflebottom Ltd and Advanced Doors Ltd were found in breach of regulation 3(1)(b) of the Management of Health and Safety at Work Regulations 1999 for not considering the risks associated to the task at hand (Health and Safety Executive, 2017). The outcome resulted in greater awareness of health and safety, being of paramount importance to the future visions of Shufflebottom Ltd.

Statistics obtained from the Health and Safety Executive for both manufacturing and construction were investigated and are discussed in the justification section 4.3. They identified that twenty four percent of injuries occurred from manual handling and twenty two percent from slips trips and falls between the periods of 2014-2017, both of which present an issue with current practices (Health and Safety Executive, 2017).

1.6 JUSTIFICATION FOR CASE STUDY.

Current issues arise in the manufacturing of bracing bringing about non-value-added costs associated with production. Potential to reduce consequential damage to machinery and reduce safety implications have been identified. However, for alternative bracing materials to be explored there must be an identifiable improvement to the current manufacturing processes that positively impact the business. This is supported by Williamson, et al (2006) whom indicate that a business's performance and regulatory requirements drive the behaviour of the organisation, along with their corporate social responsibility. A detailed account for the justification of this case study and scrutinisation of the non-value-added costs can be found in section four.

1.7 DISSERTATION STRUCTURE

The structure of the dissertation is based on the following approach. Section two covers theoretical knowledge and literature review to material substitution, discussing the benefits and rationale to the construction industry's lack of innovation. Section three explains the manufacturing process of existing steel bracing. The methodology and justification for the need for innovation, along with identifying Eurocodes and requirements of bracing in steel portal frame buildings within the United Kingdom can be found in Section four. Section five presents the case study. It appraises existing brace members using a variety of mathematical calculations to analyse and identify its properties. The factor of safety (FOS) and utilisation ratio (UR) are also explained as well as the potential for an optimised steel brace. Granta Design material intelligence™ Cambridge Engineering Selector (CES) software is introduced in Section six to identify potential substitute materials along with an adaptation of Pugh's decision-making matrix to critically evaluate these materials against key criteria established. Section seven considers manufacturing methods that are suitable for the production of bracing allowing for further analysis of potential substitute materials. Section eight further utilises CES, Solidworks™, mathematical calculations and a second decision-making matrix for a final critical appraisal to identify viable substitute materials.

Sections nine, ten and eleven present key conclusions, limitations and recommendations including future direction. The appendices provide further supporting information.

2. LITERATURE REVIEW

This section presents a literature review relevant for this dissertation topic and is split into two sections; material substitution and successful paradigm shifts within other industries.

2.1 MATERIAL SUBSTITUTION.

Tilton (1991) acknowledged that over the centuries material substitution has given rise to a cost reduction and enhanced quality of material objects. As natural resource depletion occurs it has ensured the increasing costs has not affected the expansion of technological development (Tilton, 1991). Graedel, et al (2015) stated that it is not yet appreciated how the development of materials has had a positive impact on humanity, as only twelve materials were in wide global use just over half a century ago; wood, brick, iron, copper, gold, silver, and few plastics.

Material substitution is of vital importance for innovation and development, with driving forces such as:

- Environmental and social expectations or legislation (e.g. WEEE regulations).
- Threat to human health and safety (e.g. REACH regulations).
- Depletion of non-renewable materials.

(Kline & Rosenberg, 1986).

Material substitution appears to be a simple concept; however, it is not straightforward and many barriers need to be overcome before successful substitution occurs, supported strongly by Graedel, et al., (2015) and Tilton, (1991). Tilton (1984) highlights that Government regulations, although less influential than technological developments and material prices, impact on the adoption. He further implies that the material price encourages the development of new technologies.

For the adoption of substitute materials to become widely accepted within the construction industry, Mahapatra & Gustavsson (2008) believe that new innovations in material substitution need to be promoted through market intervention. However, Tilton (1991) challenges this and believes new technology is the primary driver for adoption of materials.

Hammond, et al (1999) highlights that due to cognitive barriers, acceptance of new materials limits their use, strongly supported by U.S. Congress (1985), whom identify that the designers and consumers can be the greatest hurdle in the acceptance. Further supported by Biron (2015) whom states that currently there appears to be a social disinterest within the construction industry for the movement to alternative materials. This is reinforced by the reaction from some key personnel at Shufflebottom Ltd who believe that nothing will replace steel within the agricultural building sector as steel is reputable of being a strong and durable product. For a new material to be successful a common perspective must be achieved, supported by Zavadskas, et al (1998) and Waeyenbergh & Pintelon (2002).

Material substitution requires multi-criteria decision-making (MCDM) and can be influenced by several factors. This is supported by the US Congress (1985) whom state that for a new material to be adopted, it must go through rigorous testing, to achieve certification and quantification that it will meet established requirements and prove to be robust. However, research has also identified significant technical problems with previously promising substitutes once large-scale tests were undertaken (U.S. Congress, 1985).

2.2 SUCCESSFUL PARADIGM SHIFTS.

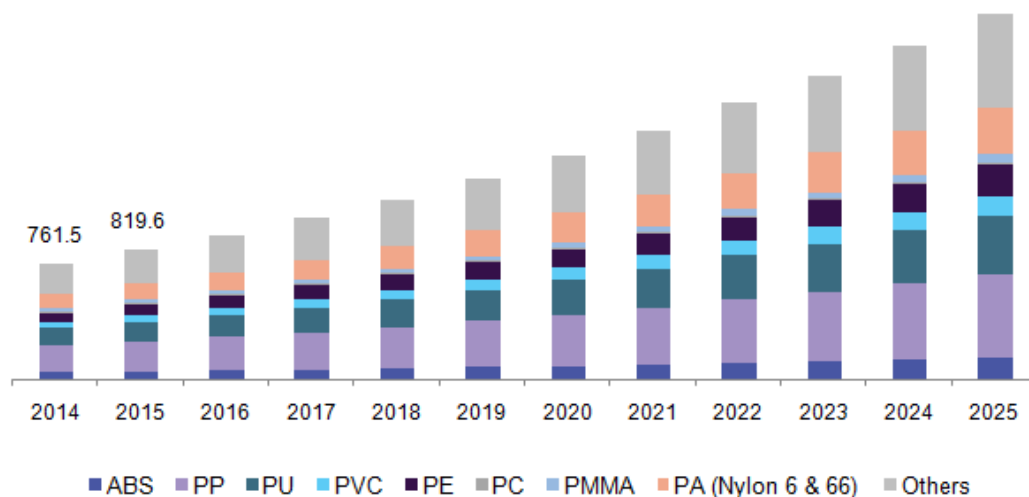
Adoption of alternative materials can have many benefits, such as those widely experienced by aerospace and automotive industries, but they can also require costly investment to new infrastructure, assets, methodology or operational change such as adjustment to manufacturing methods or retraining employees (Pistorius, 2017; U.S. Congress, 1985). These difficulties can reduce the acceptance of alternative materials as they try to distinguish a record for their reliability. Organisations need to be proactively involved to increase the likelihood of their acceptance and adoption (Graedel, et al., 2015).

In undemanding environments there is potential for materials such as plastics, aluminium and titanium, to be utilised as a substitute to steel, without compromising performance (U.S. Congress, 1985). Metal to polymer conversion has been around since the 1950s when engineered resins were introduced, however many manufacturers are still not utilising the conversion benefits (Kutz, 2016). Sawyer (2015) has predicted that organisations could see an overall cost saving of twenty-five to fifty percent by converting from metal to plastics. Significant advances in polymers over the past twenty years has

seen the uses of polymers increase threefold within the United States of America in areas such as aerospace, industry and biotechnology (National Research Council, 1994). The rapid growth has been due to technological advancements improving structural integrity due to the amalgamation of polymer compounds with various fillers and reinforcements (National Research Council, 1994). Currently there are over twenty-five thousand engineered polymeric materials which can be utilised for manufacturing applications as they can exhibit greater properties than metal with attention to smarter designs of individual elements (Biron, 2015).

Automotive and aerospace have been most active in converting (International Organization for Standardization, 2015), further supported by US Congress (1985) who stated that aircraft and automotive industries have reaped the rewards of polymer substitution. International Organization for Standardization (2015) believe that this is due to the drive to reduce weight and improve efficiency to comply with various environmental regulations such as the 'Paris Climate Agreement' (United Nations, 2015). To show the increasing demand for polymeric materials and future projections expected within the automotive industry Table 1 was acquired.

Table 1: U.S. automotive plastics market volume by product, 2014-2025 (Kilo Tons).
(Grand View Research, 2017)



Britain was first said to have used fibre-reinforced polymer (FRPs) in the construction of Spitfires in World War II although exact parts and quantities are not noted (Bakis, et al., 2012). Polymers have recently started to make an imprint within the construction of houses and other buildings, despite difficult competition with more traditional materials such as steel and brick (Biron, 2015). FRPs have been utilised in the construction industry in the last few decades, however these have been mainly in non-structural components (Karlsson, 2014). Germany has led Europe with the development of the first FRP highway bridge in 1986, ISIS (2003) and ACI (2006) state that Canada has been the global leader in developing extensive research alongside the Canadian highway administration.

In 1992 the world's first advanced composite footbridge was erected in Aberfeldy, Scotland. This bridge remains the longest span composite bridge in the world and has been a lead in demonstrating the viability and drawbacks of long span composite bridges (Skinner, 2009). Studies on the Aberfeldy bridge have recommended future considerations to include anti-fungal additives to prevent growth of mould and lichen on the composite surface, as well as areas of degradation which designers should have considered in the intended use. Over the past decade there have been numerous successful developments of bridges utilizing composites such as the 2009 Axion International Holdings bridge in North Carolina, USA, made of ninety-four percent recycled materials; the 2011 pedestrian footbridge in Santa Rosa Valley, California and the 2011 Vertech Composites Ltd bridge in Scotland. The Vertech Composites Ltd bridge is made from forty-four tonnes of recycled plastic (Kim, 2011). Figure 3 shows the unique cross-sectional design of the polymer bridge, key to the strength, durability and success of the bridge.

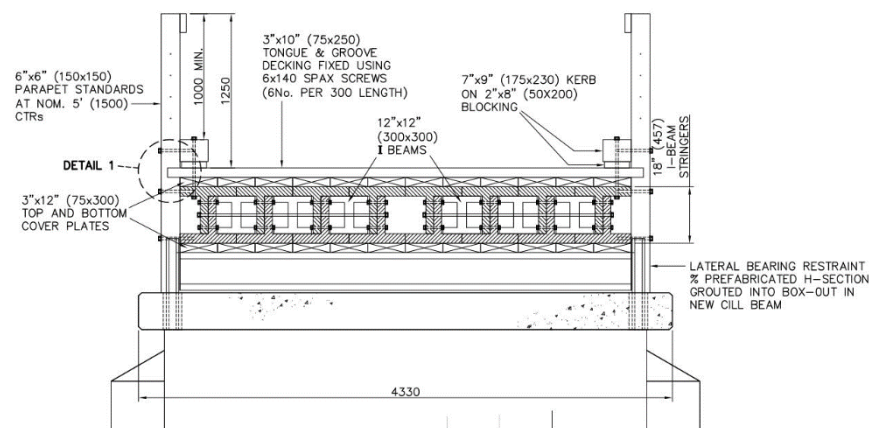


Figure 3: Vertech bridge Scotland

(Kim, 2011)

It could be justifiable to state from US Congress (1985) research, that as polymers develop a successful proven track record within construction of bridges which have now been in operation for nearly twenty years, and due to their superior properties, have the potential to become more widely accepted soon. Further supported by The American Society of Mechanical Engineers (2013). Bringing this to the forefront of engineering may allow for acceptance with today's improved technologies.

Numerous studies have indicated the potential of bamboo in construction, compared to steel which has greater costs and not renewable (Agarwal, et al., 2014), further supported by Ghavami (2005) who suggest that bamboo has the potential to be used as a substitute for steel in structural members. This is additionally supported by Adewuyi, et al (2015) whom found that bamboo was suitable for non-load bearing and lightweight reinforced concrete structures. Abdul Khalilal, et al (2012) determined a sustainable and well-engineered industrial product developed from natural fibres such as bamboo can be used as bio-composites. Further supported by Zakikhani, et al (2014) and Hebel, et al (2014) who developed composites using bamboo fibre which could yield maximum tensile capacity of 180 MPa. Providing a very promising prospect that a bamboo composite can achieve the equivalent tensile strength to that of nickel, silver and slightly less than that of steel.

There are many new innovations that are continually being studied and developed such as the 'self-healing' concrete which has the potential to improve the life-span and sustainability of buildings (SARCOS, 2018) and the 'Breathe Brick' which removes pollution from the atmosphere and stores it in a container (Humphries , 2015). Credibility of this literature is unknown as these technologies are still in their infancy, undergoing testing and research to which at present there is no reliable literature from peer reviewed material.

3. CURRENT MANUFACTURING PROCESS

This section gives insight to the methods of how a circular hollow section (CHS) is created and the process of transforming a CHS to a structural steel brace.

3.1 MANUFACTURE OF STEEL AND CIRCULAR HOLLOW SECTIONS

Metallic materials are categorised as ferrous which contain iron and non-ferrous metals which have no iron content. Non-ferrous metals are not magnetic, give better resistance to corrosion and improved conductivity properties and are generally regarded as more expensive than ferrous. Examples of non-ferrous metals would be copper, magnesium and aluminium (Gibbons, 1980). The steel making process is shown in Figure 4, to which a slab is rolled into a sheet of desired dimensions. Further processing gradually rolls the sheet longitudinally into a cylindrical section to where the seam is laser welded completing a CHS.

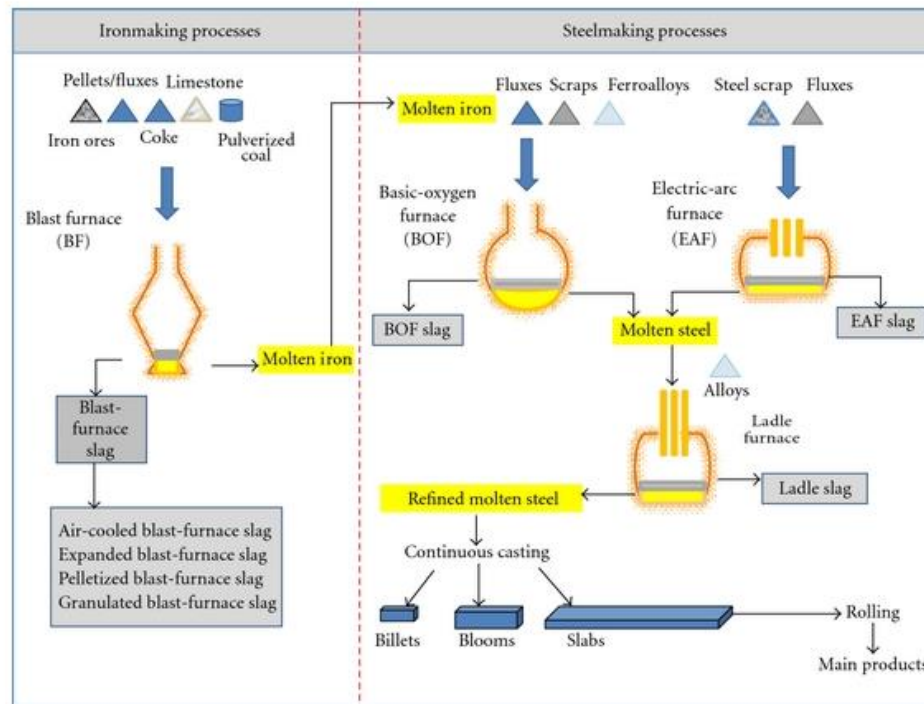


Figure 4: Flow chart of iron steel making process.

(Yildirim & Prezzi, 2011)

3.2 MANUFACTURE OF BRACING AT SHUFFLEBOTTOM LTD

Shufflebottom Ltd purchase CHS steel in bulk from steel stock holders across the United Kingdom at competitive prices. CHS arrive at Shufflebottom Ltd.'s manufacturing facility in Cross Hands, Llanelli. From here it is transferred to a steel stock pile, ensuring a constant ready supply when a building is commissioned. When braces are to be manufactured a batch of CHS of the desired diameter are transferred to a steel processing machine, a Gietart VSB-1500 Shot-blaster, Voortman V630 drill and VB1050 horizontal band saw line.

Initial surface preparation is required from shot blasting to clean the steel of mill scale and corrosion providing adequate surface conditions for fusion of welding and adhesion of paint applications. Once cleaned a cross transport conveyor system moves the material to a handler (measuring truck) where the section is secured. The truck moves the material through lasers for accurate measurement and continues through to a triple headed automated drill saw line. CHS do not undergo drilling processes and therefore move directly to the saw. The machine is programmed to perform an initial twenty-millimetre trim cut to ensure the finished section has two uniform ends. The material handler then moves the section through to the specified length and proceeds the final cut. The completed section moves to another cross-transport system where a forklift truck will collect it and place it in a stock pile awaiting fabrication.

Arriving at the fabricator the CHS are manually marked to gain a datum line of symmetry. End plates are tack welded to both ends before being fully seam welded using a three phase MiG welder. Completed braces are chosen at random by the quality department who use dye penetrant to assess weld quality and inspect for failures such as fractures or insufficient fusion. Further checks are undertaken to ensure all dimensions are within tolerance. If the braces are to be painted they are transported to an in-house paint facility. The paint facility is controlled to remain at 22°C. The paint is applied to the braces via an air driven high power airless spray system (Graco/Wagner spray pumps). Two options are available; standard primer or a two-pack self-curing paint. From the paint facility the braces are transported via forklift to a holding area before being secured as a batch and placed onto a vehicle for dispatch. A significant amount of handling operations is involved in the processing of the braces and universal beams (UB). The reasoning for excessive handling is the expansion of the business remains within the historical design configuration having to excessively move steel with forklift trucks for processing. Improvements would be a

single production line with a single overhead gantry, best suited to minimise traffic, employees, space, long term expenditure, handling and time of manufacture. Although creating this ideal vision would temporarily stop operations, need large investment, support from local council for approval and large infrastructure. Handling adds additional risk to all employees further increasing costs and production time. Figure 5 shows a flow chart for the manufacture of a brace where each arrow represents fork lift transportation.

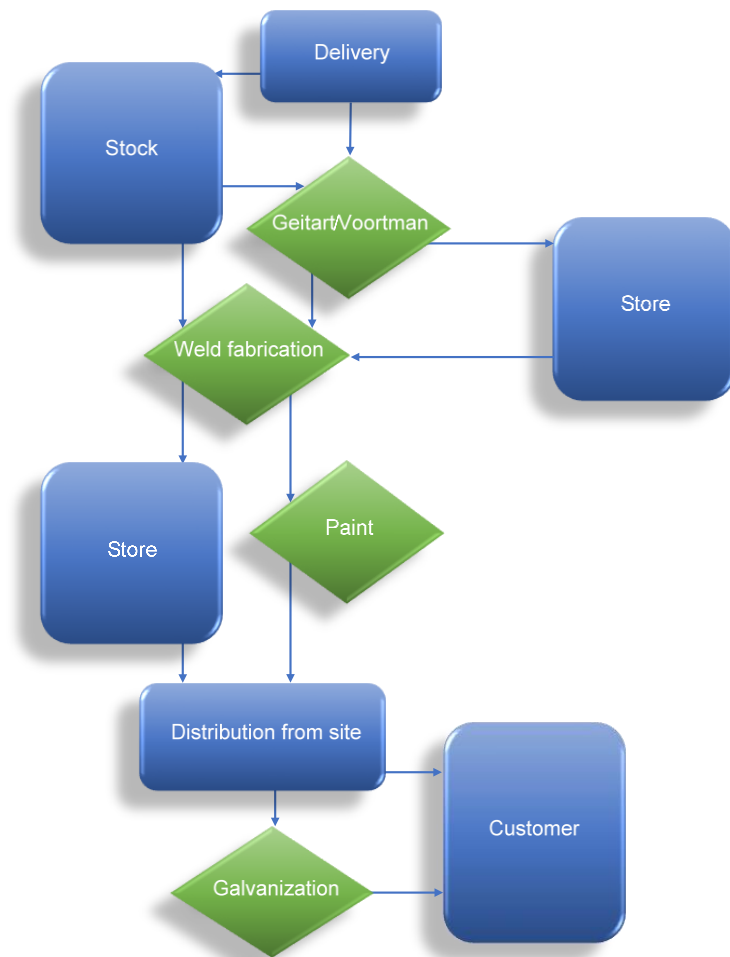


Figure 5: Production flow chart of brace manufacture

4. JUSTIFICATION

This section identifies seven justifications that currently impact Shufflebottom Ltd. Justification not only related to costings but other aspects such as health and safety, regulatory, environmental concerns and paradigm shift.

4.1 ISSUES THAT ARISE FROM MANUFACTURING PROCESS

The greatest issue within the factory is that experienced from the Gietart VSB-1500 shot-blaster machine. The machine is specifically designed to blast and effectively clean universal beams (UB). However, issues arise in the processing of CHS. The shot enters the hollow section to which there are no methods of extraction. Numerous methods have been attempted by the team at Shufflebottom Ltd however, proved unsuccessful. The decision was made to accept the depletion as expenditure. This report measures just how much expenditure has resulted from this decision (Appendix A).

As CHS are manoeuvred around the factory during processing, shot naturally falls out creating several issues. This depletion of shot needs replenishing, shot is extremely invasive on all post processing, causing premature wear on machinery, resulting in increased maintenance and cleaning costs. The extent of this has been experienced as one machine was beyond repair due to the shot destroying the vital component of the machine.

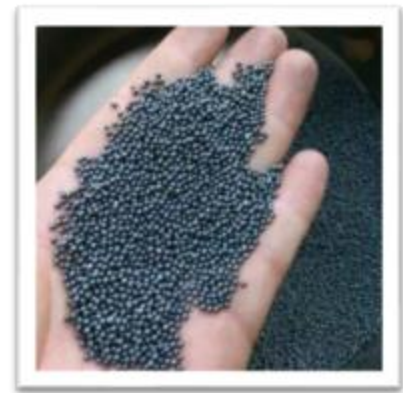


Figure 6: Example of abrasive shot.

The machines age means no 'new' parts are available and the complexity of having a new part specially engineered would be expensive, leaving limited options, one of which is replacement. Fallout from transportation further increases health and safety implications, once built up on the floor. The shot is extremely unstable under foot giving rise to slips trips and falls. The health and safety manager was contacted to give further insight into the severity of this along with manual handling injuries, however data was unable to be provided. Resolution came in the form of a road sweeper to clean shot from the floor twice a month. This impacts production, further increasing hazards of vehicles manoeuvring amongst employees.

To understand depletion, collaboration with machine operators to remove samples of various CHS from the production line was achieved. It was important to not disrupt production, so a schedule was created between maintenance and operators. The schedule allowed removal of seven CHS and extraction of shot to retrieve quantities of weight in each member which could be averaged. Calculations in Appendix A found that in 2016, 5.09 tonne of abrasive shot had depleted from the machine, which had to be replenished resulting in a cost of £3,730.97. Cleaning operations equated to £2,976.00 per annum.

4.2 CURRENT MANUFACTURE METHOD COSTINGS

Detailed calculations regarding costings associated with existing bracing manufacture can be found in Appendix A.

Data was obtained from Shufflebottom Ltd in the period of 2016. The data concluded a total of 4103 braces were manufactured with two main sizes, eighty-eight and one hundred and fourteen-millimetre outside diameters pipes, having an average weight of 50kg using 208 tonnes of steel. Of these 2273 were painted and 1830 galvanise coated. From these basic quantities, costing details are shown in Table 2.

Alternative bracing materials have the potential to significantly reduce direct costs (specifically raw materials, painting and galvanising, and labour wages) and to significantly reduce the indirect costs.

Table 2: 2016 data for costing and justifying bracing.

Direct costs associated with braces manufactured in 2016				
Operation	Measurement	Cost	Total Annual Cost	
Raw material CHS S355J2H; 114.3x3.6	208.35 tonne	£670.00/tonne	£139,594.50	
Gietart shot-blasting machine	69 hrs/year	11.0120p / unit	£455.89	
VSB1050 drill saw line	138 hrs/year	11.0120p / unit	£303.93	
Painting	2273 = 115.42 tonne	£2.20 per litre	£2431.00	
Galvanising	1830 = 92.93 tonne	£226 per tonne	£21,002	
Heating of paint facility – rental of gas tank	2 tanks/year	£60.00 a tank/year	£120.00	
Bulk Propane purchase	1379 kWh/month	£330.96 per month	£3971.52	
Climate change levy on Propane purchase	£8.83 per month		£105.96	
Machine operator wages	2,028 hrs/year	£10.00/hour	£20,280.00	
Welder/fabricator wages	2,028 hrs/year	£10.00/hour	£20,280.00	
Painter wages	2,028 hrs/year	£10.00/hour	£20,280.00	
Total direct costs			£228,704.80	
Indirect costs associated with braces manufactured in 2016				
Overheads – need to take out the direct running costs of the machines off this	2016 annual consumption	879154.6 units	£118,666.85	
Cleaning of shot	96 hrs/year	£31.00/hour	£2976.00	
Maintenance	Taken from Shufflebottom Ltd Voortman maintenance report		2016 £28667.14	2017 £39359.87
Replenishment of shot	5.09 tonne	£733.00 per tonne	£3,730.97	
Fuel costs taken for 44t LGV	82,949.75 miles	£5.33/gallon	£61,405.86 Per annum	
Total indirect costs			2016; £215,446.82	2017; £226,139.55
Total direct and indirect costs			£444,151.62	£454,844.35

4.3 HEALTH AND SAFETY IMPLICATIONS

Heavy industries are particularly hazardous environments. Injuries to personnel increase within more hazardous environments (European Agency for Safety and Health at Work, 2007). Reduction in weight has the potential to improve workplace injuries and fatalities. Health and Safety Executive (2017) statistics recognise in Britain 80,000 workers in the manufacturing industry suffer from work related illness each year. Of which non-fatal injuries reported to RIDDOR during a four-year period from 2014-2017 have identified that 24% of injuries are related to lifting and handling operations (Figure 7). Manufacturing and construction health and safety data are very similar, Shufflebottom Ltd operate within both industry's. In the construction industry Health and Safety Executive (2017) stated that 22% of non-fatal injuries were from slips, trips or falls and 21% were from lifting/handling.

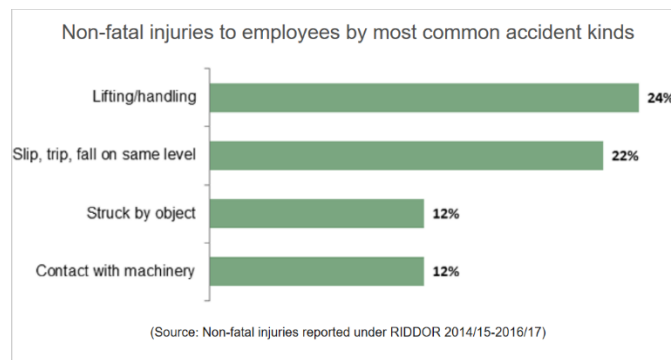


Figure 7: Non-fatal injuries by most common accident kinds within manufacturing.

(Health and Safety Executive, 2017)

4.4 WARRANTY CLAIMS AND POTENTIAL FAILURE MECHANISMS.

Warranty claims and failures were investigated although no failures were recognised by the managers. However, the fabricator indicated a relatively low number of bracings had been re-manufactured due to unsuitable lengths. To establish root cause, when buildings are specified in computer programs definitive dimensions are recognised. Real-world conditions do not directly relate to computer aided engineering (CAE), footings may not be level or inaccurately positioned. This is not an error on the behalf of the team at Shufflebottom Ltd, it highlights discrepancies between CAE and real-world conditions, supported by Shapiro, et al (2011).

A literature review of bracing failures establishes other causes for concern or issues that could potentially occur. Structural performance can be reduced by as much as sixty percent from having inadequate weld penetration (Bradley, 1986). European Committee for Standardization (2005) EN 1993-1-8 identifies cracking of the bracing at the jointed welds can occur, although the European standard primarily investigates a vast variety of the design of joints for fabricated structures with attention to chord failures when bracing is attached directly to one another.

Other failures have been seen from corrosion, overloading, shearing of bolted connection and damage. Agricultural buildings have many purposes and the intended use needs to be considered when designing. Buildings used for storage of machinery and crops will have equipment operating within the confines of the permissible space. A potential failure mode is vehicles colliding with bracing giving rise to potential failure modes such as dents or buckling.

Japan, an area of high seismic activity, reports failure mechanisms of buckling and fracturing (Arai, et al., 2016). Steel members give good resistance to small impacts however with greater forces members will tend to dent or buckle creating a weakness within the brace.

Shufflebottom Ltd do not conduct repairs to damaged steel bracing however if requested could supply a complete new member. Most failures probably go unnoticed and repairs are not undertaken, relying on the additional bracing to cope with the extra loading. Ito & Mori (2016) recognise welding a “cover plate” over the affected area regains the members strength moving the plastic hinge effects away from the weakness, the plastic hinge typically moves to the outer perimeter of the “cover plate”. Other potential substitute materials maybe able to undergo repairs but would need further investigation once their validity is established. Should viable substitute materials be identified, it will be important that if other methods of permanent joining are required (e.g. gluing), then production is quality control assured to prevent failures. Also, the maintainability of substitute material braces, including repair to permanent joins and the parent brace material damage would need be considered from the viewpoint of the building user.

4.5 SUCCESSFUL PARADIGM SHIFTS IN OTHER INDUSTRIES

With technology advancing, new materials and material compositions emerge giving possibility to substitute steel within the construction industry. Steckel & Eagan (2008)

studied and compared the potential cost savings in replacing steel joists to composite. Their study concluded that composites could be less expensive with a decreased erection time, furthermore a weight saving between thirty and fifty percent was achieved. However, this study is ten years old, further research specifically related to construction remains difficult to find, supporting the argument that the construction sector is very risk averse, not innovative and resistant to change, supported by (Pistorius, 2017).

4.6 REGULATORY REQUIREMENTS

Organisations must adhere to numerous legislations and directives imposed on them by the United Kingdom Government and European Union. The EU Industrial Emissions Directive places a responsibility and duty of care on industries to ensure they utilise the best available technology during their processes and to have the awareness to operate within environmental considerations to improve and reduce emissions to water, land and air (European Commission, 2010). Doing so will directly impact and improve public health and the environment. The EU Waste Framework Directive is a framework of legislation which looks at the collection, transport and recyclability of waste (European Commission, 2008). The objective of the framework directives is to provide an integrated approach to environmental protection. Alternative materials would need to adhere to regulations and directives.

4.7 ENVIRONMENTAL IMPACTS

Production of steel has a high environmental impact (Brown, et al., 2012). Due to the production process spanning over a period of time (extraction of ore, making of coke, electricity usage, contaminated water), the steel industry is one of the world's largest contributors of carbon dioxide (CO₂) emissions (Allwood, et al., 2012), further supported by IEA Greenhouse Gas R&D Programme (2000). The global production of steel rose from 1425 tonnes in 1990 to 1442 tonnes in 1995 (IEA Greenhouse Gas R&D Programme, 2000). This rise is confirmed by the World Steel Association (2014) whom stated from the decade 2002-2012 steel production increased from 904 tonnes to 1559 tonnes, despite the financial crisis of 2008. In 1990 the global energy consumption for steel manufacture was fifteen percent (IEA Greenhouse Gas R&D Programme, 2000) and had increased to twenty five percent by 2012 (Gutowski, et al., 2013). These percentages do not take into account the energy consumption from mining and transportation during the steel production process. Therefore the steel accounts for seven percent of global CO₂ emissions

(European Commission, 2018), probably driven by the demand for steel. However, this is opposed by HM Government (2013) whom published that the carbon emissions amount to twenty five percent.

Technologies such as smelt reduction, where a combination of heat and chemical reducing agents are used to extract base metals from ores were expected to lower energy consumption by forty five percent (IEA Greenhouse Gas R&D Programme, 2000). However, the European Commission (2018) have estimated the impact of smelt reduction would only reduce consumption by twenty to twenty five percent.

A fifty percent reduction in energy consumption in Europe has been seen in the past forty years, due to the capability of recycling and reusing scrap iron (European Commission, 2018). Further supported by Hammond & Norman (2012) whom report a reduction of approximately two percent annually on carbon emissions in the United Kingdom between 1990 and 2007. Additional support comes from the Department for Business, Energy & Industrial Strategy (2017) whom state that since 1990 the United Kingdoms CO₂ emissions have decreased by thirty seven percent. It is important to note that the production of steel not only impacts the environment with its emissions, it also contaminates water, produces hazardous waste and solid wastes (Allwood, et al., 2012).

4.8 SUMMARY OF JUSTIFICATIONS

Weight reduction can yield many benefits to manufacturing and erecting of structural steel frame buildings;

- Potential to reduce in injuries.
- Reduce energy consumption in manufacturing.
- Save money.
- Decrease erection time and ease of installation.

Changing the material could potentially give further benefits;

- Remove unsafe working conditions from shot depletion.
- Minimise machine degradation.
- Reduce processing.
- Save money.
- Improve environmental impact.
- Become a market leader.

5. CASE STUDY

A case study building was selected being representative of a typical agricultural building with structural simplicity and located in an arduous environment. Recommendations for modifications of building bracing made in this report will have potential for applicability to similar buildings, as suggested by the structural engineer.

The location of the building is Tain brome, Fendom, Tain, Ross-shire, IV19 1PE, Grid reference NH816818 (Figure 8). It comprises of a single story, single span symmetrical steel portal framed building utilised for agricultural purposes. The building size is 54m long, 19.32m wide, 7.5m to eaves with a 19° pitch roof and nine, six-meter bays.



Figure 8: Location of the case study
(Google maps, 2018)



Figure 9: Case study construction
(Google Earth, 2018)

5.1 APPRAISAL OF EXISTING STEEL BRACING

Mill test certificates (MTC) and data sheets allowed for identification of material properties and chemical composition. They provide accurate representation of the material and performance characteristics from tests carried out by the steel manufacturer (Sadowski, et al., 2015). The manufacturer has a duty to ensure all products sold meet stringent criteria, assuming all testing equipment is regularly maintained and calibrated to obtain accurate results. Granta material intelligence selector was further used in conjunction to

support the manufacturers certification (Granta Design, 2018). Some of the properties used in the calculations were obtained from the software and are listed below.

Mechanical properties of steel

Ultimate tensile strength: 350 – 510MPa

Material yield strength for nominal thickness less than sixteen-millimetre: 205 – 275MPa

Note the steel is assumed homogenous and isotropic so tensile and compressive yield strengths are taken as equal.

Temperature properties

Thermal expansion coefficient: 11 – 13 $\mu strain/^{\circ}C$

Minimum service temperature: –52 to – 24°C

Maximum service temperature: 471 – 501°C

The maximum service temperature of steel exceeds building requirements, buildings are to operate to a maximum of 100°C.

Processability

Press forming: Acceptable

Weldability: Excellent

Hot forming: Excellent

Cold forming: Excellent

Casting: Unsuitable

Material processing

Cold rolled structural steel indicates that the steel is rolled between a set of rollers at a temperature below the recrystallization point. The flat sheet is gradually rolled from multiple rollers into a cylinder shape, and the seam is laser welded to create a CHS.

Cost and availability

The cost of steel is important to establish to compare against that of alternative materials, realising that cost is not to be determined as the lowest but correct for the material in question.

The cost of structural steel ranges from $0.351\text{GBP/kg} - 0.386\text{GBP/kg}$ (Granta Design, 2018).

Environmental

The compressive and tensile forces exerted on a brace are just one of the many conditions the brace is subjected to. Environmental factors will influence performance characteristics of the existing and potential substitute materials. Therefore, environmental conditions must be understood. In the United Kingdom temperature and humidity are factors which could affect materials performance. A literature review was undertaken to better understand the factors but no information found were from reliable and credible sources, this is therefore a limitation. Humidity data was obtained using weather and climate survey data and highlighted it varied between area across the United Kingdom; Edinburgh 80%, London 73%, Cardiff 81% and Dublin 83% (Weather and Climate, 2016). Additionally, an average temperature range was between -1.5°C to 16.9°C , with Scotland tending to experience more extreme weather than Southern England (Kendon, et al., 2017).

5.2 CSC FASTRAK™ FOR STRUCTURAL DESIGN CALCULATIONS AND GENERAL ANALYSIS

CSC Fastrak™ accounts for the large number of variable loads imposed on buildings. The software allows users to comprehensively study each design and the loading, identifying areas of concern and addressing them if necessary. Data sheets showing minimum and maximum loadings along with utilisation ratios for case the study braces are in Appendix B. Force utilisation ratio has been recorded in 25% intervals to clearly differentiate between braces.

Wind loading was established to have the greatest effect on the roof bracing creating compression and tension in the members. These loads are calculated in accordance to BS6399-2:1997 and Euro Code EN1991-1-4 standards. To further understand the scope of how loads are calculated Trimble Tekla were contacted who are the license holders for CSC Fastrak software. A response established the utilisation of a BREVe database within the software. Using the BREVe database, the designer can define the location of the building site and various options to be considered in the wind analysis. Local knowledge of the site can then be used to edit the options such as building orientation and altitude, topology and air density.

CSC Fastrak™ (UK) Limited (2009) assumes a building to be fully clad to which dominant openings are not generally accounted for but can be with further calculations, in regards

to the wind loading. Research failed to clarify if the software accounts for seismic activities and extreme fifty-year storms.

The geographical location of the building is of great importance. The software establishes orientation of buildings with respect to true North, and further uses weather databases to evaluate the surrounding area and the orientation in which the building will be positioned. High rise buildings and mountain ranges will affect the wind loads imposed on the building. The software compares the geographical location to a history of weather databases giving critical information regarding the loading the building will experience. The main loads the building needs to account for are wind loads and snow loads. Other more intrinsic loads can also be expressed in the software such as internal loads which will put the bracing in tension rather than compression. Such loads can develop from storage facilities where stockpiling material will bulk against the inside wall, machines driving into the bulk material using the building as the stop to collect, or even animals pressing against the building. The software is an extremely powerful tool and invaluable to the building manufacture industry to quickly analyse loading scenarios.

5.3 IMPOSED LOADING

Research has identified three indicative loads are considered when designing buildings.

- ✓ Live loads.

Live loads will change over time and can be considered as personnel moving in the building, or livestock or storage of bulk materials within the confines of the building. The intensity of these load will change daily.

- ✓ Dead loads.

Loads that typically do not change over time such as the weight of the material the building is constructed from, Mezzanine flooring, plumbing, electrical installations.

- ✓ Service loads.

Service loads also known as environmental loads will consider environmental conditions such as snow, wind and rain. Also incorporating expansion/contraction which will apply further loading

5.4 UTILISATION RATIO

CSC Fastrak™ calculated maximum compression force of 47.6kN is experienced by brace BR11/2/13-9/B/1 and the maximum tensile force of 46.6kN is experienced by brace

BR14/1/14-11/2/13. Eaves truss bracing towards either end of the building experience larger compression forces. Compression forces decrease towards the centre of the building with the centre brace experiencing the least force.

To aid analysis use has been made of utilisation ratios. The utilisation ratio for a brace is defined as the actual performance value (e.g. imposed compression or tensile force) divided by the corresponding maximum allowable performance value (Moynihan & Allwood, 2014). All forty-four bracings in the building were categorised into utilisation ratio ranges 0-25%, 26-50%, 51-75% and 76-100% (Table 3). Note a brace with a utilisation ratio of 100% or greater exceeds its theoretical failure condition. As the building has been commissioned and erected expectations were to see no theoretical failures, this was confirmed.

Table 3: Force utilisation ratios for bracing

Force utilisation ratio %	Quantity	Bracing in building %
0-25	28	64
26-50	10	23
51-75	6	13
76-100	0	0

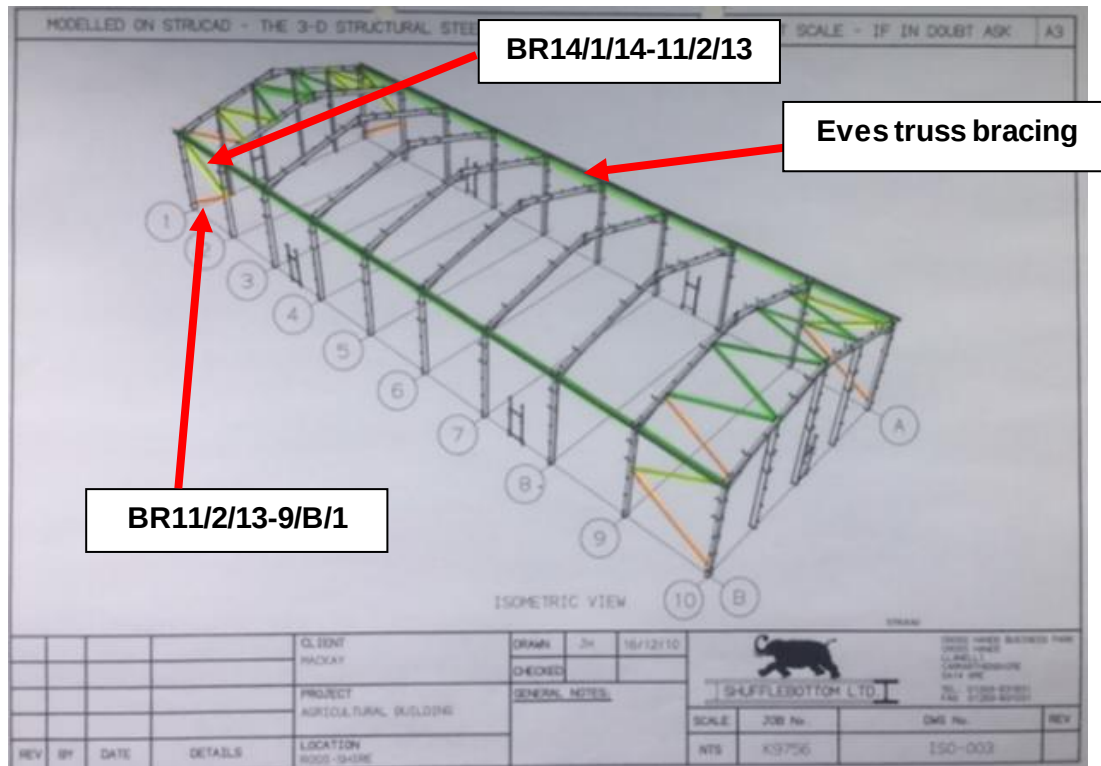


Figure 10: Utilisation ratio visualisation from the load cases in Table 3.

(Howell, 2010)

5.5 FACTOR OF SAFETY

When steel was initially used for bracing construction the factor of safety (FOS) on failure force set by British standards was four (British Standards Institution, 2003). In 2010, Eurocode 3 superseded all other design codes ultimately reducing the FOS to 1.3-1.45 (Moynihan & Allwood, 2014). It is evident that although the case study building was commissioned in 2012, it was designed to BS5502-22:2003. Table 3 shows building bracing is conservatively designed, with 87% of the bracing being less than 50% utilised. This is strengthened by Moynihan & Allwood (2014) who found that the average utilisation ratio was below 50% in a study of ten thousand beams. Studies have indicated the potential to reduce the total weight of a steel building by up to 46%, although a more recent study found this saving to be 36% (Dunant, et al., 2018). Dunant, et al (2018) also acknowledge the reluctance to design beams above an 80% utilisation, as evident in this case study building, and account this for the unused mass in steel buildings. Further suggesting under-utilisation is a fundamental characteristic of the current design practice of steel buildings.

It is evident from the utilisation ratios that the vast majority in the case study building are under-utilised. As these are not prime load bearing members they possess the greatest potential to be easily optimised and reduced in weight.

Reason for over utilised braces even after Eurocode 3 could be software out of date requiring updating or even changing. Knowledge by users to locate and design sections within the software to a higher utilised ratio. Communication between structural engineer and drafts men to correct the under-utilised members individually.

5.6 HAND CALCULATIONS OF EXISTING BRACE MEMBER

The bracing member selected for analysis had a utilization ratio in the range 0-25%, providing the greatest potential for analysis. The brace of steel grade S275 had an outside diameter (d_o) 114.3mm, inside diameter (d_i) 107.1mm, wall thickness 3.6mm and length (L) 6m. The material properties are $E = 210GPa$ and $S_y = 275MPa$.

Localised material yielding can occur when the stress experienced exceeds the compressive yield strength of a material. Long compression members will experience failure due to buckling before the yield strength of the material is experienced. Sudden occurrence of large deflections perpendicular to the centroidal axis of the structural member is known as buckling. The Rankine-Gordon formula analyses the crushing effect of members usually identified by a low slenderness ratio. The Euler formula analyses the buckling effect of members, usually identified by a high slenderness ratio. The value of the slenderness ratio at which Euler critical stress equals half the compressive yield strength can be used to calculate the transitional slenderness ratio of compression members. The Euler validity limit is the point at which the Euler stress is equal to the yield or crushing strength, at this point the member will experience both failure mechanisms.

Research into the steel column categorisation by slenderness ratio (SR) proved difficult with contradicting ratios stated (Mahgub, 2016; Nutakor, 2012 and Joannides & Weller, 2002). For this report column categories shall be short for a SR less than 50, intermediate for a SR between 50 and 250, and long for a SR greater than 250. For long columns modulus of elasticity of material dominates the behaviour.

Bracing end conditions must be specified correctly to ensure calculated forces on a brace member are accurate. The effective length ' l ' depends on brace boundary conditions and unsupported length ' L ', as follows:

- both ends pinned, $l = L$
- both ends fixed, $l = \frac{L}{2}$
- one end fixed the other pinned, $l = 0.7L$
- one end fixed the other free, $l = 2L$
- ends fixed in direction but not in position, $l = L$

Assumptions:

- Brace cross sectional thickness is uniform throughout entire length of material. This assumption is true for seamless sections. Deposited weld metal may change cross-sectional thickness for seamed sections, however analysis of this is outside the scope of this project.
- Material is homogenous and isotropic. The effects of these are accommodated for in the material specification and design codes. For the materials analysed this assumption has been taken to apply.
- The brace does not deflect under its own weight. Building bracings will naturally deflect under their own weight when installed horizontally between portal frames, however analysis of this is outside the scope of this project.
- The force is applied along the brace central axis and there are no asymmetric loads applied. For the bracing analysed this assumption has been taken to apply.
- The brace investigated has both ends pinned. The brace ends have a variety of fixture arrangements and the majority relate to typical pinned end conditions.
- Pinned end boundary conditions are frictionless. In reality pinned end conditions are not completely frictionless, friction will be generated by clamping forces between the fixture arrangements dependant on torque and use of lubrication.
- The length of the CHS is assumed to end at the bolting location, neglecting the cleat dimensions.

Moment of inertia

$$I = \frac{\pi(d_o^4 - d_i^4)}{64}$$

$$I = \frac{\pi(0.1143^4 - 0.1071^4)}{64}$$

$$I = 1.92 \times 10^{-6} m^4$$

Cross sectional area

$$A = \frac{\pi(d_o^2 - d_i^2)}{4}$$

$$A = \frac{\pi(0.1143^2 - 0.1071^2)}{4}$$

$$A = 1.252 \times 10^{-3} m^2$$

Radius of gyration

$$r = \sqrt{\frac{I}{A}}$$

$$r = \sqrt{\frac{1.92 \times 10^{-6}}{1.252 \times 10^{-3}}}$$

$$r = 0.0392 m$$

Slenderness ratio

Calculation of the slenderness ratio will determine if the brace is likely to buckle (long brace) or crush (short brace) at failure.

$$SR = \frac{L}{r}$$

$$SR = \frac{6}{0.0392}$$

$$SR = 153.2$$

The slenderness ratio categorises the brace member as intermediate.

Euler buckling force

The force (Pe) would cause the member to fail from buckling.

$$Pe = \frac{\pi^2 EI}{l^2}$$

For pinned-pinned $l = L$

$$Pe = \frac{\pi^2 \times 210 \times 10^9 \times 1.92 \times 10^{-6}}{6^2}$$

$$Pe = 110.5kN$$

Rankine-Gordon crushing force

The force (Pr) would cause the member to fail from crushing (material yield).

$$a = \frac{1}{7500}$$

$$Pr = \frac{\sigma_y A}{1 + a(SR)^2}$$

$$Pr = \frac{275 \times 10^6 \times 1.252 \times 10^{-3}}{1 + \frac{1}{7500}(153.2)^2}$$

$$Pr = 83.4kN$$

Transitional slenderness ratio

$$R_t = \sqrt{\frac{2\pi^2 E}{K^2 S_y}}$$

$$R_t = \sqrt{\frac{2\pi^2 210 \times 10^9}{1^2 \times 275 \times 10^6}}$$

$$R_t = 122.79$$

Buckling will occur if $SR > R_t$ and crushing if $SR < R_t$. The calculation shows the bracing member of steel will theoretically buckle at 110,500N as $SR > R_t$.

5.7 EXISTING BRACE HAND CALCULATIONS – VALIDATION WITH FEA ANALYSIS.

An FEA study in Solidworks™ was conducted to confirm the manual calculations for the bracing member. A model of a steel brace was constructed within the software and studied further in a simulation for buckling. The brace was treated as a beam and the material selected 'steel cold rolled', with a yield strength of 275N/mm². The constraints placed on each end of the model to replicate pinned-pinned were as follows:

- Fixed, four degrees of freedom. Translation of 'X', 'Y', 'Z' and rotation about 'Z'
- On the opposite end, three degrees of freedom were fixed. Translation 'X', 'Y' rotation about 'Z'.
- A force of one newton was applied to the centroidal axis of the beam, this was chosen as the Euler's buckling force assumes force is applied to the centroidal axis.

A mesh was generated and the study was run. The results from the study, Figure 11, show the first load factor to be 110,280N. This compression force is 220N less than the hand calculated Euler's buckling force of 110,500N confirming accuracy.

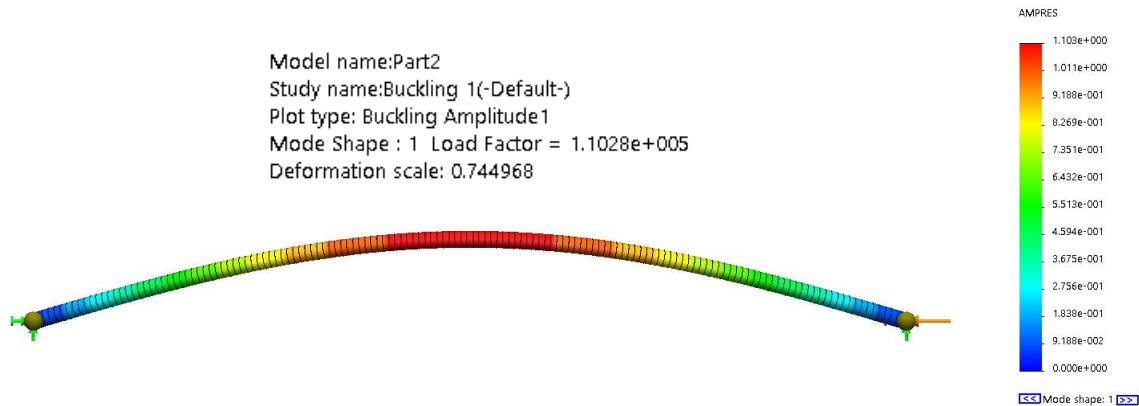


Figure 11: FEA of steel member in Solidworks™ to validate hand calculations.

The hand calculations show the ratio of the maximum applied force to Euler buckling force is less than 25%. This correlates with CSC Fastrak™ calculated utilisation ratio for the braced member, supporting accuracy of hand and FEA calculations. Generally, CSC Fastrak™ and Solidworks™ will calculate the buckling force more accurately than hand calculations. Reasoning could be, hand calculations make simplistic assumptions which limit the use and complexity. High computational power enables less assumptions to be made further increasing the complexity of the calculations and solving in less time, reinforced by (Akin, 2009). Failure in reality will be less than calculated do to the load not acting down the centroidal axis and small deflections under its own weight.

5.8 EXISTING BRACE SLENDERNESS RATIO, APPLIED FORCE AND MODE OF FAILURE.

The maximum compression force imposed on bracing members with a utilisation ratio in the range of 0-25% is 17.4kN (Appendix B). Therefore, the maximum compression force allowable with the Eurocode 3 FOS for these members is $17.4 \times 1.45 = 25.23kN$. This force will be used in the less conservative design approach in compliance with Eurocode 3 FOS.

To visualise the relationship between the existing 114.3mm outside diameter brace slenderness ratio, applied force and mode of failure, calculated data has been graphically portrayed in Figure 12 with support of an Excel™ expert. The graph displays the calculated

maximum force imposed on the 6m brace, the maximum force allowable with the Eurocode 3 FOS, and the Euler elastic buckling force. The design of the 6m brace with a slenderness ratio of 153 is conservative with a FOS on Euler buckling force of greater than six. Elastic buckling force calculated 110kN, applied force 17kN, allowable force with Eurocode 3 FOS 25.2kN. It can be seen that a compression member in a structure, with an SR > 200 has little strength to support applied loads and would be rarely used.

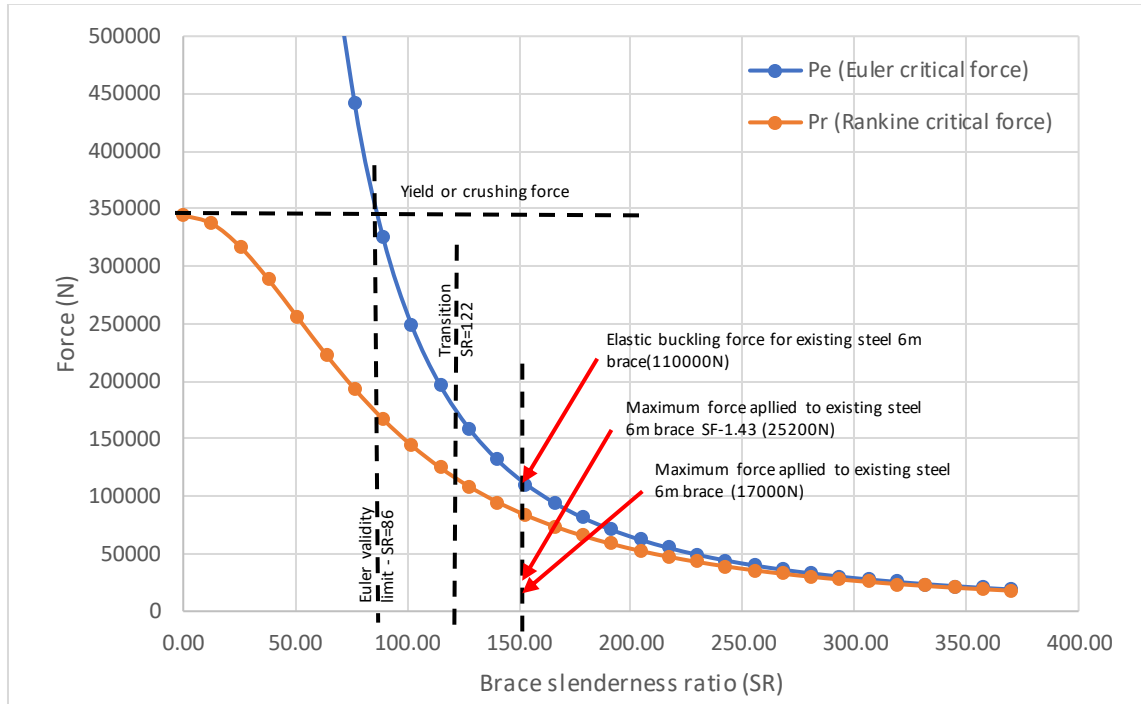


Figure 12: Critical force V Brace Slenderness Ratio.

(White & Hinds, 2018)

5.9 HAND CALCULATIONS FOR AN OPTIMISED STEEL BRACE MEMBER.

Alternatives to the 64% of existing 114.3mm outside diameter steel braces with a utilisation ratio in the range 0-25% were designed using the maximum allowable compression force with the Eurocode 3 FOS, i.e. a Euler buckling force limit of 25.23kN. This was to identify more optimal bracings with potential to be used as a direct replacement in the building.

Moment of inertia

$$P_e = \frac{\pi^2 EI}{L^2}$$

$$I = \frac{P_e L^2}{\pi^2 E}$$

$$I = \frac{25.23 \times 10^3 \times 6^2}{\pi^2 \times 210 \times 10^9}$$

$$I = 4.38 \times 10^{-7} m^4$$

This is the minimum moment of inertia required of a 6m brace of any cross-section to resist buckling.

Diameter of solid bar section

$$I = \frac{\pi(d_o^4 - d_i^4)}{64}$$

$$d = \sqrt[4]{\frac{64I}{\pi}}$$

$$d = \sqrt[4]{\frac{64 \times 4.38 \times 10^{-7}}{\pi}}$$

$$d = 0.055m$$

Minimum diameter of a solid bar brace to resist buckling is 55mm.

Diameter and wall thickness of CHS

An Excel™ spreadsheet was established to calculate the minimum wall thickness required for commercially available diameters of pipe. Commercially available pipe is shown in the standardised carbon steel chart obtained from Pudget sound pipe & supply (2018) (Appendix C). Pipe outside diameters > 55mm were input to the spreadsheet and the required wall thicknesses calculated. The data was cross-referenced against the standardised carbon steel chart to identify potential pipe diameters and schedules with the best weight per meter. This method quickly and efficiently allowed for identification of the best optimised CHS available. The transposition of formula is as follows.

$$I = \frac{\pi(d_o^4 - d_i^4)}{64} \quad \text{①}$$

$$d_o - d_i = 2t$$

$$d_o - 2t = d_i \quad \text{②}$$

Put ① in to ②

$$I = \frac{\pi(d_o^4 - (d_o - 2t)^4)}{64}$$

$$64I = \pi(do^4 - (do - 2t)^4)$$

$$\frac{64I}{\pi} = do^4 - (do - 2t)^4$$

$$\frac{64I}{\pi} - do^4 = -(do - 2t)^4$$

$$\sqrt[4]{\frac{64I}{\pi} - do^4} = -do + 2t$$

$$2t - \sqrt[4]{\frac{64I}{\pi} - do^4} = do$$

$$2t = do + \sqrt[4]{\frac{64I}{\pi} - do^4}$$

$$t = \frac{do + \sqrt[4]{\frac{64I}{\pi} - do^4}}{2} \quad \text{③}$$

Calculations showed an 88.9mm outside diameter steel pipe required a 1.6mm wall thickness. A standardised carbon steel chart obtained from Pudget sound pipe & supply (2018) showed schedule 5 pipe to be the smallest commercially available section with a wall thickness of 2.1mm possessing improved moment of inertia and reduction in weight. The pipe weighs 4.51kg/m giving a total weight of 27.06kg, reducing the weight of the brace by 32.9kg.

The existing 114.3mm outside diameter steel brace weighs on average 50kg, the steel costing £765 per tonne (Appendix D). To quantify the information an estimation was calculated for the data retrieved in 2016. Of these braces 64% had a utilisation ratio in the range 0-25%. These braces, 657 (64% of the 1046 manufactured in 2016) in number, would have weighed a total of 39.4 tonnes costing £30,141. Optimised steel braces of 88.9mm outside diameter have the potential to save £16,524 per annum due to a weight saving of 21.6 tonne. Further benefits will be seen in reduced machining time due to the schedule and diameter reductions. Less shot entering the CHS when being shot-blasted. Reduction in weight by half and therefore improving health and safety. Further saving will be evident from reduced fabrication time, reductions in spraying and further cost savings in transportation.

5.10 OPTIMISED BRACE SLENDERNESS RATIO, APPLIED FORCE AND MODE OF FAILURE.

To visualise the relationship between the optimised 88.9mm outside diameter brace slenderness ratio, applied force and mode of failure, calculated data has been graphically portrayed in Figure 13 with support of an Excel™ expert. The graph displays the calculated maximum force imposed on the 6m brace, the maximum force allowable with the Eurocode 3 FOS, and the Euler elastic buckling force. The design of the 6m brace with a slenderness ratio of 195 is significantly less conservative compared with the existing 114.3mm outside diameter brace with a FOS on Euler buckling force of less than two. Elastic buckling force calculated 31kN, applied force 17kN, allowable force with Eurocode 3 FOS 25.2kN. it can be seen that the optimised brace has a SR approaching 200 and would require further consideration before use.

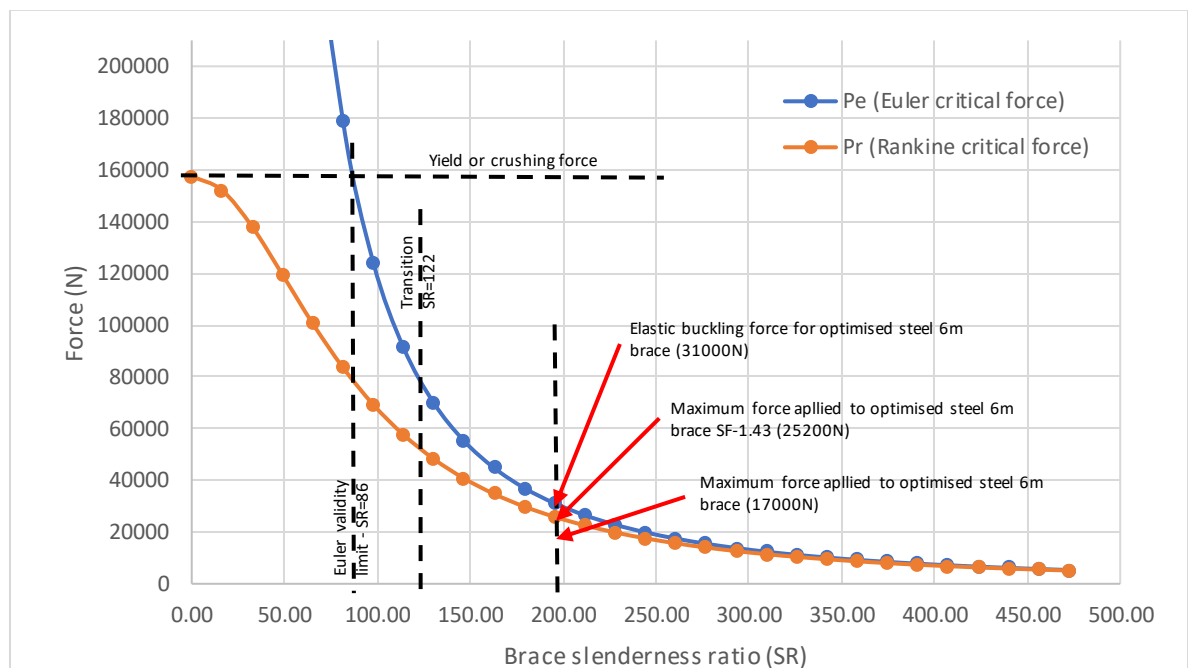


Figure 13: Critical Force V Brace Slenderness Ratio

(White & Hinds, 2018)

6. GRANTA CES

Granta Design material intelligence™ Cambridge Engineering Selector (CES) material software (2018) was extensively utilised to establish the material properties of the steel brace currently used, and to identify essential material criteria and viability of potential substitute materials. It is a software comprising of three levels of investigation that enables material data to be identified and explored. Level two of CES was used as this provided a more comprehensive range of materials compared to level one. Level three was considered, however the larger number of materials identified and their evaluation was not required to meet the aims of the study. The use of level three could be used to further understand and evaluate the materials identified within this report.

CES was utilised to investigate basic material properties and not fillings or additives of polymers. Further utilisation allowed analysis of manufacturing processes suitable for creating a CHS from a primary manufacturing process.

Limitations to some of the CES data was identified such as costings which were not accurate when compared with real-world costings; perhaps the software is not able to adapt to the volatility of the market. Compared with metallics, polymer materials seem to be more inaccurate, this could be due to polymers being so reliant on the cost of oil. Recognising this costs for polymers was attained from

6.1 IDENTIFICATION OF ESSENTIAL MATERIAL CRITERIA

Expectations including material characteristics of potential substitute materials of construction for the case study brace member were qualitatively identified at a meeting conducted with the team at Shufflebottom Ltd, along with the need and drive for change (Hinds, 2018). At the meeting criticisms such as 'the need for change' were expressed and accepted, but overall a very positive outcome was achieved. Expectations from key personnel were:

- Accountant; wanted to reduce costs.
- Erectors; decided ease of installation and manual handling to be advantageous reducing build time.
- Structural engineer; wanted the best performing member and structural integrity to not be jeopardised.

- Directors and management; importance was placed towards improvement on health and safety issues whilst structural integrity and cost were also objectives to be considered.
- Machine operators; reduction in production time and if possible elimination of shot blasting operations.
- Fabricator/welder; ease of set up and installation of end cleat fixtures.

Using limits on material properties and characteristics, including some representative of the expectations of Shufflebottom Ltd, searches in CES identified potential substitute materials. As a rule of thumb, the minimum of existing brace steel properties was input as the maximum of potential substitute materials:

- ✓ Steels density. Reduction in bracing weight was a justification of the project. Outcome = eighty-nine materials. Max $7800\text{kg}/\text{m}^3$.
- ✓ Maximum and minimum service temperature. This was identified as an important criterion to ensure the materials would not fail in a different mode. Maximum and minimum service temperatures were set to 350°C and -68.2°C respectively. Outcome = fifty-three materials.
- ✓ Processability, Machinability. The new material would need to be able to be machined for its purpose. Parameters of three to five were input in machinability. Outcome = forty-nine materials.
- ✓ Durability – built environments. Steels property was ‘acceptable’ in ‘rural atmosphere’ so the same was entered along with excellent as the case study was for an agricultural building. Outcome = forty-nine materials.
- ✓ Durability – thermal environments. Up to 150°C was selected as most structures are required to operate in the range of 0 - 100°C . This is applicable to all industry sectors as stated in CES software. Outcome = thirty-five materials.
- ✓ Materials recyclability. There were two options considered. It would be important to either have a material that would be recyclable and/or renewable. Recyclable outcome: twenty materials (five metals / fifteen polymers). Renewable outcome: ten materials (eight organic / two polymers).

Cost was considered however expenditure in the justification identified a large percentage of costs of existing braces were for the manufacturing process of the steel. Even though initial costs for potential substitute materials may be greater their processing costs may be a lot less. Therefore, cost was not used as criterion input to CES.

Some materials were removed based on engineering judgement – leather, cork, foams, hard-wood and soft-wood across the grain. Further analysis and reduction was undertaken utilising an adaptation of the Pughs-decision matrix, a quality function deployment (QFD).

6.2 QUALITY FUNCTION DEPLOYMENT

QFD is an analytical approach in engineering to highlight desired features of a product in terms that are understood by an organisation. It was utilised to rate potential substitute materials against criteria identified as critical (weighted nine), important (weighted three) and desirable (weighted 1) (Wu & Lai-Kow, 2002).

Critical criterion for potential substitute materials was identified as "strength". Important criterion was identified as the material being sustainable/renewable, recyclable and having the ability to be machined or moulded. Desirable criterion was identified as density, cost and its fire resistant/proof tolerance.

Potential substitute materials were compared against each criterion and allocated a rating. Where a material rated excellent nine was allocated, good three was allocated, satisfactory one was allocated, and none zero was allocated.

Potential substitute materials were given a score against each criterion equal to the product of criterion weighting and material rating. The scores for each criterion were totalled to give a total score.

Regard the critical criterion strength, the CES software was used to compare material property Young's Modulus. For each potential substitute material, Young's Modulus was used to calculate the required moment of inertia and solid bar diameter for the existing brace maximum allowable compression force of 110kN and a reduced Eurocode 3 maximum allowable compression force of 25.3kN. Strength ratings were given based on ratio of potential substitute material and existing brace steel solid bar diameters as follows:

- Ratio $<1.75 = 9$
- Ratio 1.75 to 2.0 = 3
- Ratio $>2.0 = 1$

Calculated ratios and ratings are shown in Appendix E.

Regard the important criteria the CES indicated if potential substitute materials were or were not sustainable/renewable or recyclable, ratings given were nine and zero respectively.

Regard the desirable criterion fire resistant/proof, engineering judgement was used for substitute materials to give ratings of nine, three and one.

Regard all other criteria the CES provided quantitative values for potential substitute materials, engineering judgement was used to select ranges of values given ratings nine, three and one.

Table 4 details the twenty-three potential substitute materials identified using CES along with their total scores. Further analysis was undertaken to reduce the number.

Table 4: QFD of potential material substitutes as identified in CES Fastrak™.

Materials	Critical: 9	Important: 3				Desirable: 1			Total Rating
	Strength	Sustainable/ renewable	Recyclable	Machineability 4/5	Mouldability 4/5	Density	Cost	Fire resistant/proof	
Bamboo	27	27	0	27	0	9	9	1	100
Hardwood – along grain	81	27	0	27	0	9	9	1	154
Plywood	27	27	0	27	27	9	9	1	127
Softwood – along grain	81	27	0	27	0	9	9	1	154
ABS	9	0	27	27	27	9	3	1	103
CA	27	27	27	27	9	9	1	1	128
I	9	0	27	27	27	9	1	1	101
Nylons, PA	9	0	27	27	9	3	1	3	79
PC	9	0	27	27	27	3	1	3	97
PE	9	0	27	27	27	9	3	1	103
PET	9	0	27	27	27	3	3	1	97
PHA/PHB	9	27	27	27	27	3	1	1	122
Acrylic, PMMA	9	0	27	27	27	3	1	1	95
Acetel, POM	9	0	27	27	27	3	1	1	95
PP	9	0	27	27	27	9	3	1	103
PS	9	0	27	27	27	9	1	1	101
tpPUR	9	0	27	27	27	3	1	1	95
tpPVC	9	0	27	27	27	3	3	3	99
Wrought magnesium alloys	81	0	27	27	0	1	1	9	146
Cast magnesium alloys	81	0	27	27	0	1	1	9	146
Non-age hardening wrought AL – alloys	81	0	27	27	0	1	3	9	148
Age hardening wrought AL-Alloys	81	0	27	27	0	1	3	9	148
Cast AL-Alloys	81	0	27	27	0	1	3	9	148

7. INVESTIGATION OF MANUFACTURING PROCESSES

Manufacturing methods suitable to produce bracing from potential material substitutes was investigated in CES. This facility is known as the 'process universe' and is a data base within CES. The aim was to further differentiate the potential material substitutes.

Bracing shape was established initially to be prismatic, circular. Circular cross sections possess the greatest strength for compression as they remove as much of the material away from the centroidal axis, supported by Chaudhury & Datta (2017), However further research identified equilateral triangle cross sections to give even greater strength for compression (Keller, 1960). Therefore prismatic, circular and non circular were selected for the search within CES. This allowed for both shapes to be manufactured and resulted in forty-eight potential processes under seven manufacturing methods.

- Additive manufacturing – fifteen processes
- Casting – eight processes
- Composite forming – five processes
- Deformation – five processes
- Machining – seven processes
- Moulding – six processes
- Powder methods – two processes

'Primary shaping process' was imperative as it gives the desired geometric dimension of the end product efficiently, requiring little secondary processing. CES search with selection of 'primary shaping processes' resulted in all machining processes being impractical. Reasoning for this is machining is a post process usually taking place after the primary process.

For the remaining forty-one potential processes, a further limit of labour intensity was introduced in the CES search. Early discussions with Shufflebottom Ltd management established the greatest expenditure was that of employees. With this considered, economic compatibility was highlighted with labour intensity selected to be low to medium. Reduced labour and smarter manufacturing methods could offer long term competitive advantage for the organisation.

For the remaining nineteen potential processes, further analysis was undertaken using CES to evaluate each of the manufacturing methods and suitable processes.

- 3D printing
- Bulk moulding compound
- Ceramic shell
- Evaporative pattern
- Filament winding
- Fused deposition
- Gravity die cast
- High pressure die cast
- Low pressure die cast
- Powder injection
- Pressing and sintering
- Pultrusion
- Extrusion metal
- Rolling
- Sheet forming
- Expand foam moulding
- Reaction inject moulding
- Polymer extrusion
- Inject moulding

Additive manufacturing is restricted by its capability of mass production (Go, et al., 2017). It is also subjected to a limit in its length capabilities, however Stratasys Ltd (2016) have designed a prototype machine which has broken this barrier. The prototype is being trialled by Boeing and Ford to produce low volume light-weight parts. As this is a new technological advancement in early developmental stages it was not considered as a manufacturing option but could be a consideration in the near future if it is able to provide mass production in large lengths.

Casting is limited by its size and complex shape capabilities as well as a restricted choice of materials that are suitable. It can also leave defects in the structure which may have a detrimental impact on any structural products (Charmeux, 2007). Size capability is also a limitation for powder manufacture methods (Groover, 2002). Composite forming requires significant manufacturing times partly due to the nature of the materials needing to be layered, imbedded and cured, combined with relatively large expenditure of tooling required (Barfuss, et al., 2016).

The utilisation of criteria revealed the current method of steel manufacture, deformation, and moulding to be practical methods to produce bracing, see Table 5.

Table 5: Comparison of manufacturing methods.

Manufacturing method	Length capabilities	Diameter capabilities	Mass production	Manufacturing time
Additive manufacturing		✓		
Casting		✓		
Composite forming	✓	✓	✓	
Deformation	✓	✓	✓	✓
Moulding	✓	✓	✓	✓
Powder methods		✓	✓	

Under these two possible methods of manufacture are the following practical methods to effectively manufacture prismatic circular hollow sections.

Deformation

- Extrusion
- Rolling
- Sheet forming (Current method for steel brace)

Moulding

- Expanded foam moulding
- Reaction injection moulding
- Polymer extrusion
- Injection moulding

8. CRITICAL ANALYSIS OF SUBSTITUTE MATERIALS

A final critical appraisal of the potential substitute materials was undertaken using CES, Solidworks™, mathematical calculations and an advanced QFD.

An analysis was undertaken considering the suitable manufacturing methods (Table 5) and the potential substitute materials total scores (Table 4). All materials will have environmental impacts associated with each stage of its life; from raw material extraction to manufacture, maintenance and end of life disposal. A life-cycle assessment (LCA) is an established technique used to assess a materials impact on the environment and this was considered for the materials (Kourmentza, et al., 2017).

Within the QFD the materials can be split into three sub-categories; organic, polymeric and metallic. From the twenty-three potential substitute materials within the QFD, further analysis of the critical criteria, 'strength' was undertaken using calculations done by hand and FEA analysis in Solidworks™. Closely linked to strength is weight which relates to the desirable criterion density. Calculating the volume of each commercially available section and multiplying by density allowed for the weight to be calculated.

8.1 ORGANIC MATERIALS

Organic was not considered in the manufacturing analysis as it is most practical used as a solid member (Ramage, et al., 2017). If it were to be manufactured into a pipe then further processing would be costly, as supported by Lun, et al (2016) whom state that most of energy consumption and environmental impact arises from the manufacturing process of wood. This process is believed to contribute to ninety percent of the carbon footprint of wood, however Puettmann & Wilson (2005) argue the consumption and carbon emission associated with the regeneration and harvesting of wood aids this. Although the manufacture process of wood has a large environmental impact, it still consumes significantly less than manufacturing of alternatives such as polymerics and metallics (Puettmann & Wilson, 2005).

Organic materials such as wood benefit from acoustic, thermal, electrical, mechanical, aesthetic and vibration properties, however it also has numerous limitations. Ramage, et al (2017) recognise potential aging mechanisms which can occur; biotic (fungi, bacteria, insects, natural decay) and abiotic (degradation of elements such as sun, wind and water). To overcome these the organic matter would have to be treated. Organic materials can

have natural weaknesses embedded within which cannot be quality assured (Ramage, et al., 2017). Considering all the above and engineering knowledge, organic was ruled out as a potential substitute material.

8.2 METALLIC MATERIALS

It was previously established that casting manufacturing method was unsuitable and therefore ruled out cast aluminium alloy and cast magnesium alloy as potential substitute materials. Magnesium alloy was further ruled out as a potential substitute material as the cost was greater than that of aluminium alloy. Of the two remaining potential aluminium alloys (Al-alloy) further analysis determined which would have the best potential for material substitution. Further investigation towards wrought aluminium was undertaken. Many aluminium series became present which require further knowledge of the material to be sought. Different series of Al-alloy are achieved from the incorporation of principle alloying elements which are detailed in Table 6.

Table 6: Aluminium principle alloying series classifications.

Alloy Series	Principal Alloying Element
1xxx	99.000% Minimum Aluminium
2xxx	Copper
3xxx	Manganese
4xxx	Silicon
5xxx	Magnesium
6xxx	Magnesium and Silicon
7xxx	Zinc
8xxx	Other Elements
9xxx	Unused Series

(Doran & Cather, 2014)

Doran & Cather (2014) state there are a range of seventeen suitable aluminium alloys for structural applications depending on requirements. Su, et al (2014) identified and tested two series of aluminium alloys; 6061-T6 and 6063-T5 for structural applications. They identified failure modes which were validated with FEA results. Although the testing was conducted for bending, similar localised material failures would be present for buckling, this was considered applicable. A common alloy 6061 appeared in literature for structural applications (Khan, et al., 2017; Doran & Cather, 2014; Su, et al., 2014; Sanders, 2001). Research recognised there is a vast array of aluminium alloys, so the common alloy of 6061 was considered for this report. However, considered an assumption as further knowledge is required that there could be a more suitable aluminium series for the application of bracing.

Benefits of aluminium over steel are corrosion resistance which means protective coatings would not be required and that density is a third of that than steel (Gitter, 2008); further strengthened by CES material properties (Granta Design, 2018). From research 6061 was identified to have acceptable strength, weldability, formability, corrosion resistance and is widely available.

Modes of failure of aluminium differ to that of steel and therefore requires greater knowledge. Fatigue behaviour and microstructure change in heat affected zones (HAZ) and both are well known concerns of aluminium. 6061 alloy provides acceptable stability in the HAZ.

Environmental considerations

It was also important to consider environmental impact of Al-alloys. Copper, magnesium, silicon, chromium and tin are common alloy elements utilised and have great environmental impacts (Gomez, et al., 2016). This is supported by numerous EU studies which regard these elements as ecological risks and vulnerable (Swan, 2008). Elements such as lead and iron reduce the environmental impact. An AL-alloy with a high percentage of these elements could be a suitable substitute as iron improves mechanical strength and lead improves machinability (Heinemann, 2016). An average environmental impact of an AL-alloy from its LCA is 63.6GJ per 1000kg of material and 11068kg CO₂ per 1000kg (Franklin Associates, 2011).

8.3 POLYMERIC MATERIALS

With the vast number of polymers present in the QFD, mouldability was selected to identify the potential for moulding processes, typical of many polymers manufactures. Still within the “limit” category of CES, mouldability had initially been set between four and five, highlighting fourteen materials. Further tightening the focus of mouldability to five (excellent mouldability capabilities), typical of polymer manufacturing for mass production, reduced the potential materials to twelve.

- | | |
|--------------|-----------------|
| ✓ ABS | ✓ PHA/PHB |
| ✓ I | ✓ Acrylic, PMMA |
| ✓ Nylons, PA | ✓ Acetel, POM |
| ✓ PC | ✓ PP |
| ✓ PE | ✓ PS |
| ✓ PET | ✓ tpPVC |

All polymers had the potential for moulding manufacture so the highest rated in the QFD would be further critically analysed; PHA/PHB; ABS; PE; PP. Ede (2015) support the selection of polymers, recognising plastics such as PS and PVC are starting to be widely used in construction in Nigeria. This supports the selection process used, however Ede investigates the total extent within the construction industry, noting limited knowledge of more advanced polymers. This report investigates polymer use in a specific application of bracing, thus giving an end selection of different polymers. Drawing comparison between this report and Ede (2015) recognise that similar polymers have structural capabilities. Ede (2015) also acknowledges a barrier to polymer acceptance is the minimal knowledge from personnel but that their cost and weight reduction encourages the acceptance.

Environmental considerations

The four polymers could all be extrusion moulded which was highlighted as one of the suitable manufacturing methods, however they have different environmental impacts. The manufacture of the type of polymer will have specific energy consumption and this will have the greatest impact on the environment. The type of machine used for the moulding will have a substantial impact in the energy consumption; if it is hydraulic, hybrid or electric. Also, the shape of the pipe will impact on the specific energy consumption (Thiriez & Gutowski, 2006).

According to Franklin Associates (2011) and Yu & Chen (2008) the polymers environmental impacts during their LCA are as detailed in Table 7.

Table 7: LCA - Environmental impacts of polymers.

Material	GJ per 1000kg of material	Kg CO₂ per 1000kg
ABS	105	3,805
PE	78.3	1,897
PHA/PHB	110	4900
PP	77.0	1,860

ABS

ABS has three main methods of manufacture with extrusion moulding being the most cost effective. Although it can be recycled and reused it is important to note that research has found a degradation in its mechanical properties when recycled (Das, et al., 2017). This may indicate that if ABS were to be a substitute material, it may only be suitably made from virgin and not recycled ABS.

PE

PE is predominately manufactured by extrusion moulding from virgin polyethylene granules and recycled PE. One of the benefits of PE is over recent years its recycling process has dramatically improved and therefore if recycled properly could positively impact the environment as the production of the granules will reduce (Sangwan & Bhakar, 2017).

PP

PP has been found to have a twenty four percent lower carbon footprint than such plastics as PET and is competitive with the life cycle of PE (INTERK, 2010).

PHA/PHB

PHA/PHB consumes a large amount of steam during its manufacturing leading to high fossil fuel impact, however Zhong, et al (2009) believe they are the 'green' polymers of the future. They can possess similar mechanical properties as PP and PE but can be more

easily recycled. One of the limitations of this material is large production costs, estimated to be four times greater than that of more conventional polymers such as PP and PE (Kourmentza, et al., 2017). This polymer is not manufactured from crude materials, it is manufactured within a laboratory from bacteria (CLT, n.d.).

8.4 CALCULATIONS FOR POTENTIAL SUBSTITUTE MATERIAL BRACING MEMBERS

Potential substitute materials for the existing steel braces with a utilisation ratio in the range 0-25% were designed as CHS using the existing steel brace calculated Euler buckling force of 110kN and the maximum allowable compression force with the Eurocode 3 FOS of 25.23kN. This allowed for further assessment of the remaining five materials as direct replacement braces in the building.

Moment of Inertia

$$P_e = \frac{\pi^2 EI}{L^2}$$

$$I = \frac{P_e L^2}{E \pi^2}$$

This is the minimum moment of inertia required of a brace of any cross-section and material with pinned-pinned ends to resist buckling.

Diameter of solid bar selection

$$I = \frac{\pi(-d_i^4)}{64}$$

$$d = \sqrt[4]{\frac{I 64}{\pi}}$$

This is the minimum diameter of a solid bar brace of any material with pinned-pinned ends to resist buckling.

Young's modulus for the remaining five materials was attained (Appendix F). The calculated moments of inertia and solid bar diameters for the five remaining materials are shown in Table 8.

Table 8: Solid bar diameter of potential substitute materials

Material	Length (m)	Buckling force (N)	Young's modulus (GPa)	Moment of inertia (m ⁴)	Diameter (mm)
ABS	6	110000	2.9	0.000138	230.39
	6	25200	2.9	3.17e-05	159.39
PE	6	110000	0.89	0.000451	309.54
	6	25200	0.89	0.000103	214.15
PHA/PHA	6	110000	4	0.0001	212.59
	6	25200	4	2.3e-05	147.07
PP	6	110000	1.55	0.000259	269.45
	6	25200	1.55	5.93e-05	186.41
Al-alloy 6061	6	110000	89	4.51e-06	97.88
	6	25200	89	1.03e-06	67.72

An FEA study in Solidworks™ was conducted to confirm the manual calculations for the potential substitute bracing materials. A model of each brace with appropriate outside diameter and length 6m was imported into the simulation for buckling. The constraints placed on each end of the model to replicate pinned-pinned were as follows:

- Fixed, four degrees of freedom. Translation of 'X', 'Y', 'Z' and rotation about 'Z'
- On the opposite end three degrees of freedom were established. Translation 'X', 'Y' rotation about 'Z'.
- A force of one newton was applied to the centroidal axis of the beam, this was chosen as the Euler's buckling force assumes force is applied to the centroidal axis.

A mesh was created and the study was run. PHA/PHB was unable to be validated as there was no option for this material within Solidworks™. Time constraints didn't allow for manual entering of the material which could have been undertaken. It is also important to note discrepancies between the CES material data and the data within Solidworks™ was recognised. Young's modulus within Solidworks™ had to be adjusted to ensure the data matched the CES data. Table 9 shows the FEA analysis predicted buckling forces are in close agreement with the stated Euler buckling forces.

Table 9: Validation of buckling forces with FEA analysis.

Material	Length (m)	Buckling force (N)	Buckling force in FEA (N)	Difference in buckling force (N)
ABS	6	110000	108910	1090
	6	25200	25074	126
PE	6	110000	109460	540
	6	25200	25135	65
PHA/PHB	6	110000	Material properties not available in Solidworks TM	
	6	25200		
PP	6	110000	109180	820
	6	25200	25105	95
Al-alloy 6061	6	110000	109880	120
	6	25200	25182	18

8.5 DIAMETER AND THICKNESS OF SUBSTITUTE MATERIAL CHS.

Using the same principle for calculating the optimised steel brace, equation 3 was utilised to calculate the wall thickness of AL-alloy and polymer tubes. A table showing the calculations can be found in Appendix G.

Standard aluminium pipe sizes were obtained from (Market and Metals (N.d). Stocked items are for series 5083, however supply of 6061 is also available in the same dimensions. Difficulties in finding reliable sources was a limit of identifying suitable sections. Gitter (2008) contests the calculations which accounts wall thickness as the dominant method of establishing what CHS to use. They highlight a proven rule that when changing materials from steel to aluminium if the section dimensions are increased by 1.4 the same stiffness will be maintained and the weight reduced by 50%. The results support Gitters findings, increased size of aluminium sees a reduction in weight for the same stiffness of the aluminium section.

Al-Alloy 6061 CHS

The smallest viable size was pipe with an outside diameter of 88.9mm with a calculated wall thickness of 4.3mm. The following equations were used to calculate the weights of viable al-alloy CHS shown in Table 10.

$$Volume V = \pi(r_o^2 - r_i^2)L$$

$$Weight W = V\rho$$

Table 10: Calculated weights of viable Al-alloy CHS.

DIAMETER (mm)	WEIGHT (kg/m)	TOTAL WEIGHT (kg)
88.9	4.17	25
101.6	2.74	16.43
114.3	3.09	18.54
141.3	4.23	25.40

London Metal Exchange (2018) establish the current price of aluminium to be \$1800 per tonne. Converting this at current exchange rate of 1.41 United State Dollar to Great British pound;

The lightest viable alloy brace with an outside diameter of 101.6mm would cost:

$$\frac{£1276.60}{1000kg} \times 16.43 = £21.03$$

The cost assumes one brace would be ordered and does not consider discounts for bulk order. These costs will also vary depending on the current value of aluminium on the stock market.

Being of least weight and least cost, the 101.6mm outside diameter brace will be compared in more detail to other potential substitute materials.

Polymer CHS

Research identified that polymer pipes could be purchased directly from a polymer pipe stockist in diameters ranging from 10mm to 630mm, with wall thicknesses of 0.5mm to 50mm (CPV Engineering Pipework Solutions, 2013). This indicates suitable pipes could be purchased and imported in the required dimensions reducing the manufacturing costs for Shufflebottom Ltd.

A standard polymer pipe chart (Appendix G) was obtained from ips flow systems (2018) whom supply a wide range of polymer pipes in both imperial and metric dimensions. Calculations were completed for wall thickness of commercially available outside pipe diameters. These were cross referenced against the polymer pipe chart to select appropriate CHS. Weights for each CHS were calculated.

Table 11: Calculated weights of viable polymer CHS.

Material	Diameter (mm)	Weight (<i>kg/m</i>)	Total weight (kg)
ABS	200	8.91	53.46
	225	10.09	60.54
	250	11.29	67.74
PE	280	12.00	72.00
	315	6.96	41.76
PHA/PHB	200	9.20	55.20
	225	10.43	62.58
	250	11.66	69.98
PP	250	8.49	50.94
	280	11.38	68.25
	315	6.60	39.59

Cost per kilogram was obtained from the CES material data sheet. It was compared with the exchange rates which change daily and identified that the costings on CES vary considerably compared to the current market. Table 12 shows the costings for of the lightest commercially available polymer pipe.

Table 12: Cost per member of lightest polymer based on material cost per kg.

Material	CES cost per member (£)	Stock market cost per member (£)
ABS	39.00	34.75
PE	56.00	45.94
PHA/PHB	98.86	391.92
PP	46.00	49.89

(Plastic Portal EU, 2017; Aslan, et al., 2016)

Again, these calculations, as for the aluminium, assume price for one pipe and do not consider bulk purchase discounts.

Being of least weight and least cost, the 200mm outside diameter ABS and PHA/PHB pipes and 315mm PE and PP pipes will be compared in more detail to other substitute materials. For PE and PP materials being of lower Young's modulus, require a larger diameter with associated larger moment of inertia to give the same stiffness of the cross section compared to ABS and PHA/PHB. This can be further supported by Appendix H.

8.6 COMPARISON OF VIABLE POTENTIAL SUBSTITUTE MATERIALS USING QFD.

A final comprehensive critical analysis of each material was undertaken using a more detailed QFD with additional criteria, see Table 13. From this analysis using a total score threshold of at least 300, ABS and Al-alloy can be identified as viable substitute materials for existing low utilised steel braces. The optimised steel circular hollow section is also a viable alternative for existing low utilised steel braces. Validation by real world testing should be further considered.

Table 13: Quality function deployment map of viable substitute materials

	Criterion	Materials						
		ABS 200mm outside diameter x wall thickness 12.5mm	PE 315mm outside diameter x wall thickness 7.5mm	PHA/PHB 200mm outside diameter x wall thickness 12.5mm	PP 315mm outside diameter x wall thickness 7.5mm	Al-alloy (6061) 101.6mm outside diameter x wall thickness 4.3mm	S275 steel 88.9mm outside diameter x wall thickness 2.1mm	S275 steel 114.3mm outside diameter x wall thickness 3.6mm
Critical	Strength	81	81	81	81	81	81	81
	Ease of joining	81	27	9	81	81	81	81
Important	Cost	27	9	0	9	27	27	9
	Thermal expansion	3	9	3	9	27	27	27
	Weight	27	9	27	9	27	27	3
	CO ₂ footprint primary production	3	9	3	9	3	27	27
	Reduction in manufacturing processes	27	27	27	27	9	3	3
	Manufacturing speed	27	27	9	27	9	3	3
	Renewable	0	0	27	0	0	0	0
	Recyclable	9	27	27	9	27	27	27
	Low water absorption	27	27	27	27	27	27	27
Desirable	Colour options	9	1	3	3	9	9	9
	Diameter of pipe	3	1	3	1	9	9	3
Total Score		321	254	246	291	327	348	300

9. CONCLUSIONS

Key criteria for potential substitute materials was established in collaboration with the team at Shufflebottom Ltd, critical criteria being strength and ease of joining. Important and desirable criteria were also established. This was applicable to Shufflebottom Ltd's future vision for their specific business requirements.

QFD was adopted in the decision making. QFD is widely regarded as being appropriate for evaluating engineering options. Using a screening QFD five viable substitute materials ABS, PE, PHA/PHB, PP and Al-alloy were identified. Commercially available circular hollow sections for these brace materials were identified. Using a more detailed QFD with additional criteria, ABS and Al-alloy were identified as viable substitute materials for existing low utilised steel braces. An optimised steel circular hollow section is also a very promising viable alternative for existing low utilised steel braces. Validation by real world testing should be further considered.

The potential substitute brace materials and optimised steel brace were sized based on hand calculations for imposed compression forces compliant with Eurocode 3. Calculations were validated with the use of Solidworks™ FEA confirming credibility.

Emphasis on the utilisation ratios and how it impacts the construction industry, not necessarily changing material but reducing size of low utilised members could have a significant impact on health and safety, expenditure, environment and reduced manufacturing times supported by Pistorius (2017) and Moynihan & Allwood (2014).

Bracing specification is determined by the structural engineer with the aid of specialist computer software CSC Fastrak™. The software will flag up bracing members that fail to meet strength requirements, thus allowing the engineer to increase specification of the bracing. However, a fundamental drawback in the design process is that all braces in a given building are given the increased specification, leading to over engineering of braces in some cases by ninety three percent supported by Moynihan & Allwood (2014). This case study building has a majority of braces utilised less than 50% due to significantly varying magnitude of imposed loads throughout the structure supported by Dunant, et al (2018).

10. LIMITATIONS

There are several limitations within this report which are important to acknowledge.

The report considers a single storey portal frame building subjected to high average wind loads. Salter, et al., (2004) recognise twelve portal frame designs with each having specific considerations in construction and reaction forces. Design specifications usually differ from project to project and therefore very little duplication of design solutions occurs. As a result, most construction projects tend to be 'one-off' jobs (M.F.Humphreys, n.d.).

Due to the time constraints and the complexity of all loads that impact a building, not all reactions, moments or bending forces were considered. Further detailed analysis would need to be undertaken to give a greater understanding of how these would impact the potential substitute materials and optimised steel brace. The most common crushing and buckling modes of failure have been considered, their applicability to polymers is uncertain.

Cognitive barriers towards alternative materials maybe met from most people having a bias to current practices (Hammond, et al., 1999).

Increasing competence in the use of CES software could prove an invaluable and effective selection of materials. Limits of knowledge and experience of the software were realised, however it remained successful in identifying potential candidates. CES also had limitations that not all information could be established from level 2. Manufacturing speeds and mass production processes could not be established. To overcome this literature review was utilised in establishing criteria CES could not identify. Altering to CES level 3 may have presented more options however was not investigated. It is also important to state that CES cannot keep up with the cost volatility of the market, as stated in the costings calculations of the members. Unless updated regularly the software data will not be current.

Custom size CHS could be manufactured for this specific application however, this was beyond the scope of this project. Commercially available standard stock sized materials were used.

Numerous companies were contacted throughout the case study to obtain first hand data but only a small percentage responded and of those the information was not useable.

Literature review did not identify this type of study being conducted before, therefore this is first of its kind. Underutilisation has been studied and quantified for entire buildings by Moynihan & Allwood (2014) and Dunant, et al (2018). However, this report looks directly at the underutilisation of bracing. It suggests the bracing is one of the largest contributors to the underutilisation of buildings supporting Moynihan & Allwood (2014) and Dunant, et al (2018).

The study does not consider extra rigidity associated with fixtures and fittings such as purlins, cladding and ground anchorage. All of these will further increase the stability and strength of the building.

11. RECOMMENDATIONS AND FUTURE DIRECTION

Recommendations for building bracing made in this report will have potential for applicability to other buildings, as suggested by the structural engineer. Ultimately the report found:

- The majority of existing steel bracing manufactured are significantly over engineered.
- To update or renew CSC Fastrak structural building software. Retrain users to gain greater knowledge of the software.
- Existing steel braces with a force utilisation ratio of 0-25% can be replaced with reduced section size saving direct costs of approximately £17,000 per annum and significantly improving the majority of the justifications highlighted. All of which can be manufactured within the current facility, essentially no investment required, just smarter design.
- The existing steel grade advantageous with cost and many properties remains an attractive material. However less conservative design of bracing can bring about improved competitive advantage and manufacturing processes less troublesome with more reliable machinery.
- ABS and Al-alloy offer potential as substitute materials of construction for low utilised braces. Further analysis is required including applicability of buckling and crushing modes of failure.

These recommendations shall be presented to stakeholders at Shufflebottom Ltd in Q3-2018.

While undertaking this report Shufflebottom Ltd has expanded, investing in more assets with prospects of a new machinery to increase productivity. The cost savings identified in this report could potentially increase further, with the greater focus on producing more.

It has been considered that a cylindrical cross section is the strongest for bracing. However, Keller (1960) contests this as their study indicated that an equilateral triangle is stronger. They found changing from a circle cross section increased the critical buckling load by 20.9%, and by further tapering the cross section increased the critical buckling

load by 61.2%. This would be a consideration for future designs and may result in a reduction in material used in the manufacture of the member.

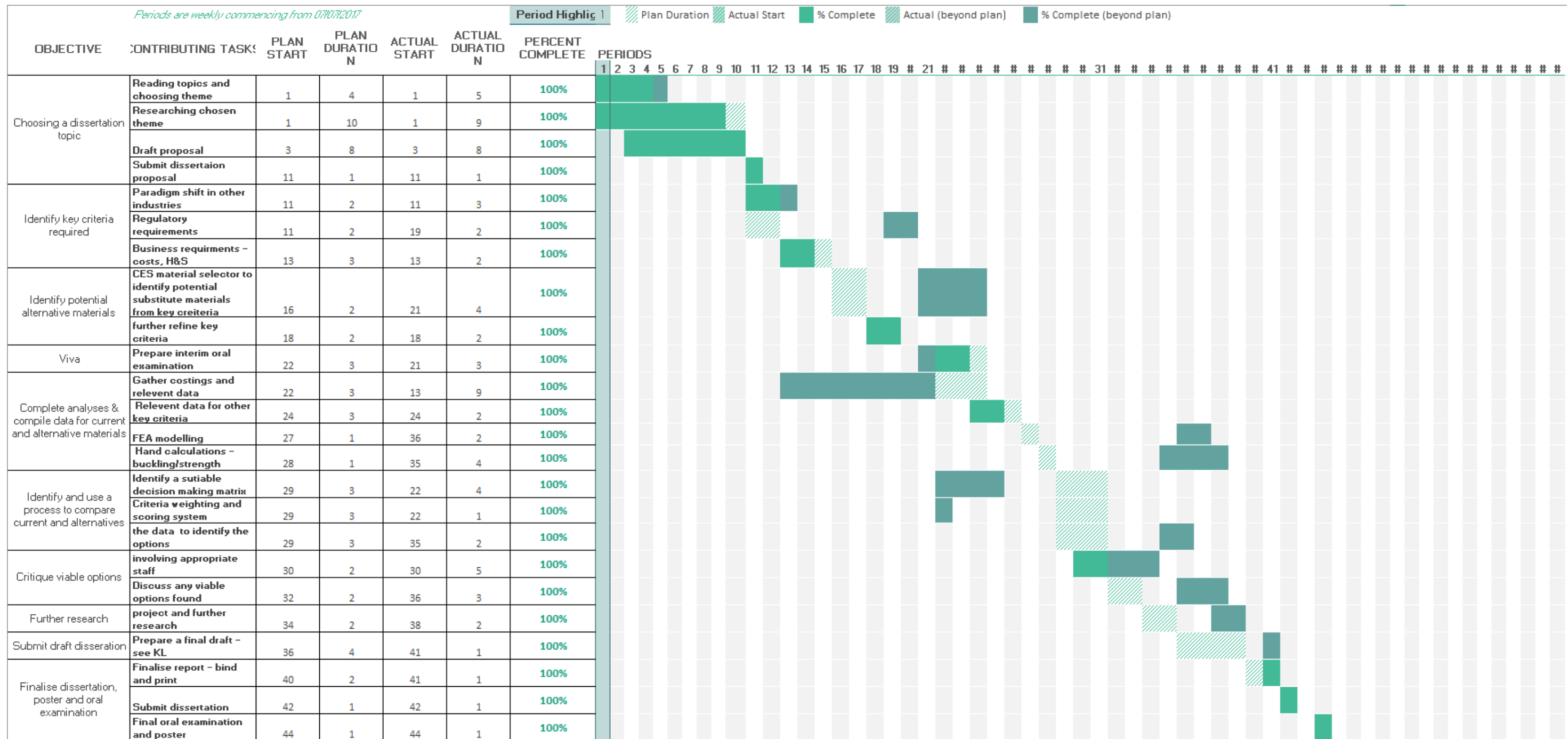
The University of Toronto have developed an efficient method of converting CO₂ into ethylene. This process has good potential for environmentally sustainable materials. However, the process requires the use of electrical currents aided by a copper catalyst creating a chemical reaction (Luna, et al., 2018)

Additive manufacturing was not considered in this case study, but with new technological advancements in the prototype stage it could have great potential in the future (Stratasys Ltd, 2016).

Base polymeric materials were the focus of study. Further insight into catalysts, fillings and additives should be considered to understand the performance characteristics of such polymeric materials.

Pistorius (2017) highlighted the risk averse attitude of the construction industry, along with its lack of innovation and resistance to change. Without a dramatic change within the construction sector it is unlikely that any changes will be incorporated.

12. GANTT CHART



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14. APPENDICES

Appendix A: Annual quantity of buildings manufactured at Shufflebottom Ltd.

Figures were obtained from a log book kept on the Voortman machine. The entries were based on entire projects the machine had processed over an annual period. The installation of the machine was in 2005 and complete logs were therefore generated from the year 2006. It is important to understand some small-scale projects such as stair cases may not include CHS bracing.

Year of production	Production	Notes
2006	280	
2007	275	
2008	284	
2009	284	
2010	456	Introduction of night time operations
2011	416	
2012	339	Larger contracts see a reduction in production
2013	355	
2014	494	
2015	435	
2016	578	
2017	474	474 buildings to date 11/10/17

Annual quantity of the production of bracing.

The fabricator manufactures all structural bracing keeping a comprehensive log for every brace fabricated. Analysing this data identified that 4103 braces were manufactured in 2016. Of which 70% are 88mm in diameter, 25% are 114mm and 5% are miscellaneous sizes such as 139 and 168mm. Further investigation identified 2273 of these were painted and 1830 were galvanised.

Pipe size diameter (mm)	Quantity produced
88	2872
114	1026
139 + 168	205
Total	4103

Calculation of the average weight of bracing.

Diameter of pipe (mm)	Length of pipe (mm)	Weight of pipe (kg)	Designation
88.9	6135	40.4	RB2
	5710	37.6	ET1
	6613	43.6	RB5
	5891	38.8	RB3
	5612	37.0	RB4
	5888	38.8	RB1
114.3	5684	55.0	ET2
	6170	59.0	SB2
	6346	61.0	SB1
	5879	56.0	SB3
	7353	71.0	SB1
	6219	60.0	RB8
	6408	62.0	RB5

$$40.4 + 37.6 + 43.6 + 38.8 + 37.0 + 38.8 + 55.0 + 59.0 + 61.0 + 56.0 + 71.0 + 60.0 + 62.0 = 660.20$$

$$\frac{660.20}{13} = 50.78kg$$

Average weight of pipe; 50.78 kg

Annual tonnage of steel bracing produced in 2016.

50.78 kg x 4103 pipes = 208,350.35 kg.

208.35 tonnes of steel had been used in the production of bracing by Shufflebottom Ltd in 2016.

Protection of bracing.

Two forms of protection are provided to buildings and the braces once fabricated. The first and most common is a base coat primer.

Painting expenditure.

From data evaluated 2273 braces had paint applied. Cost of paint was established from accounts to be £2.20 per litre of paint. The paint system used is a pneumatic driven motor directly coupled to an airless 200cc two-way pump capable of max 5000psi output.

Surface area of a cylinder: $\text{Area m}^2 = 2\pi rh + 2\pi r^2$

$$2\pi 0.0445 \times 6 + 2\pi 0.0445^2 = 1.69\text{m}^2$$

Surface area of average end plates (0.1x0.1x2) + (0.1x0.2x4) Neglecting 8mm thickness

Paint is extremely wasteful. Over spray must be accounted for even with a 314-tip fitted to a Graco XTR7 spray gun to try and reduce this as much as possible. However, this can still not be prevented even taking all measures to reduce it and with an experienced competent sprayer, roughly 10% is lost to overspray so this is taken into consideration.

Total cost of painting = £2431.00

Galvanising expenditure.

Number of braces galvanised: 1830

Average weight of brace: 50kg

The price to galvanise steel is £226 per tonne. Therefore $1830 \times 50 = 109,800$

$$109,800 \times 226 = £24,814.00$$

Shot depletion calculations.

To understand the severity of depletion collaboration with machine operators to remove samples of various pipes from the production line whilst not affecting production time was key. This allowed removal of braces and extraction of shot to retrieve average quantities of weight in each member. The information was logged.

Data collected on 12/10/17.

Shot depleting from Gietart VSB1050 Machine	
Pipe size (m)	Mass of shot collected (kg)
88x7.5	0.90
	0.88
88x6.5	1.05
	0.97
	0.98
114x7.5	1.90
	2.0

Mean average

$$0.90+0.88+1.05+0.97+0.98+1.90+2.0 = 8.68\text{kg}$$

$$\frac{8.68}{7} = 1.24\text{kg}$$

Number of pipes fabricated in 2016; 4103

$$4103 \times 1.24 = 5,087.72\text{kg}$$

In 2016, 5.09 tonne of abrasive shot had depleted from the machine and had been replaced with new shot. This shot will trickle out as the pipes are manoeuvred around the factory. The bulk of the shot will remain in the pipe once sealed.

Shot is purchased from Metalltechnik.

The shot costs £545.00 with an additional scrappage surcharge of £188.00 per tonne.

$545 + 188 = £733.00$ per tonne.

Depletion; 5.09 tonne

$5.09 \times 733 = £3,730.97$ Per annum to replace the shot which is removed from the blasting of CHS.

Cleaning of shot.

Cleaning operations to maintain a safe working environment is carried out via an external contract with RNA this is carried out twice a month.

Hours for RNA to clean the factory; 4 hours per visit two visits per month equates to 8 hours.

Cost per hour; £31.00

$8 \times 31 = £248.00$ Per month.

$248 \times 12 = £2,976.00$ per annum.

Replenishment of shot and cleaning activities combined.

$3,730.97 + 2,976.00 = £6,706.97$ Per annum.

Annual fuel consumption

Shufflebottom Ltd has four Large goods vehicles (LGV). Mileage has been obtained from MOT certificates to gain fuel consumption.

LGV Registration	Annual miles covered
CN16HLO	82506
CN66KWC	74764
CN66KWD	84815
CE13HTG	89714

Average annual mileage covered in a year by all LGV's; $82506 + 74764 + 84815 + 89714 = 331,799$ Miles

$$\frac{331,799}{4} = 82,949.75 \text{ miles}$$

MTRU (2007) identify that weight has a significant impact on the miles per gallon (MPG) of LGV vehicles, on average a weight saving of three tonnes will yield a 3% increase in MPG.

Axle weight Configuration MPG	
44t	7.2 MPG (including 3%)
41t	7.5 MPG (including 3%)

(MTRU, 2007)

£5.33 per gallon of diesel was the UK average in October 2017 (Automobile Association, 2017)

44t LGV fuel consumption costs:

$$\frac{82949.75}{7.2} = 11520.80 \text{ gallons}$$

$$11520.80 \times 5.33 = £61,405.86 \text{ Per annum}$$

41t LGV fuel consumption costs:

$$\frac{82949.75}{7.5} = 11059.97 \text{ gallons}$$

$$11059.97 \times 5.33 = £58,949.64 \text{ per annum}$$

Potentially saving £2456.22 on fuel when 3t lighter.

However, according to Bandivadekar, et al., (2008) between 12-20% reduction in fuel consumption could be achieved if a vehicles weight is reduced by up to 35%. By removing the shot from within the pipes, if the vehicles overall weight is reduced by 35% then there is a potential saving of £12,568.15 to £7,540.89 per 200,000km. looking at the average distance travelled by a Shufflebottom Ltd LGV this equates to:

$$200,000\text{km} = 124,274.24 \text{ miles}$$

$$\text{Average annual mileage} = 82949.75$$

Annual saving of £8,388.90 to £5,033.34 on fuel consumption.

If you take an average between (MTRU, 2007) and (Bandivadekar, et al., 2008) the annual potential saving is:

$$(\pounds 2,513.62 + \pounds 8,388.90 + \pounds 5,033.34) / 3 = \pounds 5,311.95$$

Amenities expenditure

A full year's electricity bill was obtained. With this information an average electricity price per annum was attained to which is; £118,666.85 at which for the entire year the rate at which it was charged was 11.120 pence per unit.

Further information from the Gietart and Voortman machines were gained from the machine manuals, these manuals identify the simultaneous load cases each machine operates.

Electricity charge per unit Days rate; 11.0120 pence.

Gietart Shot blaster; 60 kW.

60 kilowatts x 69 hours x 11.0120p = £455.89 per annum

Drill, Saw demand load; 20 kW.

20-kilowatt x 138 hours x 11.0120p = £303.93 per annum

Copies of invoices used in the calculations are included;

11. TECHNICAL DATA

		KempArc Pulse 350	KempArc Pulse 450
Connection voltage	3~50/60 Hz	400 V -15 %...+20 %	400 V -15 %...+20 %
Rated power	60 % ED		22.1 kVA
	80 % ED	16.0 kVA	
	100 % ED	15.3 kVA	17.8 kVA
Connection cable	HO7RN-F	4G6 (5 m)	4G6 (5 m)
Fuse (delayed)		25 A	35 A
Load capacity 40 °C	60 % ED		450 A
	80 % ED	350 A	
	100 % ED	330 A	350 A
Welding current and voltage range		10 V ... 50 V	10 V ... 50 V
Open circuit voltage		50 V	50 V
Open circuit power		100 W	100 W
Power factor at max. current		0.85	0.9
Efficiency at max. current		88 %	88 %
Operating temperature range		-20 ° C ... +40 ° C	-20 ° C ... +40 ° C
Storage temperature range		-40 ° C ... +60 ° C	-40 ° C ... +60 ° C
EMC class		A	A
Degree of protection		IP23S	IP23S
Minimum short circuit power S_{sc} of supply network *		5.5 MVA	5.5 MVA
External dimensions	L x W x H	590 x 230 x 430 mm	590 x 230 x 430 mm
Weight		36 kg	36 kg
Voltage supply for auxiliary devices		50 V DC / 100 W	50 V DC / 100 W
Fuse (delayed)		6.3 A	6.3 A
Voltage supply for cooling unit		24V DC / 50 VA	24V DC / 50 VA

* See paragraph 2.4

KempArc Pulse 350, 450 / © Kemppt Oy / 1044

EN

DT 400		
Operating voltage		50 V DC
Rated power		100 W
Load capacity 40 °C	80% ED	600 A
	100% ED	500 A
Operating principle		4 wheel feed
Wire feed speed		0 ... 25 m/min
Filler wires ø	Fe, Ss	0.6 ... 1.6 mm
	Flux-cored wire	0.8 ... 1.6 mm
	Al	1.0 ... 1.6 mm
		Euro
Welding gun connector		-20 °C ... +40 °C
Operating temperature range		-40 °C ... +60 °C
Storage temperature range		A
EMC class		IP23S
Degree of protection		
External dimensions	L x W x H	269 x 175 x 169 mm
Weight		4.5 kg



2 of 3

SHUFFLEBOTTOM LIMITED
SHUFFLEBOTTOM LIMITED
CROSS HANDS BUSINESS PARK
CROSS HANDS
LLANELLI DYFED
SA14 6RE

43552.
September 2017
period 01/2017



Electricity

Your site reference number
261188147



Manage your account online at
ssebusiness.co.uk



Call us with any enquiries
0345 0700766

Invoice period from 1 Sep 2017 to 30 Sep 2017
Available capacity 275 kVA
VAT number 553 7696 03



Supply to: **Shufflebottom Limited, Cross Hands Business Park,
Cross Hands, Llanelli Dyfed SA14 6RE**

Invoice

Tax point date 5 October 2017
Meter Number(s) K05D01603

Recorded MD unrestricted 237.80

Day/Night

	Units	Rate (pence)	Amount (£)
Day units	54997.00	11.0120	6,056.27
Night units	21817.50	6.1120	1,333.48
Available capacity	275.00	84.0000	231.00
Monthly charge			54.09
Unauthorised kVA - Aug2017	6.00	84.0000	5.04
Reactive power adjustment			91.61
Feed in tariff charge	76814.50	0.4710	361.80

CCL on 76814.5 units at 0.5680p 436.30

VAT at 20.00% on charges of £8,569.59 1,713.91

Total this invoice 10,283.50

Balance from previous statement 10,141.63

Payment received 23 September 2017 10,141.63 CR

TOTAL THIS ACCOUNT 10,283.50

The current contract for this supply ends on 31 January 2018. You can terminate this Agreement by giving us written notice no later than 1 January 2018. Please email us at businesscontracts@sse.com so that we can look into your future contract options.

S 00 845 300
21 9998 9650 560

7200 21.4240
5032 64 2719

ENTERED 09 OCT 2017

Date: 17/10/2017
Time: 10:43:44

Shufflebottom Limited
Supplier Activity (Summary)

Page: 1

Date From: 01/10/2016
Date To: 30/09/2017

Supplier From: VOORTMAM
Supplier To: VOORTMAM

Inc b/fwd transaction: No
Exc later payment: No

Transaction From: 1
Transaction To: 99,999,999

** NOTE: All report values are shown in Base Currency, unless otherwise indicated **

A/C:	VOORTM	Name:	Voortman Steel Machinery BV -	Contact:	Tel:	0031 548 536373			
No	Items	Type	Date	Ref	Details	Value	O/S	Debit	Credit
282167	1	PP	10/10/2016	FSP	Purchase Payment	3,324.06	0.00	3,324.06	
282427	1	PP	14/10/2016	FSP 21.10.16	Purchase Payment	5,145.10	0.00	5,145.10	
282738	1	PI	20/10/2016	90047901	SF79643 Clamp Parts	855.14	0.00		855.14
284656	1	PI	17/11/2016	90048911	SF79840 Stock	365.28	0.00		365.28
285438	1	PP	22/11/2016	Trans 25/11	Purchase Payment	855.14	0.00	855.14	
285642	1	PI	22/11/2016	90049088	SF79840 Stock	60.23	0.00		60.23
286479	1	PI	30/11/2016	90049434	SF80074 Keyboards	464.80	0.00		464.80
287268	1	PP	12/12/2016	Trans 19/12	Purchase Payment	890.31	0.00	890.31	
287382	1	PI	13/12/2016	90049768	SF80196 Stock	1,230.72	0.00		1,230.72
287950	1	PI	03/01/2017	90050467	SF80196 Stock	469.28	0.00		469.28
287951	1	PI	02/01/2017	90050444	Annual Contract	6,651.84	0.00		6,651.84
288656	1	PI	12/01/2017	90050827	SF80241 Stock	1,686.20	0.00		1,686.20
289614	1	PI	24/01/2017	90051231	SF80241 Stock	17.70	0.00		17.70
289798	1	PP	30/01/2017	FSP	Purchase Payment	8,351.84	0.00	8,351.84	
289799	1	PP	30/01/2017	Bacs	Purchase Payment	1,703.90	0.00	1,703.90	
290643	1	PI	06/02/2017	90051655	SF80734 Stock	242.15	0.00		242.15
290644	1	PI	06/02/2017	90051632	SF80750 Stock	940.32	0.00		940.32
291169	1	PI	13/02/2017	9051921	SF80840 Stock	93.45	0.00		93.45
291170	1	PI	13/02/2017	90051920	SF80840 Stock	41.52	0.00		41.52
291518	1	PI	20/02/2017	90052231	SF80855 Stock	1,025.38	0.00		1,025.38
292341	1	PI	27/02/2017	90052377	SF81061 Stock	1,510.20	0.00		1,510.20
292601	1	PI	28/02/2017	90052537	SF80855 Stock	296.50	0.00		296.50
292880	1	PP	08/03/2017	Trans 10/03	Purchase Payment	2,639.32	0.00	2,639.32	
293294	1	PC	13/03/2017	90052943	SF81061 Stock	1,447.30	0.00	1,447.30	
294460	1	PP	29/03/2017	Bacs 31/03	Purchase Payment	62.90	0.00	62.90	
295620	1	PI	12/04/2017	90054080	SF81633 Stock	571.41	0.00		571.41
296182	1	PI	26/04/2017	90054543	SF81805 Stock	53.80	0.00		53.80
296928	1	PP	05/05/2017	FSP 12.5.17	Purchase Payment	625.21	0.00	625.21	
297131	1	PI	04/05/2017	90054800	SF81932 Stock	157.95	0.00		157.95
298845	2	PI	23/05/2017	90055570	SF82061 Stock	907.95	0.00		907.95
299107	1	PI	31/05/2017	90055728	SF82224 Stock	1,568.70	0.00		1,568.70
299108	1	PI	31/05/2017	90055852	SF82061 Stock	870.75	0.00		870.75
299358	1	PP	06/06/2017	Trans 15/06	Purchase Payment	1,065.90	0.00	1,065.90	
300310	1	PI	15/06/2017	90056283	SF82543 Stock	270.10	0.00		270.10
300311	1	PI	15/06/2017	90056349	SF82498 Cables	450.94	0.00		450.94
301640	1	PI	22/06/2017	90056544	SF82297 Stock	2,775.03	0.00		2,775.03
301641	1	PI	22/06/2017	90056655	SF82498 Cables	34.87	0.00		34.87
301642	1	PI	29/06/2017	90057013	SF82498 Cables	34.87	0.00		34.87
301643	1	PI	27/06/2017	90056748	SF82730 Stock	4,557.00	0.00		4,557.00
301651	1	PP	05/07/2017	FSP 07.07.17	Purchase Payment	3,160.49	0.00	3,160.49	
301979	1	PI	06/07/2017	90057254	SF62131 Stock	388.32	0.00		388.32
301981	2	PI	06/07/2017	90057232	SF82280 Stock	1,680.66	0.00		1,680.66
302386	1	PI	11/07/2017	90057430	SF82131 Drill Cams	1,140.93	0.00		1,140.93
302891	1	PI	14/07/2017	90057552	SF83019 Stock	1,718.09	0.00		1,718.09
303103	1	PP	24/07/2017	Trans 24/07	Purchase Payment	7,401.77	0.00	7,401.77	
303826	1	PC	20/07/2017	90057802	SF82730 Stock	279.24	0.00	279.24	
304417	1	PI	31/07/2017	90058181	SF83192 Stock	1,307.20	0.00		1,307.20
305782	1	PI	21/08/2017	90058633	SF83274 Stock	324.76	0.00		324.76
305842	1	PI	21/08/2017	90058768	SF83539 Stock	1,245.36	0.00		1,245.36
307157	1	PP	06/09/2017	Transfer	Purchase Payment	5,955.96	0.00	5,955.96	
307708	1	PI	12/09/2017	90059554	SF83838 Stock	540.37	0.00		540.37
307709	1	PI	31/08/2017	90059326	SF83564 Stock	839.05	0.00		839.05
309199	1	PP	26/09/2017	Trans 29/09	Purchase Payment	2,409.17	0.00	2,409.17	

Date: 17/10/2017
Time: 10:43:21

Shufflebottom Limited
Supplier Activity (Summary)

Page: 1

Date From: 01/10/2015
Date To: 30/09/2016

Supplier From: VOORTMAM
Supplier To: VOORTMAM

Inc b/fwd transaction: No
Exc later payment: No

Transaction From: 1
Transaction To: 99,999,999

** NOTE: All report values are shown in Base Currency, unless otherwise indicated **

A/C: VOORTM Name: Voortman Steel Machinery BV - Contact: Tel: 0031 548 536373

No	Items	Type	Date	Ref	Details	Value	O/S	Debit	Credit
254874	1	PI	02/10/2015	90036007	SF73846 Stock	1,286.21	0.00		1,286.21
255817	1	PI	14/10/2015	90036484	SF74474 Stock	599.30	0.00		599.30
256479	1	PP	26/10/2015	Bacs	Purchase Payment	1,290.33	0.00	1,290.33	
256720	1	PI	30/10/2015	9036850	SF74723 Stock	173.52	0.00		173.52
257968	1	PP	12/11/2015	Transfer	Purchase Payment	2,059.03	0.00	2,059.03	
258000	1	PI	12/11/2015	900037295	SF74431 Stock	297.88	0.00		297.88
258001	1	PI	12/11/2015	900037250	SF74827 Stock	2,930.40	0.00		2,930.40
258002	2	PI	12/11/2015	90037231	SF74923 Stock	141.18	0.00		141.18
258004	1	PI	12/11/2015	90037292	SF74827 Stock	176.80	0.00		176.80
258647	2	PI	19/11/2015	90037447	SF74931 Stock	287.32	0.00		287.32
258649	2	PI	20/11/2015	90037530	SF74919 Stock	555.40	0.00		555.40
259206	1	PI	27/11/2015	90037743	SF75081 Stock	367.66	0.00		367.66
260161	1	PP	08/12/2015	Trans 11/12	Purchase Payment	4,756.64	0.00	4,756.64	
260328	1	PI	11/12/2015	90038142	SF75240 Stock	134.66	0.00		134.66
260983	1	PP	06/01/2016	Trans 11/01	Purchase Payment	134.66	0.00	134.66	
261987	2	PI	07/01/2016	323289	SF74994 Stock	1,613.29	0.00		1,613.29
261989	1	PI	05/01/2016	90038636	Annual Contract 01/01/16 to	3,992.64	0.00		3,992.64
261990	2	PI	14/01/2016	900039014	SF75579 Stock	817.81	0.00		817.81
262557	1	PP	25/01/2016	Transfer	Purchase Payment	6,423.74	0.00	6,423.74	
264129	1	PI	04/02/2016	90039637	SF75786 Stock	321.22	0.00		321.22
264215	1	PI	12/02/2016	90039873	SF75850 Stock	257.97	0.00		257.97
264216	1	PI	12/02/2016	900039848	SF75889 Stock	420.45	0.00		420.45
264932	1	PI	22/02/2016	90040081	SF75889 Bearing	17.49	0.00		17.49
265154	1	PI	26/02/2016	900040383	SF75976 Stock	580.36	0.00		580.36
265155	1	PI	26/02/2016	900040330	SF75240 Stock	110.37	0.00		110.37
265896	1	PP	07/03/2016	PP 09.03.16	Purchase Payment	1,017.13	0.00	1,017.13	
266193	1	PP	15/03/2016	Trans 29/03	Purchase Payment	690.73	0.00	690.73	
266366	1	PI	10/03/2016	90040794	SF76052 Stock	877.23	0.00		877.23
267061	1	PI	24/03/2016	90041145	SF76418 Stock	620.23	0.00		620.23
268408	1	PP	21/04/2016	Trans 25/04	Purchase Payment	1,497.46	0.00	1,497.46	
269715	2	PI	28/04/2016	90042190	SF76794 Stock	629.90	0.00		629.90
269714	1	PI	12/05/2016	900042527	SF77072 Stock	1,261.77	0.00		1,261.77
269714	1	PI	12/05/2016	90042605	SF76873 Stock	171.25	0.00		171.25
270706	1	PP	19/05/2016	FSP 27.5.16	Purchase Payment	629.90	0.00	629.90	
271744	1	PP	31/05/2016	FSP 10.06.16	Purchase Payment	1,433.02	0.00	1,433.02	
275154	1	PI	11/07/2016	900044636	SF77268 Coverplate	541.97	0.00		541.97
275155	1	PI	11/07/2016	90044637	SF77268 Oil Ring Seal	10.32	0.00		10.32
276274	1	PP	26/07/2016	Bacs 11/08	Purchase Payment	552.29	0.00	552.29	
276522	1	PI	27/07/2016	90045038	SF78043 R&M Shot Blaster	1,003.38	0.00		1,003.38
278685	3	PI	25/08/2016	90045846	SF78530 Stock	861.43	0.00		861.43
278691	1	PP	23/08/2016	Bacs 26.8.16	Purchase Payment	1,003.38	0.00	1,003.38	
279131	1	PI	31/08/2016	90046099	SF78524 Stock	2,462.63	0.00		2,462.63
279652	2	PI	08/09/2016	90046277	SF78668 Stock	1,772.87	0.00		1,772.87
280262	1	PI	15/09/2016	90046549	SF78524 Stock	132.66	0.00		132.66
280263	1	PI	15/09/2016	9006498	SF78874 Stock	676.61	0.00		676.61
280264	1	PI	15/09/2016	90046446	SF78940 Stock	694.21	0.00		694.21
281049	1	PI	23/09/2016	90046839	SF78956 Stock	1,868.75	0.00		1,868.75

Totals: 7,178.83 0.00 21,488.31 28,667.14

Amount Outstanding: 0.00
Amount paid this period: 21,488.31
Credit Limit £: 0.00

Date: 17/10/2017
Time: 10:43:44

Shufflebottom Limited
Supplier Activity (Summary)

Page: 2

309460	1	PI	26/09/2017	90060090	SF84053 Parts	1,952.03	0.00	1,952.03
309605	1	PI	29/09/2017	90060337	SR84053 R&M Voortman	19.02	0.00	19.02
Totals:						<u>-5,957.74</u>	<u>0.00</u>	<u>45,317.61</u>
Amount Outstanding:						0.00		<u>39,359.87</u>
Amount paid this period						43,591.07		
Credit Limit £						0.00		



Unit 5 Raven Industrial Estate, Garmant
Ammanford, Carmarthenshire, SA18 1NS
Tel: 0800 002 9253, Fax: 0844 504 9251

SHUFFLEBOTTOM LTD
CROSSHANDS BUSINESS PARK
CROSSHANDS
LLANELLI

Delivered to:
CROSSHANDS BUSINESS PARK
CROSSHANDS
LLANELLI

SA14 6RE

SA14 6RE

Order Date 15/09/2017
Order Time 12:01
Order Depot MAIN
Reference
Del Comment

SALES INVOICE

Account No	Invoice Date	Due Date	Invoice No
234	15/09/2017	15/10/2017	10004584

Product	Description	Quantity	Price	VAT Rate	VAT Value	Value
BULKPRO	BULK PROPANE	1379	0.2400	20.00	66.19	330.96
CCL	Climate Change Levy	1379	0.0064	20.00	1.77	8.83

ENTERED 10 SEP 2017

Nett	339.79
VAT	67.96
Total	407.75

VAT Registration Number GB 159 5706 74.

SHOULD YOU WISH TO PAY DIRECT INTO OUR BANK PLEASE USE

Sort Code: 400827
A/c No: 51505645
Reference: 0000000234



Unit 5 Raven Industrial Estate, Garnant
Ammanford, Carmarthenshire, SA18 1NS
Tel: 0800 002 9253, Fax: 0844 504 9251

SHUFFLEBOTTOM LTD
CROSSHANDS BUSINESS PARK
CROSSHANDS
LLANELLI

Delivered to:
CROSSHANDS BUSINESS PARK
CROSSHANDS
LLANELLI 78881

SA14 6RE

SA14 6RE

Order Date 12/10/2017
Order Time 14:42
Order Depot MAIN
Reference
el Comment Tank rental till Oct 2018 x 2 vessels
OK

SALES INVOICE

Account No	Invoice Date	Due Date	Invoice No
234	12/10/2017	15/11/2017	10004834

Product	Description
TNKRENT	Tank Rental

Quantity	Price	VAT Rate	VAT Value	Value
2	50.0000	20.00	20.00	100.00

2

ENTERED 13 OCT 2017

ENTERED 31 OCT 2017

Nett	100.00
VAT	20.00
Total	120.00

VAT Registration Number GB 159 5706 74.

SHOULD YOU WISH TO PAY DIRECT INTO OUR BANK PLEASE USE

Sort Code: 400827
A/c No: 51505645
Reference: 0000000234

Invoice

Shufflebottom LTD
Crosshands Business Park
Crosshands
Llanelli
Carmar
SA146RE



Invoice/Tax Date: 24/08/2017
Invoice No: INV6363917332224
Print Date: 24-Aug-17
Customer Ref.
Order No: 57719

Job No	Date	Service	Site	Qty/Rate	Net
JOB6359863607148	17/08/17	Road Sweeper Hire	Crosshands Depot	4 @ £31.00	124.00
Net sub-total					£124.00
Discount					£0.00
Net					£124.00
VAT @ 20 %					£24.80
Invoice Total					£148.80

Additional details

Service description: Hourly charged road sweeper hire. **Hire unit:** Hour. **Comments:** .

Proof of delivery

Job: JOB6359863607148, 17/08/2017

Route:
no GPS positions were recorded

no signature was recorded for this job

ENTERED 7 SEP 2017

RNA Plant Ltd

E2
Capel Hendre Industrial Estate
Capel Hendre
Carmarthenshire
SA18 3SJ

Phone: +44 (0) 845 4379523
Fax: +44 (0) 845 4379524
Mobile: +44 (0) 7831 158281
Email: info@rnaplant.co.uk
Web: www.rnaplant.co.uk

Powered by



Company No: 04501922 – VAT Reg: 272 0746 10

Metalltechnik (UK) LTD

Almore House • Yew Tree Meadow • Mamble Road • Clows Top • Worcestershire • DY14 9HX
Telephone No.: 01299 832 100 • Fax No.: 01299 832 091

Invoice

VAT Reg No: GB 549 7887 64

Shufflebottom Ltd
Cross Hands Business Park
Cross Hands
Llanelli
Carms
SA14 6RE

Invoice: M06636

Date: 28 June 2017

Description	Amount	VAT	Total
FERROSAD Steel Shot	£	£	£
Your Order No: 82626 <i>stock</i>			
8.00 tonnes of F24/S330 @ £	545.00 per unit	4,360.00	872.00
8.00 scrap surcharge of material @ £	188.00 per unit	1,504.00	300.80
	<i>733.</i>		
Delivery Note: DN17/0381a			
Delivered: week 26			
	5,864.00	1,172.80	7,036.80

For Metalltechnik (UK) Ltd

VAT: £ 1,172.80

Total: £ 7,036.80

P J Moore

Payment Terms: 30 days month end

Please pay by: 31 July 2017

Customer VAT No: GB 471 8610 68

Risk will pass to the customer upon delivery, title will remain with Metalltechnik (UK) Ltd until such time as the customer has paid for the goods in full. Until such time, the customer shall be deemed to hold the goods for Metalltechnik (UK) Ltd in the capacity of a judiciary capacity only. In the event of insolvency, liquidation or a winding up of the company, the agents of Metalltechnik (UK) Ltd shall be entitled to retrieve the unused material, even though it may not have become due for payment.

Reg No. 2577045 V.A.T. Reg GB 549 7887 64
Registered Address: Black Country House, Rounds Green Road, Oldbury B69 2DG

ENTERED 6 JUL 2017

Protega Paints Ltd
Kelvin Way
West Bromwich
West Midlands B70 7JZ
Tel. +44 (0)121 525 5665
Fax. +44 (0)121 553 2787
www.protegapaints.com



Invoice No : 0338326

Date : 01 NOV 2017

Invoice

Delivered to:

SHUFFLEBOTTOM LTD
CROSS HANDS BUSINESS PARK
CROSS HANDS
LLANELLI CARMARTHENSHIRE
SA14 6RE

SHUFFLEBOTTOM LTD

83710 Stock

Account Number
S0633M
Product Code

Customer Order No.

Despatch Date

VAT Reg No:130 8410 51
Page : 1

Terms

30 DAYS EOM
Price Per Unit VAT code

Value

Product Code	Description	Pack Size	Volume	Price Per Unit	VAT code	Value
6035002-200	ViterPrime 035 Grey 035/20003	200.000	1000.000	2.200	A	2200.00

ENTERED 01 NOV 2017

VAT Analysis

VAT code	Rate	Goods Value	VAT Amount
A	20.00	2200.00	440.00
Z	0.00	0.00	0.00
E	0.00	0.00	0.00

Total Goods	2,200.00
Total VAT	440.00
Total Payable	2,640.00

Please Make Cheques Payable to Protega Paints Ltd.

Colours may be supplied in quantities slightly different from the pack size stated
- the volume indicates the precise amount despatched and invoiced.

Subject to the Terms and Conditions of Sale printed on reverse.

Registered in England 7997189

INNOVATION PERFORMANCE VALUE



Hereford Galvanizers Limited
Westfields Trading Estate
Hereford HR4 9NS
Tel: (01432) 267664
Fax: (01432) 352735
E-mail: zinc@hereford.galvanizers.co.uk
http://www.galvanizers.co.uk

INVOICE

Shufflebottom Limited
Cross Hand Business Park
Cross Hands
Llanelli
Carmarthenshire SA14 6RE

Invoice No : OP/0102485
Invoice/Tax Date : 24/11/17
Account No : 2159
Advice Note No : 69506
Customer Order No : 84682
Works Ref.No : 1711192

QTY/TONNES	DESCRIPTION	LIST PRICE	NETT PRICE	NETT VALUE
21.920	Galvanized Columns-Beams	195.70	195.70	4289.74
21.920	Zinc Surcharge	30.00	30.00	657.60
12024 ok Buckner				
ENTERED 27 11 2017				

GOODS TOTAL	£	4947.34
VAT (@20.0%)	£	989.47
INVOICE TOTAL	£	5936.81

Terms: Nett Cash Monthly



Quality Assured
to BS EN ISO 9001
1994 Registration Number FM 2031

VAT Registration No: GB 133 5027 05



A member of the Galvanizers Association
Registered in England 817600

Appendix B: CSC Fastrak calculated bracing loads and utilisation ratios (U/R).

		Shufflebottom Ltd Cross Hands Business Park Cross Hands, Llanelli Carmarthenshire SA14 6RE	CE Marking to BS EN 1090 K9756 Steel Framed Building design to RIDBA Protocol Spm	Page 28/29
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Brace Name	Section Size	Grade	Length [m]	Combination	N [kN]
BR 5/A/9-1/A/10	CHS 114.3x3.6	S275	7.075	Str ₁ 17G _{sup} D+Y _Q I+Y _Q RI	0.8
				Str _{3.1} 17G _{sup} D+Y _Q I+Y _Q RI+EHF _X	2.5
				Str _{3.2} 17G _{sup} D+Y _Q I+Y _Q RI+EHF _X	-1.4
				Str _{3.3} 17G _{sup} D+Y _Q I+Y _Q RI+EHF _Y	0.8
				Str _{3.4} 17G _{sup} D+Y _Q I+Y _Q RI+EHF _Y	0.8
				Str _{8.1} 17G _{sup} D+Y _Q W ₀ I+Y _Q W ₀ S+Y _Q W ₁ +EHF _X	36.9
				Str _{8.2} 17G _{sup} D+Y _Q W ₀ I+Y _Q W ₀ S+Y _Q W ₁ +EHF _X	34.0
				Str _{8.3} 17G _{sup} D+Y _Q W ₀ I+Y _Q W ₀ S+Y _Q W ₁ +EHF _Y	35.5
				Str _{8.4} 17G _{sup} D+Y _Q W ₀ I+Y _Q W ₀ S+Y _Q W ₁ +EHF _Y	35.4
				Str _{8.5} 17G _{sup} D+Y _Q W ₀ I+Y _Q W ₀ S+Y _Q W ₂ +EHF _X	31.7
				Str _{8.6} 17G _{sup} D+Y _Q W ₀ I+Y _Q W ₀ S+Y _Q W ₂ +EHF _X	28.8
				Str _{8.7} 17G _{sup} D+Y _Q W ₀ I+Y _Q W ₀ S+Y _Q W ₂ +EHF _Y	30.3
				Str _{8.8} 17G _{sup} D+Y _Q W ₀ I+Y _Q W ₀ S+Y _Q W ₂ +EHF _Y	30.2
				Str _{8.9} 17G _{sup} D+Y _Q W ₀ I+Y _Q W ₀ S+Y _Q W ₃ +EHF _X	-19.7
				Str _{8.10} 17G _{sup} D+Y _Q W ₀ I+Y _Q W ₀ S+Y _Q W ₃ +EHF _X	-22.7
				Str _{8.11} 17G _{sup} D+Y _Q W ₀ I+Y _Q W ₀ S+Y _Q W ₃ +EHF _Y	-21.2
				Str _{8.12} 17G _{sup} D+Y _Q W ₀ I+Y _Q W ₀ S+Y _Q W ₃ +EHF _Y	-21.2
				Str _{8.13} 17G _{sup} D+Y _Q W ₀ I+Y _Q W ₀ S+Y _Q W ₄ +EHF _X	35.8
				Str _{8.14} 17G _{sup} D+Y _Q W ₀ I+Y _Q W ₀ S+Y _Q W ₄ +EHF _X	32.8
				Str _{8.15} 17G _{sup} D+Y _Q W ₀ I+Y _Q W ₀ S+Y _Q W ₄ +EHF _Y	34.3
				Str _{8.16} 17G _{sup} D+Y _Q W ₀ I+Y _Q W ₀ S+Y _Q W ₄ +EHF _Y	34.3
				Str _{9.1} 17G _{sup} D+Y _Q W ₁ +EHF _X	35.8
				Str _{9.2} 17G _{sup} D+Y _Q W ₁ +EHF _X	34.5
				Str _{9.3} 17G _{sup} D+Y _Q W ₁ +EHF _Y	35.1
				Str _{9.4} 17G _{sup} D+Y _Q W ₁ +EHF _Y	35.1
				Str _{9.5} 17G _{sup} D+Y _Q W ₂ +EHF _X	30.6
				Str _{9.6} 17G _{sup} D+Y _Q W ₂ +EHF _X	29.2
				Str _{9.7} 17G _{sup} D+Y _Q W ₂ +EHF _Y	29.9
				Str _{9.8} 17G _{sup} D+Y _Q W ₂ +EHF _Y	29.9
				Str _{9.9} 17G _{sup} D+Y _Q W ₃ +EHF _X	-20.7
				Str _{9.10} 17G _{sup} D+Y _Q W ₃ +EHF _X	-22.1
				Str _{9.11} 17G _{sup} D+Y _Q W ₃ +EHF _Y	-21.4
				Str _{9.12} 17G _{sup} D+Y _Q W ₃ +EHF _Y	-21.4
				Str _{9.13} 17G _{sup} D+Y _Q W ₄ +EHF _X	34.6
				Str _{9.14} 17G _{sup} D+Y _Q W ₄ +EHF _X	33.3
				Str _{9.15} 17G _{sup} D+Y _Q W ₄ +EHF _Y	34.0
				Str _{9.16} 17G _{sup} D+Y _Q W ₄ +EHF _Y	34.0

Bracing Forces (Max/Min values)

Brace Name	Section Size	Grade	Length [m]	Max Comp [kN]	Max Tens [kN]
BR 9/B/1-9/B/2	CHS 114.3x3.6	S275	6.000	1.7	-25.1
BR 9/B/2-9/B/3	CHS 114.3x3.6	S275	6.000	1.5	-25.0
BR 9/B/3-9/B/4	CHS 114.3x3.6	S275	6.000	1.2	-24.7
BR 9/B/4-9/B/5	CHS 114.3x3.6	S275	6.000	0.8	-24.6
BR 9/B/5-9/B/6	CHS 114.3x3.6	S275	6.000	0.6	-24.5
BR 9/B/6-9/B/7	CHS 114.3x3.6	S275	6.000	0.8	-24.6
BR 9/B/7-9/B/8	CHS 114.3x3.6	S275	6.000	1.2	-24.7
BR 9/B/8-9/B/9	CHS 114.3x3.6	S275	6.000	1.5	-25.0
BR 9/B/9-9/B/10	CHS 114.3x3.6	S275	6.000	1.8	-25.2
BR 9/A/1-9/A/2	CHS 114.3x3.6	S275	6.000	1.7	-24.2
BR 9/A/2-9/A/3	CHS 114.3x3.6	S275	6.000	1.5	-24.1
BR 9/A/3-9/A/4	CHS 114.3x3.6	S275	6.000	1.2	-23.9
BR 9/A/4-9/A/5	CHS 114.3x3.6	S275	6.000	0.9	-23.7
BR 9/A/5-9/A/6	CHS 114.3x3.6	S275	6.000	0.6	-23.6
BR 9/A/6-9/A/7	CHS 114.3x3.6	S275	6.000	0.9	-23.7
BR 9/A/7-9/A/8	CHS 114.3x3.6	S275	6.000	1.2	-23.9
BR 9/A/8-9/A/9	CHS 114.3x3.6	S275	6.000	1.5	-24.1
BR 9/A/9-9/A/10	CHS 114.3x3.6	S275	6.000	1.8	-24.3
BR 21/2/13-19/1/14	CHS 114.3x3.6	S275	6.377	4.8	-4.3
BR 19/1/14-17/2/13	CHS 114.3x3.6	S275	6.358	14.5	-28.0
BR 17/2/13-14/1/14	CHS 114.3x3.6	S275	6.240	27.5	-14.2

14/02/201813:23:38

CSC Fastrak FBD.exe, version: 15.0.2.1www.cscworld.com

		Shufflebottom Ltd Cross Hands Business Park	CE Marking to BS EN 1090 K9756	
SHUFFLEBOTTOM I		Cross Hands, Llanelli Carmarthenshire SA14 6RE	Steel Framed Building design to RIDBA Protocol Spm	Page 29/29

Brace Name	Section Size	Grade	Length [m]	Max Comp [kN]	Max Tens [kN]
BR 14/1/14-11/2/13	CHS 114.3x3.6	S275	6.224	26.2	-46.6
BR 11/2/13-9/B/1	CHS 114.3x3.6	S275	6.377	47.6	-26.9
BR 12/9/13-9/B/10	CHS 114.3x3.6	S275	6.480	45.6	-15.1
BR 15/10/14-12/9/13	CHS 114.3x3.6	S275	6.480	15.1	-45.7
BR 18/9/13-15/10/14	CHS 114.3x3.6	S275	6.480	17.4	-4.7
BR 21/10/13-18/9/13	CHS 114.3x3.6	S275	6.480	4.7	-17.4
BR 21/10/13-18/9/14	CHS 114.3x3.6	S275	6.480	4.7	-15.2
BR 18/9/14-15/10/13	CHS 114.3x3.6	S275	6.480	15.3	-4.7
BR 15/10/13-12/9/14	CHS 114.3x3.6	S275	6.480	15.1	-39.7
BR 12/9/14-9/A/10	CHS 114.3x3.6	S275	6.480	39.6	-15.1
BR 21/2/13-19/1/13	CHS 114.3x3.6	S275	6.377	4.2	-4.9
BR 19/1/13-17/2/14	CHS 114.3x3.6	S275	6.358	14.6	-24.4
BR 17/2/14-14/1/13	CHS 114.3x3.6	S275	6.240	24.0	-14.2
BR 14/1/13-11/2/14	CHS 114.3x3.6	S275	6.224	26.2	-41.6
BR 11/2/14-9/A/1	CHS 114.3x3.6	S275	6.377	42.3	-26.9
BR 9/B/1-5/B/2	CHS 114.3x3.6	S275	7.075	37.7	-36.5
BR 5/B/2-1/B/1	CHS 114.3x3.6	S275	7.075	36.4	-37.8
BR 9/A/1-5/A/2	CHS 114.3x3.6	S275	7.075	37.8	-35.8
BR 5/A/2-1/A/1	CHS 114.3x3.6	S275	7.075	35.8	-37.8
BR 9/B/10-5/B/9	CHS 114.3x3.6	S275	7.075	22.6	-36.9
BR 5/B/9-1/B/10	CHS 114.3x3.6	S275	7.075	36.9	-22.6
BR 9/A/10-5/A/9	CHS 114.3x3.6	S275	7.075	22.6	-36.9
BR 5/A/9-1/A/10	CHS 114.3x3.6	S275	7.075	36.9	-22.7

14/02/2018

13:23:38

CSC Fastrak FBD.exe, version: 15.0.2.1, www.cscworld.com

	SHUFFLEBOTTOM Ltd	CE Marking to BS EN 1090	
	Cross Hands Business Park	K9756	
	Llanelli SA14 6RE	Steel Framed Building design to	
	Tel 01269 831831	RIDBA Protocol	
		Spm	Page 1

Steel Design Code: EC3 UK NA
Composite Design Code: EC4 UK NA

Column Summary

Column Ref	Lift No.	Section Size, Grade	Concrete Grade	U/R	Status
GC 1/13	1	Rolled, UB 356x171x45, S275		0.794	Pass
GC 1/14	1	Rolled, UB 356x171x45, S275		0.932	Pass
GC 1/15	1	Rolled, UB 356x171x45, S275		0.910	Pass
GC 1/16	1	Rolled, UB 356x171x45, S275		0.707	Pass
GC 10/21	1	Rolled, UB 356x171x45, S275		0.920	Pass
GC 10/20	1	Rolled, UB 356x171x51, S275		0.977	Pass
GC 10/17	1	Rolled, UB 356x171x45, S275		0.987	Pass

Column Ref	Critical Stack X No.	λ_{critx}	Critical Stack Y No.	λ_{crity}
PFC A/10	1	279.345	1	19.021
PFC B/10	1	279.360	1	19.024
PFC B/6	1	201.142	1	19.200
PFC B/5	1	201.149	1	19.200
PFC B/7	1	209.017	1	19.200
PFC B/4	1	209.039	1	19.200
PFC B/8	1	226.782	1	19.206
PFC B/3	1	226.825	1	19.206
PFC A/6	1	201.118	1	19.210
PFC A/5	1	201.125	1	19.210
PFC A/7	1	208.992	1	19.210
PFC A/4	1	209.014	1	19.210
PFC A/8	1	226.755	1	19.216
PFC A/3	1	226.798	1	19.216
PFC B/1	1	288.030	1	19.241
PFC A/1	1	288.005	1	19.245
PFC B/9	1	259.925	1	24.271
PFC A/9	1	259.893	1	24.283
PFC B/2	1	260.004	1	24.531
PFC A/2	1	259.973	1	24.543
GC 1/16	1	359.089	1	26.769
GC 1/13	1	359.067	1	26.774
GC 10/21	1	366.791	1	27.353
GC 10/17	1	366.774	1	27.354
GC 1/15	1	394.943	1	30.401
GC 1/14	1	394.934	1	30.402
GC 10/20	1	408.933	1	32.569

Bracing Summary

Brace Ref	Section Size	Grade	U/R	Status
BR 9/B/1-9/B/2	CHS 114.3x3.6	S275	0.072	Pass
BR 9/B/2-9/B/3	CHS 114.3x3.6	S275	0.071	Pass
BR 9/B/3-9/B/4	CHS 114.3x3.6	S275	0.071	Pass
BR 9/B/4-9/B/5	CHS 114.3x3.6	S275	0.070	Pass
BR 9/B/5-9/B/6	CHS 114.3x3.6	S275	0.070	Pass
BR 9/B/6-9/B/7	CHS 114.3x3.6	S275	0.070	Pass
BR 9/B/7-9/B/8	CHS 114.3x3.6	S275	0.071	Pass
BR 9/B/8-9/B/9	CHS 114.3x3.6	S275	0.071	Pass
BR 9/B/9-9/B/10	CHS 114.3x3.6	S275	0.072	Pass
BR 9/A/1-9/A/2	CHS 114.3x3.6	S275	0.068	Pass
BR 9/A/2-9/A/3	CHS 114.3x3.6	S275	0.068	Pass
BR 9/A/3-9/A/4	CHS 114.3x3.6	S275	0.067	Pass
BR 9/A/4-9/A/5	CHS 114.3x3.6	S275	0.066	Pass
BR 9/A/5-9/A/6	CHS 114.3x3.6	S275	0.066	Pass
BR 9/A/6-9/A/7	CHS 114.3x3.6	S275	0.066	Pass
BR 9/A/7-9/A/8	CHS 114.3x3.6	S275	0.067	Pass
BR 9/A/8-9/A/9	CHS 114.3x3.6	S275	0.068	Pass
BR 9/A/9-9/A/10	CHS 114.3x3.6	S275	0.068	Pass
BR 21/2/13-19/1/14	CHS 114.3x3.6	S275	0.060	Pass
BR 19/1/14-17/2/13	CHS 114.3x3.6	S275	0.158	Pass
BR 17/2/13-14/1/14	CHS 114.3x3.6	S275	0.303	Pass
BR 14/1/14-11/2/13	CHS 114.3x3.6	S275	0.274	Pass
BR 11/2/13-9/B/1	CHS 114.3x3.6	S275	0.540	Pass

CSC Fastrak FBD.exe, version: 14.1.0.24, www.cscworld.com

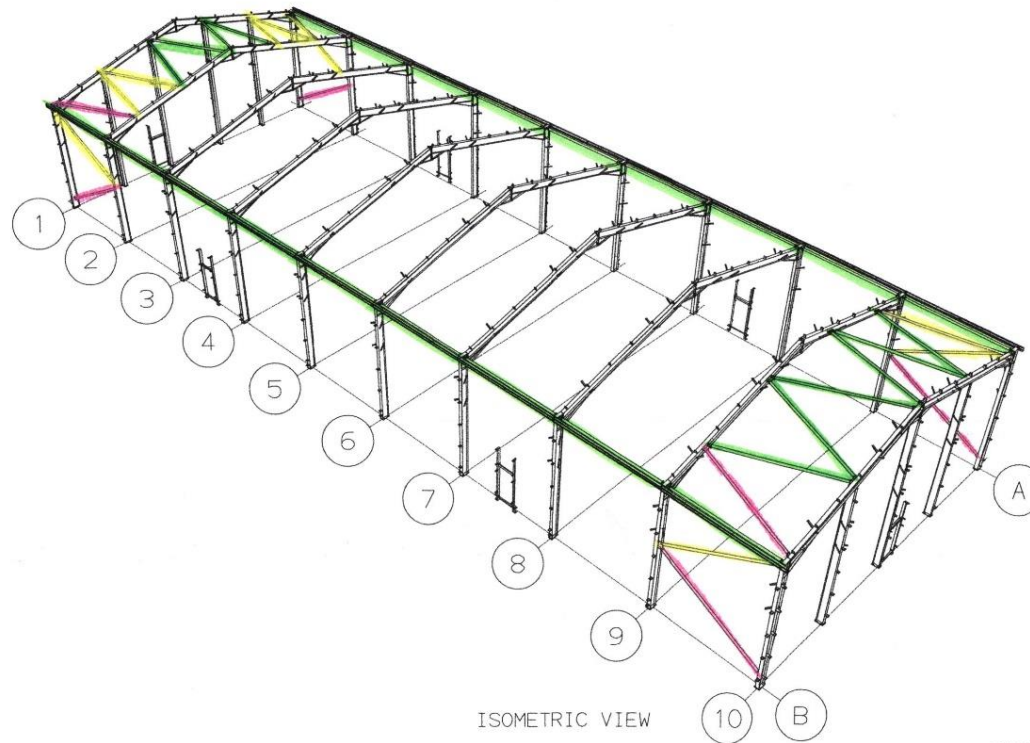
Brace Ref	Section Size	Grade	U/R	Status
BR 12/9/13-9/8/10	CHS 114.3x3.6	S275	0.533	Pass
BR 15/10/14-12/9/13	CHS 114.3x3.6	S275	0.170	Pass
BR 18/9/13-15/10/14	CHS 114.3x3.6	S275	0.206	Pass
BR 21/10/13-18/9/13	CHS 114.3x3.6	S275	0.053	Pass
BR 21/10/13-18/9/14	CHS 114.3x3.6	S275	0.053	Pass
BR 18/9/14-15/10/13	CHS 114.3x3.6	S275	0.180	Pass
BR 15/10/13-12/9/14	CHS 114.3x3.6	S275	0.170	Pass
BR 12/9/14-9/A/10	CHS 114.3x3.6	S275	0.464	Pass
BR 21/2/13-19/1/13	CHS 114.3x3.6	S275	0.053	Pass
BR 19/1/13-17/2/14	CHS 114.3x3.6	S275	0.158	Pass
BR 17/2/14-14/1/13	CHS 114.3x3.6	S275	0.263	Pass
BR 14/1/13-11/2/14	CHS 114.3x3.6	S275	0.274	Pass
BR 11/2/14-9/A/1	CHS 114.3x3.6	S275	0.470	Pass
BR 9/B/1-5/B/2	CHS 114.3x3.6	S275	0.505	Pass
BR 5/B/2-1/B/1	CHS 114.3x3.6	S275	0.498	Pass
BR 9/A/1-5/A/2	CHS 114.3x3.6	S275	0.505	Pass
BR 5/A/2-1/A/1	CHS 114.3x3.6	S275	0.479	Pass
BR 9/B/10-5/B/9	CHS 114.3x3.6	S275	0.303	Pass
BR 5/B/9-1/B/10	CHS 114.3x3.6	S275	0.502	Pass
BR 9/A/10-5/A/9	CHS 114.3x3.6	S275	0.303	Pass
BR 5/A/9-1/A/10	CHS 114.3x3.6	S275	0.503	Pass

	QTY
0 - 25 %	28
25 - 50 %	10
50 - 75 %	6
75 - 100 %	0

MODELLED ON STRUCAD - THE 3-D STRUCTURAL STEEL DETAILING SOLUTION.

DO NOT SCALE - IF IN DOUBT ASK

A3



STRUCAD

				CLIENT MACKAY	DRAWN	JH	16/12/10	 SHUFFLEBOTTOM LTD. CROSS HANDS BUSINESS PARK CROSS HANDS LLANELLI CARMARTHENSHIRE SA14 6RE TEL: 01269-831831 FAX: 01269-831031		
					CHECKED					
				PROJECT AGRICULTURAL BUILDING	GENERAL NOTES:					
				LOCATION ROSS-SHIRE	SCALE			JOB No.	DWG No.	REV
REV	BY	DATE	DETAILS		NTS			K9756	ISO-003	

Appendix C: Weights and dimensions of carbon steel pipe.

Weights and Dimensions of Carbon Steel Pipe

Blue: Wall Thickness in Millimeters
Red: Weight Per Meter in Kilograms

PIPE SIZE	O.D. in mm	A.S.A. PIPE SCHEDULES													DBLE. E.H.
		5	10	20	30	40	STD	60	80	E.H.	100	120	140	160	
1/8"	10.287	.089 0.21	1.24 0.28			1.73 0.37	1.73 0.37		2.41 0.47	2.41 0.47					
1/4"	13.716	1.24 0.38	1.65 0.49			2.24 0.63	2.24 0.63		3.02 0.80	3.02 0.80					
3/8"	17.145	1.24 0.49	1.65 0.63			2.31 0.84	2.31 0.84		3.20 1.10	3.20 1.10					
1/2"	13.716	1.65 0.80	2.11 1.00			2.77 1.62	2.77 1.62		3.73 0.80	3.73 0.80				4.78 1.95	7.47 2.55
3/4"	26.670	1.65 1.03	2.11 1.28			2.87 1.69	2.87 1.69		3.91 2.20	3.91 2.20				5.56 2.90	7.82 3.64
1"	33.401	1.65 1.30	2.77 2.09			3.38 2.50	3.38 2.50		4.55 3.24	4.55 3.24				6.35 4.24	9.09 5.45
1-1/4"	42.164	1.65 1.65	2.77 2.70			3.56 3.39	3.56 3.39		4.85 4.47	4.85 4.47				6.35 5.61	9.70 7.77
1-1/2"	48.260	1.65 1.91	2.77 3.11			3.68 4.05	3.68 4.05		5.08 5.41	5.08 5.41				7.14 7.25	10.15 9.56
2"	60.325	1.65 2.40	2.77 3.93			3.91 5.44	3.91 5.44		5.54 7.48	5.54 7.48				8.74 11.11	11.07 13.44
2-1/2"	73.025	2.11 3.69	3.05 5.26			5.16 8.63	5.16 8.63		7.01 11.41	7.01 11.41				9.53 14.92	14.62 20.39
3"	88.900	2.11 4.51	3.05 6.45	3.96 8.29	4.78 9.92	5.49 11.29	5.49 11.29		7.62 15.27	7.62 15.27				11.13 21.35	15.24 27.68
3-1/2"	101.600	2.11 5.18	3.05 7.40			5.74 13.57	5.74 13.57		8.08 18.63	8.08 18.63					16.15 34.20
4"	114.300	2.11 5.84	3.05 8.36	4.78 12.91	5.56 14.91	6.02 16.07	6.02 16.07	7.14 18.87	8.56 22.32	8.56 22.32		11.13 28.32		13.49 33.54	17.12 41.03
5"	141.300	2.77 9.47	3.40 11.57	4.78 16.09	5.56 18.61	6.55 21.77	6.55 21.77	7.14 23.62	9.53 30.97	9.53 30.97		12.70 40.28		15.88 49.11	19.05 57.43
6"	168.275	2.77 11.32	3.40 13.84	4.78 19.27	5.56 25.38	7.11 28.26	7.11 28.26	9.53 37.31	10.97 42.56	10.97 42.56	12.70 48.73	14.27 54.20		18.26 67.56	21.95 79.22
8"	219.075	2.77 14.78	3.76 19.96	6.35 33.31	7.04 36.81	8.18 42.55	8.18 42.55	10.31 53.08	12.70 64.64	12.70 64.64	15.09 75.92	18.26 90.44	20.62 100.27	23.01 111.27	22.23 107.92
10"	273.050	3.40 22.63	4.19 27.78	6.35 41.77	7.80 51.03	9.27 60.31	9.27 60.31	12.70 81.55	15.09 96.01	12.70 81.55	18.26 114.75	21.44 133.06	25.40 155.15	28.58 172.33	25.40 155.15
12"	323.850	3.96 31.25	4.57 36.00	6.35 49.73	8.38 65.20	10.31 79.73	9.53 73.88	14.27 108.96	17.48 132.08	12.70 97.46	21.44 169.91	25.40 186.97	28.58 208.14	33.32 238.76	25.40 186.97
14"	355.600	3.96 34.36	6.35 54.69	7.92 67.90	9.53 81.33	11.13 94.55	9.53 81.33	15.09 126.71	19.05 158.10	12.70 107.39	23.83 194.96	27.79 224.65	31.75 253.56	35.71 281.70	
16"	406.400	4.19 41.56	6.35 62.64	7.92 77.83	9.53 93.27	12.70 123.30	9.53 93.27	16.66 160.12	21.44 203.53	12.70 123.30	26.19 245.66	30.96 286.64	36.53 333.19	40.49 365.35	
18"	457.200	4.19 46.81	6.35 70.57	7.92 87.71	11.13 122.38	14.27 155.80	9.53 105.16	19.05 205.74	23.83 254.55	12.70 139.15	29.36 309.62	34.93 363.56	39.67 408.26	45.24 459.37	
20"	508.000		6.35 78.55	9.53 117.15	12.70 155.12	15.09 183.42	9.53 117.15	20.62 247.83	26.19 311.17	12.70 155.12	32.54 381.53	38.10 441.49	44.45 508.11	50.01 564.81	
22"	558.800		6.35 86.54	9.53 129.13	12.70 171.09		9.53 129.13	22.23 294.25	28.58 373.83	12.70 171.09	34.93 451.42	41.28 527.02	47.63 600.63	53.98 672.26	
24"	609.600		6.35 94.53	9.53 141.12	14.27 209.64	17.48 255.41	9.53 141.12	24.61 355.26	30.96 442.08	12.70 187.06	38.89 547.71	46.02 640.03	52.37 720.15	59.54 808.22	
26"	660.400	6.35 102.36	7.92 127.36				9.53 152.87	10.31 165.18		12.70 202.72	14.27 227.23				
28"	711.200	6.35 110.34	7.92 137.32				9.53 164.85			12.70 218.69					
30"	762.000	6.35 118.31	7.92 147.28	12.70 234.67	15.88 292.18		9.53 176.84	10.31 191.11	11.13 206.09	12.70 234.67					
32"	812.800	6.35 126.31	7.92 157.24				9.53 188.82	10.31 204.08	11.13 220.08	12.70 250.64					
34"	863.600	6.35 134.30	7.92 167.20				9.53 200.31	10.31 217.05	11.13 234.08	12.70 266.61					
36"	914.400	6.35 142.13	7.92 176.96	12.70 282.27	15.88 351.70	19.05 420.42	9.53 212.56	10.31 229.76	11.13 247.31	12.70 282.27					
40"	1016.00						9.53 236.53			12.70 314.22					
42"	1066.80	7.92 207.92					9.53 248.52			12.70 330.19					
48"	1219.20						9.53 284.24			12.70 377.79					

Weights and Dimensions of Carbon Steel Pipe

Blue: Wall Thickness in Millimeters
Red: Weight Per Meter in Kilograms

(Pudget sound pipe & supply, 2018)

Appendix D: Cost of steel CHS per metric tonne purchased by Shufflebottom Ltd.

Shufflebottom Limited
Cross Hands Business Park
Cross Hands
Llanelli
Carmarthenshire
SA14 6RE
Tel : 01269 831831

VAT Reg No: 431 8610 68

PURCHASE ORDER **Page 1**

National Tube Stockholders Ltd
Dalton Industrial Estate
Dalton
Thirsk
North Yorkshire
YO7 3HE

Order No	85917
Order Date	08/02/2018
Your Order No	
Account Ref	NATIONLT

This is not a V.A.T Invoice

Qty Ordered	Product Code	Product Description	Unit Price	Net Amount
10.1547	114.3X3.6CHSCOLD	3 t x 6.5/6.6, 3 t x 7.6 , 4 t x 12 m	765.0000	7,768.35

Total Net	£	7,768.35
Carriage	£	0.00
Total VAT Amount	£	1,553.67
Order Total	£	9,322.02

Appendix E: Strength rating based on ratio of existing steel bar diameters

Potential material	Buckling force (N)	Young's Modulus (GPa)	Moment of Inertia (m ⁴)	Bar diameter (mm)	Ratio of diameter to steel diameter	Strength rating
Existing steel S275	110000	210	1.91013e-06	79.0	1.0	9
	25200	210	4.37594e-07	54.6	0.7	
Bamboo	110000	20	2.00564e-05	142.2	1.8	3
	25200	20	4.59474e-06	98.4	1.2	
Hardwood – along grain	110000	25.2	1.59178e-05	134.2	1.7	9
	25200	25.2	3.64662e-06	92.8	1.2	
Plywood	110000	13	3.0856e-05	158.3	2.0	3
	25200	13	7.06883e-06	109.5	1.4	
Softwood – along grain	110000	10.3	3.89445e-05	167.8	2.1	9
	25200	10.3	8.92182e-06	116.1	1.5	
Acrylonitrile butadiene styrene (ABS)	110000	2.9	0.00013832	230.4	2.9	1
	25200	2.9	3.16878e-05	159.4	2.0	
Cellulose polymers (CA)	110000	12	3.34273e-05	161.5	2.0	3
	25200	12	7.6579e-06	111.8	1.4	
Ionomer (I)	110000	0.42	0.000946056	372.6	4.7	1
	25200	0.42	0.000216733	257.8	3.3	
Polyamides (Nylons, PA)	110000	3.2	0.000125352	224.8	2.8	1
	25200	3.2	2.87171e-05	155.5	2.0	
Polycarbonate (PC)	110000	2.44	0.000164397	240.6	3.0	1
	25200	2.44	3.76618e-05	166.4	2.1	
Polyethelene (PE)	110000	0.89	0.000450705	309.5	3.9	1
	25200	0.89	0.000103253	214.2	2.7	
Polyethelene-terephthalate (PET)	110000	4.14	9.68908e-05	210.8	2.7	1
	25200	4.14	2.21968e-05	145.8	1.8	
Polyhydroxyalkanoates (PHA/PHB)	110000	4	0.000100282	212.6	2.7	1
	25200	4	2.29737e-05	147.1	1.9	
Polymethyl methacrylate (Acrylic, PMMA)	110000	3.8	0.00010556	215.3	2.7	1
	25200	3.8	2.41828e-05	149.0	1.9	
Polyoxymethylene (Acetel, POM)	110000	5	8.02256e-05	201.1	2.5	1
	25200	5	1.83789e-05	139.1	1.8	
Polypropylene (PP)	110000	1.55	0.000258792	269.5	3.4	1
	25200	1.55	5.92869e-05	186.4	2.4	
Polystyrene (PS)	110000	2.6	0.00015428	236.8	3.0	1
	25200	2.6	3.53441e-05	163.8	2.1	
Polyurethane (tpPUR)	110000	2.07	0.000193782	250.7	3.2	1
	25200	2.07	4.43936e-05	173.4	2.2	
Polyvinylchloride (tpPVC)	110000	4.14	9.68908e-05	210.8	2.7	1
	25200	4.14	2.21968e-05	145.8	1.8	
Wrought magnesium alloys	110000	47	8.53464e-06	114.8	1.5	9
	25200	47	1.95521e-06	79.4	1.0	
Cast magnesium alloys	110000	47	8.53464e-06	114.8	1.5	9
	25200	47	1.95521e-06	79.4	1.0	
Non-age hardening wrought AL - alloys	110000	72	5.57122e-06	103.2	1.3	9
	25200	72	1.27632e-06	71.4	0.9	
Age hardening wrought AL- Alloys	110000	80	5.0141e-06	100.5	1.3	9
	25200	80	1.14868e-06	69.5	0.9	
Cast AL- alloys	110000	89	4.50705e-06	97.9	1.2	9
	25200	89	1.03253e-06	67.7	0.9	

Appendix F: Calculating E and I of potential substitute materials.

Material	Length (M)	Buckling force (N)	Youngs modulus (E)	Moment of inertia (I)
Bamboo	6	110000	20	2.00564e-05
	6	25200	20	4.59474e-06
Hardwood – along grain	6	110000	25.2	1.59178e-05
	6	25200	25.2	3.64662e-06
Plywood	6	110000	13	3.0856e-05
	6	25200	13	7.06883e-06
Softwood – along grain	6	110000	10.3	3.89445e-05
	6	25200	10.3	8.92182e-06
Acrylonitrile butadiene styrene (ABS)	6	110000	2.9	0.00013832
	6	25200	2.9	3.16878e-05
(CA)	6	110000	12	3.34273e-05
	6	25200	12	7.6579e-06
(I)	6	110000	0.424	0.000946056
	6	25200	0.424	0.000216733
(Nylons, PA)	6	110000	3.2	0.000125352
	6	25200	3.2	2.87171e-05
Polycarbonate (PC)	6	110000	2.44	0.000164397
	6	25200	2.44	3.76618e-05
Polyethelene (PE)	6	110000	0.89	0.000450705
	6	25200	0.89	0.000103253
Polyethelene-terephthalate (PET)	6	110000	4.14	9.68908e-05
	6	25200	4.14	2.21968e-05
Polyhydroxyalkanoates (PHA/PHB)	6	110000	4	0.000100282
	6	25200	4	2.29737e-05
Polymethyl methacrylate (Acrylic, PMMA)	6	110000	3.8	0.00010556
	6	25200	3.8	2.41828e-05
Polyoxymethylene (Acetel, POM)	6	110000	5	8.02256e-05
	6	25200	5	1.83789e-05
Polypropylene (PP)	6	110000	1.55	0.000258792
	6	25200	1.55	5.92869e-05
Polystyrene (PS)	6	110000	2.6	0.00015428
	6	25200	2.6	3.53441e-05
Polyurethane (tpPUR)	6	110000	2.07	0.000193782
	6	25200	2.07	4.43936e-05
Polyvinylchloride (tpPVC)	6	110000	4.14	9.68908e-05
	6	25200	4.14	2.21968e-05
Wrought magnesium alloys	6	110000	47	8.53464e-06
	6	25200	47	1.95521e-06
Cast magnesium alloys	6	110000	47	8.53464e-06
	6	25200	47	1.95521e-06
Non-age hardening wrought AL - alloys	6	110000	72	5.57122e-06
	6	25200	72	1.27632e-06
Age hardening wrought AL- Alloys	6	110000	80	5.0141e-06
	6	25200	80	1.14868e-06
Cast AL- alloys	6	110000	89	4.50705e-06
	6	25200	89	1.03253e-06

Appendix G: Calculated wall thickness of steel, Al-alloy and polymer tubes

Material	Moment of inertia (m ⁴)	Outside diameter (m)	Minimum thickness required (mm)	Pipe Schedule	Weight (kg)	Cost per brace (£)
Steel	0.000000438	0.1143	0.76	sch 5	35.04	£26.81
	0.000000438	0.0889	1.68	sch 5	27.06	£20.70
	0.000000438	0.073	3.28	sch 40	51.78	£39.61
	0.000000438	0.0603	7.38	sch 160	66.66	£50.99
Al-alloy	0.000001032	0.07302	10.42	N/A		
	0.000001032	0.0889	4.33	sch 40S	25.02	£32.03
	0.000001032	0.1016	2.72	sch 10S	16.43	£21.03
	0.000001032	0.1143	1.85	sch 10S	18.54	£23.73
	0.000001032	0.1413	0.95	sch 10S	25.4	£32.51
ABS	3.16878E-05	0.16	51.95	5mm	17.64	£34.75
	3.16878E-05	0.2	12.11	12.5mm	53.46	£105.32
	3.16878E-05	0.225	7.87	12.5mm	60.54	£119.26
	3.16878E-05	0.25	5.52	12.5mm	67.74	£133.45
PE	0.00010325	0.225	39.29	12.5mm	48	£52.80
	0.00010325	0.25	21.97	12.5mm	53.76	£59.14
	0.00010325	0.28	13.92	15mm	72	£79.20
	0.00010325	0.315	9.18	7.5mm	41.76	£45.94
PHA/PHB	2.29737E-05	0.16	21.50	5mm	18.24	£129.50
	2.29737E-05	0.2	8.29	12.5mm	55.2	£391.92
	2.29737E-05	0.225	5.53	12.5mm	62.58	£444.32
	2.29737E-05	0.25	3.92	12.5mm	69.98	£496.86
PP	5.92869E-05	0.2	29.63	12.5mm	40.19	£50.64
	5.92869E-05	0.225	16.57	12.5mm	45.54	£57.38
	5.92869E-05	0.25	11.04	12.5mm	50.94	£64.18
	5.92869E-05	0.28	7.45	15mm	68.25	£86.00
	5.92869E-05	0.315	5.07	7.5mm	39.59	£49.88



System design

Dimensions of plastic piping systems

Dimensional comparison

A wide range of thermoplastic piping systems, are available in both inch and metric dimensions. In all such cases, the outside diameter (O.D.) is a strictly controlled dimension fixed by internationally recognised manufacturing standards. The inside diameter changes according to the material, its wall thickness, and the pressure rating and therefore it is given a nominal dimension only, referred to as the nominal bore (N.B.).

Errors can occur both with the interpretation of the dimensional standards and in the definition of the required size. In general terms, systems of the same material made to either inch or metric sizes are not dimensionally compatible, except (for some materials) 2½" pipe which has the same outside diameter as 75mm pipe, and 5" pipe which has the same outside diameter as 140mm pipe. Transition fittings are needed to connect between inch and metric sized systems in all other dimensions.

Care needs to be taken to use a clear definition of the pipe size being used. Inch systems are always referred to using their nominal bore dimension (measured in either inches or mm). Metric systems, whilst always measured in millimetres, may be described by the outside diameter (O.D.) or more usually by their nominal bore dimension (DN), which is always expressed in millimetres. The following table shows a comparison between the approximate equivalent inch and metric sizes:

Nominal Bore (inch)	Inch System		Metric System	
	Outside Diameter		Nominal Bore (DN)	Outside Diameter
	British Standard (mm)	ASTM (mm)	(mm)	(mm)
			8	12
3/8	17.1	17.1	10	16
1/2	21.4	21.4	15	20
3/4	26.7	26.7	20	25
1	33.6	33.6	25	32
1¼	42.2	42.2	32	40
1½	48.3	48.3	40	50
2	60.3	60.3	50	63
2½	75.2	73.0	65	75
3	88.9	88.9	80	90
4	114.3	114.3	100	110
			110	125
5	140.2	141.3	125	140
6	168.3	168.3	150	160
			175	200
8	219.1	219.1	200	225
			225	250
10	273.0	273.0	250	280
12	323.9	323.9	300	315
14	355.6	355.6	350	355
16	406.4	406.4	370	400

(ips flow systems, 2018)