Effect of T-Joint and Corner Joint Geometry on the Design and Structural Properties of HDPE Hull and GRP Sandwich Superstructure Boat Construction

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2019

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A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF SOCIAL SCIENCES
OF
IZMIR UNIVERSITY OF ECONOMICS

BY

AYBERK SÖZEN

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR
THE DEGREE OF MASTER OF DESIGN STUDIES
IN
THE GRADUATE SCHOOL OF SOCIAL SCIENCES

2019

Approval of the Graduate school of Social Sciences

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Abstract

EFFECT OF T-JOINT AND CORNER JOINT GEOMETRY ON THE DESIGN AND STRUCTURAL PROPERTIES OF HDPE HULL AND GRP SANDWICH SUPERSTRUCTURE BOAT CONSTRUCTION

Sözen, Ayberk

Design Studies Master Program, Graduate School of Social Sciences
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2019

This study aims to design a hybrid high density polyethylene (HDPE) boat with glass reinforced plastic (GRP) superstructure, through the development of a joint between those two materials. The main goal is to design a more environmental friendly, longer lasting boats with better aesthetics and appeal.

This research compares HDPE and GRP and other hull materials with qualitative and quantitative methods. The advantages and disadvantages of both HDPE and GRP are explained in detail. Specimen testing for three different joint types were conducted. The specimens were attached with strain gauges in order to plot the stress distribution at critical points and the parts. ANSYS software and Finite Element Analysis (FEA) were used to create the same strain tests in a virtual environment to compare experimental test results.

Furthermore a survey was held in order understand the opinion of 152 potential boat users about this new design that involves HDPE hulls. According to the survey, users may prefer HDPE hulls because it is more safer and more environmental friendly. This study indicates that a hybrid HDPE-GRP boats could be a viable alternative for the future marine industry.

Keywords: HDPE, GRP Sandwich Systems, T-Joint, Corner Joint, Boat Structure, Yacht Design

Özet

YAT TASARIMINDA, T-BİRLEŞİM VE KÖŞE BİRLEŞİM GEOMETRİSİNİN, HDPE KARİNA VE CTP SANDVİÇ ÜST YAPILARA OLAN TASARIMSAL VE KONSTRÜKTİF ETKİSİ

Sözen, Ayberk

Tasarım Çalışmaları; Yüksek Lisans Programı, Sanat ve Sosyal Bilimler Fakültesi

Danışman: Prof. Dr. Murat Bengisu

2019

Bu çalışma; yüksek yoğunluklu polietilen bir karina ve cam takviyeli polyester (CTP) bir üst yapıdan oluşan melez bir tekne için birleşim detayı geliştirmeyi hedeflemektedir. Buradaki ana amaç; daha çevreci, kullanım ömrü uzun olan ve estetik olarak daha çekici bir tekne tasarlamaktır.

Bu çalışma HDPE ve CTP ile diğer gemi inşaat malzemelerini nitel ve nicel olarak karşılaştırmaktadır. HDPE ve CTP materlyallerinin gemi inşaattaki avantaj ve dezavantajları detaylı olarak açıklanmıştır. Üç farklı birleşim detayı için çekme testleri gerçekleştirilmiştir. Test numunelerinin gerilme noktalarına gerinim ölçerler konulmuştur. ANSYS yazılımı kullanılarak sonlu elemanlar analizi uygulanmış ve ideal ortamda testler canlandırılmıştır.

Ayrıca olası tekne kullanıcılarının HDPE karina içeren bu yeni tasarım hakkındaki görüşlerini anlamak için 152 kişiyle bir anket yapılmıştır. Anket sonuçları, kullanıcıların daha güvenli ve çevreye duyarlı olması nedeniyle HDPE karinayı tercih edebileceğini göstermiştir. Bu çalışma HDPE – CTP melez teknenin gelecekte denizcilik sektöründe tercih edilen bir seçenek olabileceğini göstermiştir.

Anahtar Kelimeler: HDPE, GRP Sandviç Sistemler, T-Bağlantı, Köşe Bağlantı, Tekne Yapısı, Yat Tasarımı

Acknowledgements

I would like to express my special thanks to all those who has provided the possibility to me to complete this research. First of all I would like to thank my thesis advisor Prof. Dr. Murat Bengisu. He was always there whenever I had a question about my research. He steered me in the right direction whenever he thought I needed it.

I would also like to thank Prof. Dr. Gökdeniz Neşer with the experiments for this research. Without him and Nahit Öztoprak the experiments would not have been completed.

A very special gratitude goes out to all down at Gözüyılmaz Marine Engineering and Mercan Yachting for their help and contribution for the test specimen production process.

Furthermore I would also like to acknowledge Dr. Emre Ergül for his guidance on the thesis and his advices which has helped throughout the research.

Last but not least, many thanks go to Mr. Barışcan Özkalay as the second reader of this thesis, and I am grateful for his very valuable comments on this thesis.

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List of Abbreviations

ANOVA	: Analysis of Variance
CTP	: Cam Takviyeli Polyester
EAYK	: Ege Açıkdeniz Yat Kulübü
FEA	: Finite Element Analysis
GPa	: Gigapascal Pressure Unit
GRP	: Glass Reinforced Plastic
HDPE	: High Density Polyethylene
IARC	: International Agency for Research on Cancer
IBM	: International Business Machines Corporation
kN	: Kilo newton
LDPE	: Low Density Polyethylene
MPa	: Mega Pascal Pressure Unit
MSc	: Master of Science
N	: Newton
PhD	: Doctor of Philosophy
RIB	: Rigid-Inflatable Boat
SPSS	: Statistical Package for the Social Sciences

1. Introduction

GRP (Glass Reinforced Plastic) is one of the most common material for marine small crafts. GRP has been used for many years in the marine sector. However, with new developments and an expanded range of new composite materials, the use of GRP in marine structures and vessels has increased tremendously. The most important advantages that GRP brings to the marine industry are the complex configurations and the seamless hull designs even the forms are amorphous. GRP is used to replace monolithic materials (mostly metals), to reduce weight. It enables in increase of speed, payload and less fuel consumption. GRP is also effective with vibration damping. Another advantage of GRP is the reduced assembly costs, rapid fitting since large and complicated parts or components can be constructed in one piece. GRP also is resistant to corrosion and impact compared to other materials such as aluminum and steel. Last but not least GRP requires less maintenance and less effort for repairs (Zisimopoulos, 2015).

HDPE (High Density Polyethylene) is a subclass of Polyethylene. HDPE is the most common plastic for marine use. In marine industry HDPE is being used for pipes and tubing wires, cable coating, sheets and geomembranes (Müller, 2007). Advantages of HDPE materials are low moisture absorption, exceptional chemical and corrosion resistance, high impact strength, excellent tensile strength, energy absorption, abrasion resistance, low cost production, machinability and maybe the most important of all ease of recyclability.

This study focuses on finding and developing a joint technique for HDPE hull and GRP superstructures. The aim is to use HDPE for the hull material is to make the boat more impact resistant. Also HDPE does not require antifouling paint application, so that harmful chemicals won't affect the life underwater. It is also recyclable, anticorrosive and has increased life cycle. On top of the HDPE hull, the reason behind constructing the superstructure from GRP is because of the weight reduction as well as aesthetic concerns.

1.1. Scope of Study

Inspiration for this study began while questioning the possibilities for marine vessel hulls and the superstructures. Hull construction (also the superstructure) with HDPE and GRP is very common. GRP allows the manufacturers to construct amorphous forms in one piece, but it comes with a downside. GRP is recyclable, however the process is difficult and expensive. On the other hand HDPE is easier to recycle and also cost effective.

Considering the advantages and disadvantages of those two materials inspired this study. Why don't we use GRP and HDPE together for strength and also for a better looking vessel? This study focuses up to 24 meter vessels which can be described as Small Crafts (ISO, 2016). However over 16 meters it is not feasible due to elastic behavior of HDPE (Siswandi & Aryawan, 2016). More structural elements such as more frames and girders has to be used to support the weight and the bending of the hull. GRP as well as aluminum are the materials used in vessels over 16 meters up to 40 meters. Over 40 meters, steel is the only material. Below 5 meters, HDPE's main manufacturing method becomes rotational molding, but this study focuses on plastic welded vessels so that method is excluded.

In this research only the connection between HDPE and GRP is tested, however joining other materials may also be possible for further research studies. Three best possible joining methods are tested and evaluated with the help of the related literature or previous research studies.

1.2. Aims and Structure

1.2.1. Aims of the Study

The main goal of this research is to increase the usage of high-density polyethylene boats in order to make the marine industry more environment friendly. There are couple of reasons behind this research. Another objective is to decrease the carbon footprint by using HDPE hulls rather than GRP. With the decrease of the GRP surface the vessel will become easier and cost effective to recycle.

Also safety of the boats and at the construction sites are another reason. HDPE is far more impact resistant than GRP. In case of an impact, GRP would be fractured and fibers would disintegrate. However with HDPE there will be only damage at the location of impact. In order to produce GRP, glass fibers and epoxy are used together. Both of the materials are harmful to human body. IARC (International Agency for Research on Cancer) classifies epoxy as a Group 1 carcinogen (Thun, Linet, Cerhan, Haiman, & Schottenfeld, 2018). On the other hand HDPE welding creates only carbon dioxide, and the amount is very low.

Another reason of this research can be summarized as an aesthetic issue. People tend to buy or use products which appeal more to human eye. It does not end up well in most situations however it is not a rule that better looks means better products. HDPE has limited form possibility because of the construction method, however with GRP it is easier to create such different yet amorphous forms (Figure 1, and 2). If both materials are used in a vessel, better looking yachts can be designed and constructed.

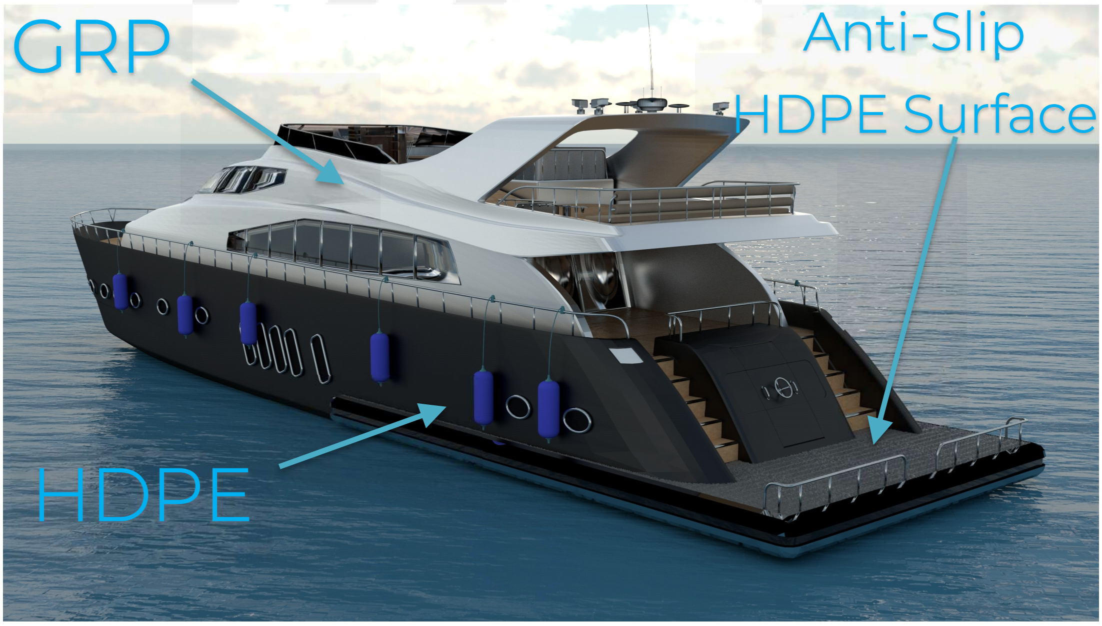


Figure 1. Formability of GRP Superstructure

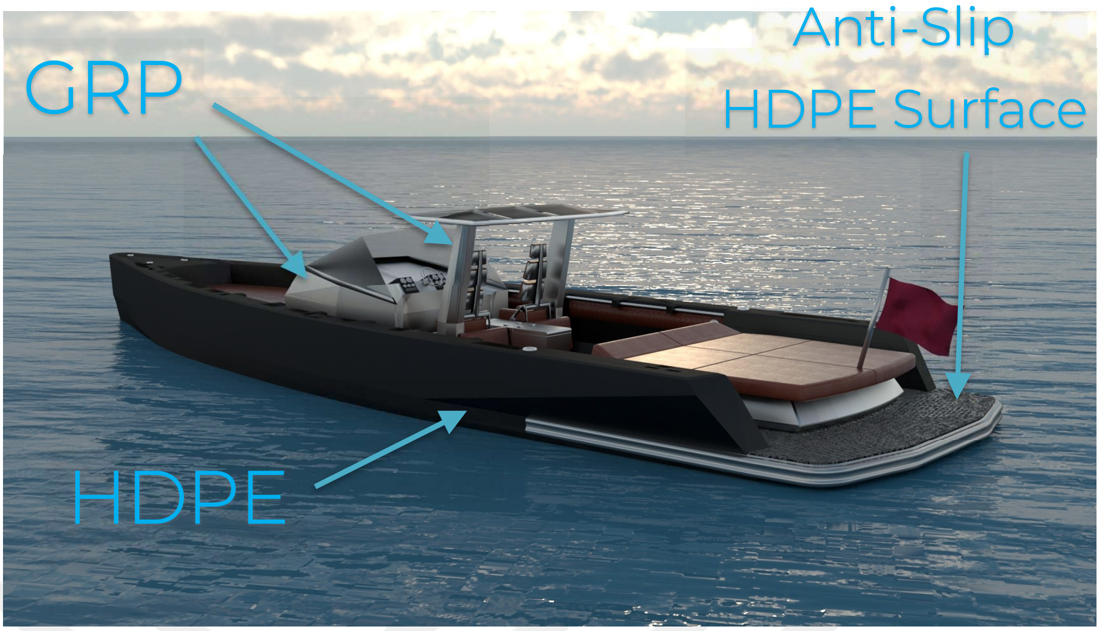


Figure 2. Formability of GRP Superstructure

1.2.2. Structure of the Study

- Investigating and finding potential GRP to HDPE joints,
- 3D modelling of the joints by using a commercial software,
- Producing specimens for the tests,
- Testing the specimens for tensile strength and evaluate the results to find the best alternative,
- Make a questionnaire addressed to boat owners, fishermen, sailors and sea enthusiasts to understand their perspective on GRP and HDPE vessels.
- Compare GRP and HDPE materials in boat building industry by all means (construction methods, coatings, durability, feasibility and etc.) and also include a third material which is a hybrid of both GRP and HDPE.

1.3. Literature Review

Since GRP is the most common material for yacht construction nowadays, most of the companies use their know-how for estimated cost, weight and structural strength. However it can also be calculated to a certain point with the empirical formulas. If it is a complicated hull or a structure which might be exposed to high pressure or forces then it has to be calculated with advanced software.

GRP needs good craftsmanship for manual manufacturing. It also requires detailed engineering to prevent untouched fibers with resin which creates structural problems in the long term (especially under the waterline) and can cause "osmosis". Osmosis can be defined as "The passage of a liquid (in this case sea water) through a semipermeable membrane (the hull) to equalize the solution strengths".

GRP has proven itself in the marine industry and it has been the most commonly used material for production. On the other hand, there is an important downside, which affects the environment, i.e. difficulty of recycling. GRP is recyclable, however the methods are not cost efficient and the process involves chemical treatment (Job, 2014). In order to recycle, first step would be to separate glass fibers from the epoxy resin (Du Plessis, 2013). Then fibers have to be powdered, then with the addition of a little amount (0, 5 - 1%) of this powder to epoxy resin and polyurethane foam significant improvements in strength can be achieved. On the other hand in many cases the composites created by the recycling process tend to have inferior properties (i.e. decreased strength, lower impact resistance and toughness etc.)

The majority of fibers in reinforced plastics are glass fibers; they account for over 90% of the total amount the composites. The reason is that glass fibers have good strength to weight ratio and also they are inexpensive. Glass fibers have excellent tensile strength; however when loads are applied for a long period of time glass fibers start to deteriorate. Different types of fibers are available in the market for different purposes and budgets. Polymer fibers (Kevlar) are low weight; they have high tensile strength and modulus, impact and fatigue resistant, however compressive performance is relatively poor. Carbon fibers offer the highest stiffness and strength among all and can be exposed to high temperatures. However the major drawback for carbon fiber is the cost.

Polyethylene is one of the most popular polymer in the world. It is the polymer which grocery bags, bottles and toys are made of. Polyethylene family consists of many grades of polymers, but most common ones are high density polyethylene (HDPE) and low density polyethylene (LDPE). HDPE is produced by the polymerization of the ethylene. This method was discovered in 1950 (Benham & McDaniel, 2002). HDPE is much stronger than Ldpe while Ldpe is cheaper and easier to produce.

Polyethylene classifies as a thermoplastic while GRP is a thermoset. Thermoplastic materials melt at 110 to 130 °C respectively. Thermoplastic materials can be heated, shaped or welded together and cooled, and if needed this process can be done over and over again. On the other hand thermoset plastics such as polyester can only be heated once (that allows to separate resin from the fibers). If thermoset is heated again it would simply burn (Tooley, M. H., 2010).

There are few downsides of HDPE. Compared to GRP, empirical formulas for the boats structural analysis do not exists, advanced software are used for HDPE construction calculations. The analysis and calculations require time as well as it is a complex procedure (J., & Aryawan, W. D., 2015). Also know-how for this material is another issue, most of the shipyards in Turkey are not even aware of HDPE. Unlike laboratory testing and investigation is possible for marine steel behavior on long term periods, behavior of HDPE in long term lacks a lot of information (Gkatzogiannis, Weinert, Engelhardt, Knoedel, Ummenhofer, 2019). Last but not least researches show that aging process decreases the ultimate tensile strength (Valadez-Gonzalez & Veleva, 2004).

Joining two different materials most of the time conduce to problems (Campilho, 2009). Some problems can be easily handled some may not. Visual problems are the ones to be handled without much effort. However chemical, structural, and mechanical problems can cause fatal failures.

In the marine industry there can be found several examples of two different materials joined together. One of these pairs is aluminum and steel and their joining solution is called “Triclad” (Liu, Ma, Atabaki, & Kovacevic, 2015). It is a high quality material that is developed specially to weld steel and aluminum. Triclad, as it can be understood from its name, is a composition of three layers; steel, pure aluminum and corrosion-resistant aluminum. Strength and durability of this joint however have to be investigated further for marine use (Boyd, S. W., 2006).

GRP is becoming more common in marine industry because of the low weight to strength ratio. One of the most common materials in the marine industry is steel. However it has its downsides such as high density, short maintenance periods, low corrosion resistance, etc. To make the vessels more stable, some of the superstructures are built from GRP, which results to a lower center of gravity.

To connect GRP with steel a joint has to be developed (Campilho, Banea, Pinto, da Silva, & De Jesus, 2011). The first step was to model and testing it. Finite element model is also used to predict the response of the joint. The criteria for this joint is defined by the progressive damage, large deformation theory and non-linear stress-strain relationship.

Another joint example is steel and HDPE. A research study about connecting HDPE and steel pipes have been done in 2006. In order to transmit liquid and gas, different pipes had to be used. For underground transmission HDPE pipes are the solution and for the above ground steel pipeline has to be used. To connect those two was the problem. To solve this issue, Tušek (2006) came up with a joint proposal and first calculated the stresses then run the joint through multiple tests.

Last part of the research contains the survey and statistical processing of the results. The survey is held in order to plot the HDPE and GRP vessel usage. It will also provide the data about what are the top priorities for people when buying a yacht, if people buy new or second hand yachts etc.

2. Materials & Methods

2.1. Finite Elements Analysis (FEA)

FEA is used to virtually test and to oversee the behavior of the objects, structures, components, and etc. subjected to static and/or dynamic load conditions.

There are numerous software packages that can do these calculations and plot virtual data of the stresses due to the load conditions. In the present research study ANSYS software (v R17.2) was used to calculate the stresses on the joints. A limited number of tensile tests were held, however the rest of the specimens were tested by FEA.

Joints between the two materials (HDPE and GRP) were modelled and meshed through the software. Their material properties also were added to the model in order to provide better yet realistic results. With the usage of the software's FEA tool, the local stresses and the points where they occurred were found and plotted as in Figure 3.

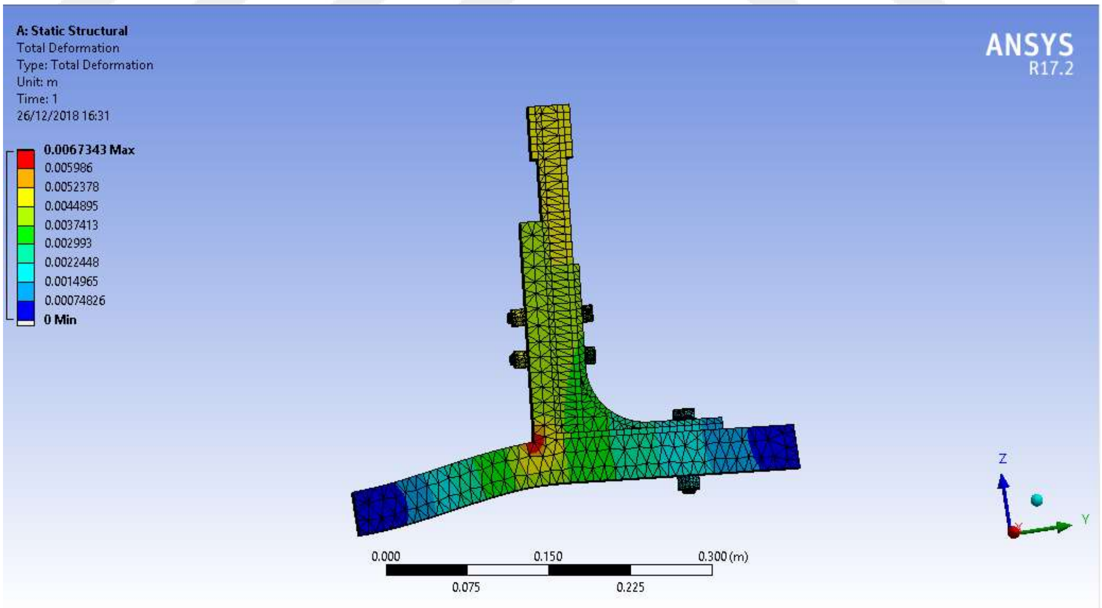


Figure 3. ANSYS Software, total deformation of specimen 7

2.2. Tensile Tests

Under perfect conditions the tests should give exactly the same results, however it is not possible because of the real life conditions. So this whole process will provide us estimated values and results about the tensile tests of the specimens.

Because of the limited time it wasn't possible to produce all the specimens, however 12 specimens were produced and tested for tensile strength in the laboratory (Figure 4, Specimen testing).

To measure the stresses over the joints, strain-gauges were placed to the specimens. Strain-gauges are small resistance circuits which are used to measure strain on an object. Attaching strain-gauges to HDPE surface with standard glues were impossible however it was possible to stick them over the GRP surfaces with standard glues.

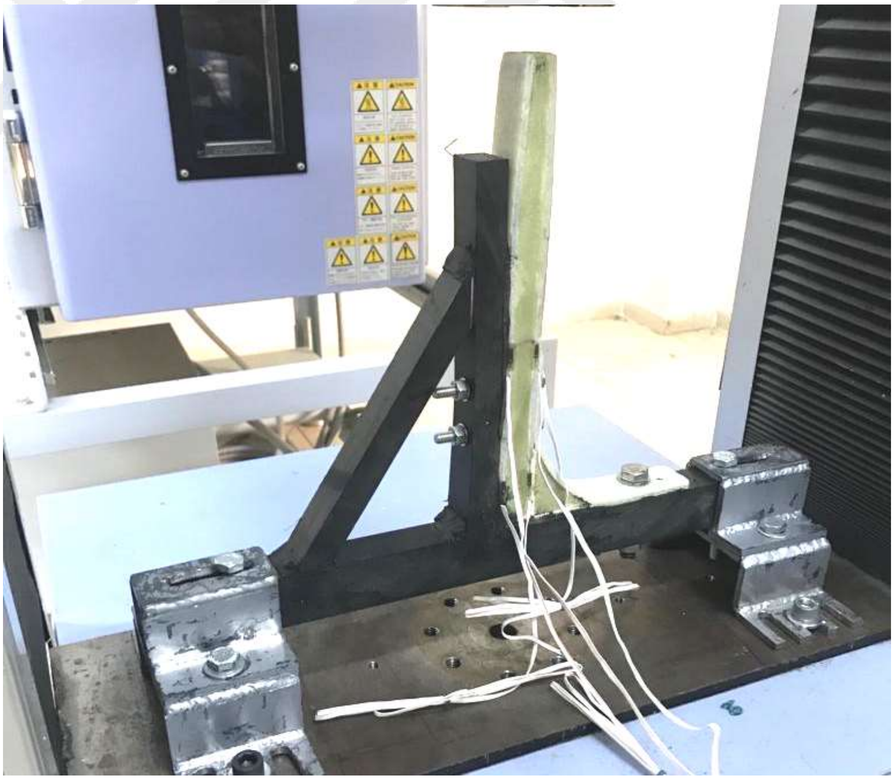


Figure 4. Specimen testing

2.3. Survey

The questionnaire has a total of 31 questions, and it is divided into 3 categories. The categories are demographic questions, questions about design and experience on marine vessels and about seafaring. The reason for this questionnaire is to estimate what people expect from the vessel, whether they would be willing to buy such a boat, or how much they're willing to spend on maintenance or repair (time and money), how much knowledge they have about their yachts etc. The participants were selected according with their relevance to the subject. Most of the participants are located in Aegean region however some participants from the marinas from İstanbul (Ataköy Marina, Kalamış Marina) were also included in the survey.

2.4. Statistical Processing

By the usage of the IBM's SPSS (Statistical Package for the Social Sciences) software the data gathered from the questionnaire can be analyzed. With the help of SPSS the answers were sorted in such a way that estimations can be done around people's priorities when buying a yacht in certain ways for example: type of the yacht, materials used for the construction, maintenance costs, how much time the owner is willing to spend on the sea etc.

Those answers will provide the data in order to support the need of HDPE hull's with GRP superstructures.

3. Definition of the Problem

3.1. HDPE

HDPE has its downsides as well as it brings advantages to marine industry. One of the most important downside for boat construction is that its limitations of its forming capabilities. Forming HDPE is easy when the thickness is small. For marine vessels on the other hand, the hull has to be thicker in order to fulfill the requirements for the Lloyds regulations (Figure 5, HDPE RIB production design).Which makes the material thicker, so that the thickness would not allow some curvatures. To people who are interested in soft forms and curves because of this downside won't prefer HDPE, since the boat would not satisfy their aesthetic needs.

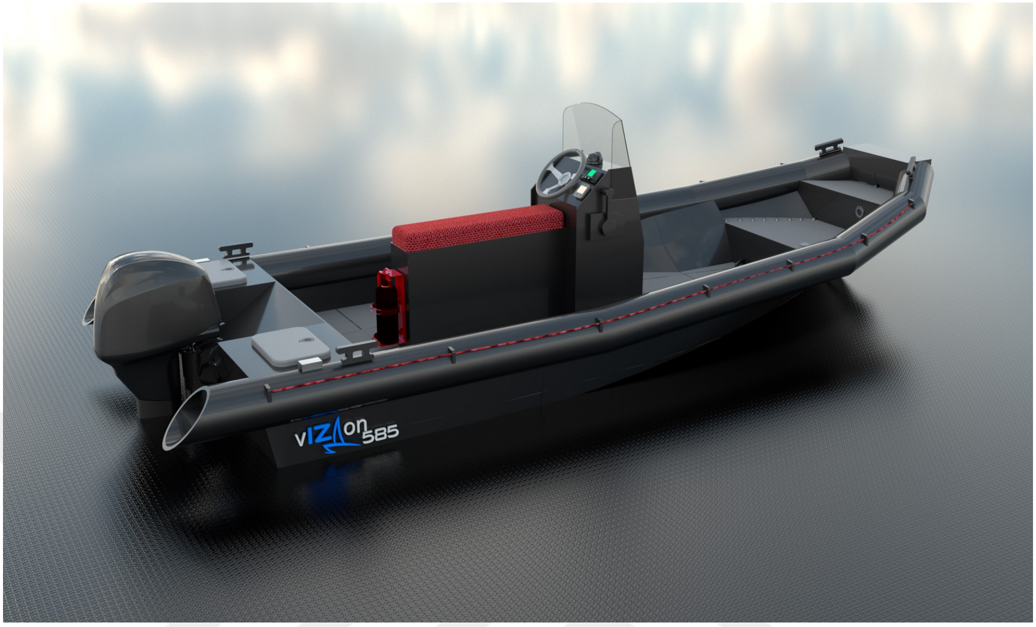


Figure 5. HDPE RIB production design. Courtesy of Gözüyılmaz Marine Engineering

Also thicker hull by itself would not provide enough strength and durability for the sea conditions, so that stiffeners for both longitudinal and transverse have to be fitted, however even with those stiffeners longer boat construction is not possible due to the materials bending and flexing.

In the literature review section it was briefly mentioned that empirical calculations for HDPE did not exist. To be precise they do exist but it is impossible to use them because of the lack of description and instructions. In the regulations of Turkish Lloyd Polyethylene crafts (Turkish Lloyd, 2014) there are total of 12 pages and in this booklet there is only one formula for the hull thickness given with the following equation.

$$t_y = ks\sqrt{\frac{PF}{L\ 6.7}}(14 + 3.6\ L)\ \ mm$$

where

k = 1.0 for LDPE

k = 0.85 for MDPE

k = 0.72 for HDPE

s = stiffener spacing in meter

PF = pressure factor for bottom, respectively side (PFb and PFs), taken from the figures in below:

Formula 1. Empirical formula of hull thickness for polyethylene boats. Source: Tentative Rules for Polyethylene Crafts.

Compared to the preliminary equations used for GRP (Gerr, 2011) this equation seems to be quite insufficient. To someone with know-how, this might not be an issue, however to someone who is in need of some calculations this would not be sufficient.

Another downside of HDPE material concerns the Safety on Life at Sea (SOLAS) convention rules (SOLAS, 2005). HDPE is a flammable material, which makes it dangerous in case of a fire. The Lloyds require certain types of isolation materials applied to the HDPE in crucial compartments.

3.2. GRP

Majority of the GRP material is used to construct mass produced boats by well-known brands. Not only the leader companies in the marine industry uses GRP, because of its prevalence even the startup companies construct vessels from GRP. This often leads to failures, losses, and reputation damages.

GRP construction might seem to be an easy process; but it is not. It is a very complex and onerous series of procedures (Figure 6, GRP vacuum infusion process).Every step has to be taken serious and completed by following the guidelines. If not, there won’t be any visual indication to show you the process was not done correctly, so that one ends up with a faulty construction. Which can lead to serious damage to the user and the others.

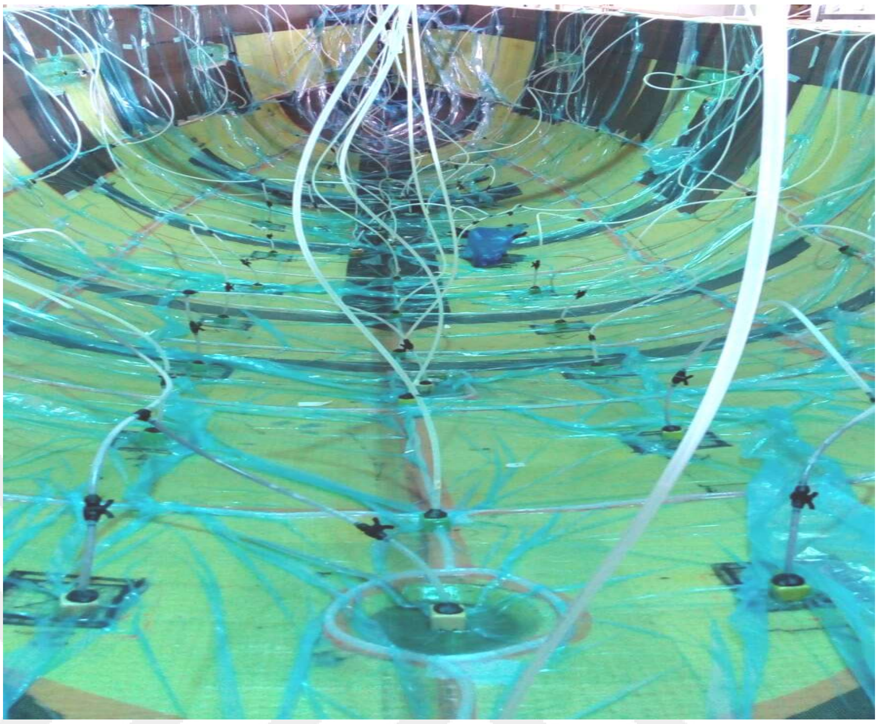


Figure 6. GRP vacuum infusion process (complicated and messy). Courtesy of CSC Composites.

Another handicap for GRP is that construction process is messy. To keep the production area clean is really hard even for the professional builders. Also because of chemicals are involved in the processes it creates some concerns on occupational health issues in long term and short term.

Not only the chemicals can harm the workers, the final product (hull) needs antifouling in order to protect itself, which harms the underwater life.

Last but not least, massive downside of GRP is that in case of an accident (i.e. puncture to the hull), the material does allow it to bend or dent. The crashing object or structure penetrates the hull, while shattering the GRP, scattering the fibers into the whole place. This makes an accident very dangerous to the human when working or accommodating around the GRP structures. In case of an accident not only the structure is harmed also the small and sharp pieces are dangerous to a certain area around the incident (Figure 7, anchor piercing through a hull).

Figure 7. Anchor piercing through the hull. Courtesy of Genco Sindel.

3.3. Research Limitations

Limitations of this research study have briefly mentioned in the introduction section. One of the key issues when connecting two materials together is that those materials have different properties. Which leads to a major problem when creating a joint. If two materials are not connected properly this causes a gap which allows leakage. Also if those two materials are not connected then the rigidity, and the durability of the whole structure would be out of the question.

4. Comparative Analysis

Before proceeding to testing, further analysis and a conclusion it is necessary to know about the specifications of the materials used in boat building industry. Most common products for each type of materials and their most important specifications can be found in the Table 1 below.

Table 1. Specifications of the major construction materials

Material Specifications	*Mahogany Wood*	*Grade A Steel*	*6061 Aluminum Alloy*	*Injection Molded HDPE*	*E-Glass Fiber*
Density (g/cm^3)	0.6	7.8	2.7	0.93-2.55	2.54
Tensile Strength (σt) (MPa)	2.4	400-490	124-290	7.60-43	3450-3790
Young's modulus (E) (GPa)	8.7	200	68.9	0.45-1.50	72.4
Thermal conductivity (k) (W/(m x K))	1.85	52	151-202	0.288-0.480	1.3
Melting temperature (Tm) (Celcius)	-	1500	585	118-137	1725

In order to wrap up the previous chapters, all the similarities, advantages, and disadvantages can be plotted in to a table (Table 2). With the use of this table, it would be easier to have information about the different materials. Also it'll ease the process when choosing a material for the hull and superstructure construction.

Table 2. Comparison of Materials

	WOOD	STEEL	ALUMINUM	HDPE	GRP	HDPE + GRP
GENEREAL						
Weight*	8000 kg	6000 kg	3000 kg	2000 kg	1500 kg	2000 kg
Lifespan (Average)	25 Years	40 Years	40 Years	50 Years	20 – 25 Years	50 Years
Up to (meters)	45 mt	150 mt	150 mt	16 mt	60 mt	16 mt
Know-how (Since)	8,000 BCE	1839	1891	2000's	1942	2000's
WORKMANSHIP						
Maintenance Required*	2 Years	5 Years	5 Years	10 Years	10 Years	10 Years
Construction Difficulty*	Moderate	Easy	Easy	Easiest	For one off production difficult; for mass production, easiest	Easiest
Construction Duration*	5 Months	3 Months	3 Months	2 Months	3 Weeks (for mould ready construction)	2 Months
Operating Cost	High	Moderate	Moderate	Cheapest	Cheap	Cheapest

Table 2. Comparison of Materials

	WOOD	STEEL	ALUMINUM	HDPE	GRP	HDPE + GRP
SAFETY & DURABILITY						
Impact Resistance	Moderate	Best	Moderate	Good	Moderate	Good
Melting temperature (Tm) (Celcius)	-	1500	585	118-137	1725	118-137
Corrosion Resistance	Good	Poor	Poor	Best	Good	Best
Antifouling Application	3 Years	3 Years	3 Years	N A	1 Year	N A
UV Resistance	Good	Best	Best	Good	Good	Poor
AESTHETICAL						
Shaping	Moderate	Good	Good	Poor	Best	Moderate
Compatibility with other materials	Best	Best	Best	Poor	Best	Good
ENVIRONMENTAL						
Recyclability**	N A	Best	Best	Best	Possible but expensive	Good

** The data were gathered from the past constructions and know-how from the boat building companies Gözüyılmaz Engineering & Marine Industries Ltd. and Agantur Yachting Inc. Cost, construction duration, and weight is calculated for a 12m hull.*

*** Wooden hulls can be recycled for furniture making, heating etc. however it is not possible to use the wooden plankings in same way to build another hull. When wooden logs become value added product for the boat, there's no chance constructing another hull.*

5. Production Techniques

5.1. GRP

In order to understand the production techniques of composite materials the components have to be understood first. Most of the Fibers were mentioned in the previous chapter (Literature Review). However the second and bonding component (resin) was mentioned briefly however wasn't defined in depth.

Resin is a glue like liquid which, when mixed with its catalyst (hardening component), becomes a stiff, durable plastic. Marine industry has many brands of few resin types. Because of the applications simplicity and the low cost polyester is the most common resin in the industry. Vinyl Ester comes the second in the usage charts. Vinyl Ester has advantages over polyester such as superior corrosion resistance, hydrolytic stability, and excellent impact and fatigue resistance. Since it costs more than polyester it is not in demand such as the polyester. Also there is another resin type, epoxy. Epoxy resins have the best performance characteristics of all of the resins in the marine industry, however their handling difficulties and higher costs limit the usage in the marine industry. (Figure 8, Resin usage in marine industry)

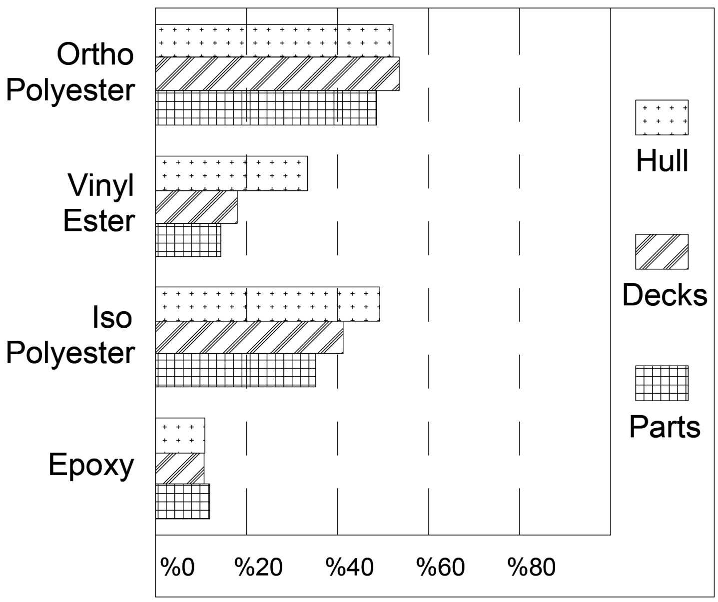


Figure 8. Resin usage in marine industry. Adapted from Use of Fiber Reinforced Plastics in the Marine Industry.

5.1.1. Hand Lay-up

Hand Lay-up is one of the most common methods for production. Since there is no mechanical or electronic devices need the production many companies use this method. Hand lay-up requires more resin and the finishing surfaces appear to be rough compared to other methods.

For this method, first step is to apply a gel coat to the high-quality surface. When the gel coat has the right consistency fiberglass sheets are placed on the surface. Then the resin is applied by either pouring, brushing or spraying. Commonly rollers are used to evenly distribute the resin and remove the air bubbles. (Figure 9, Hand Lay-up method)

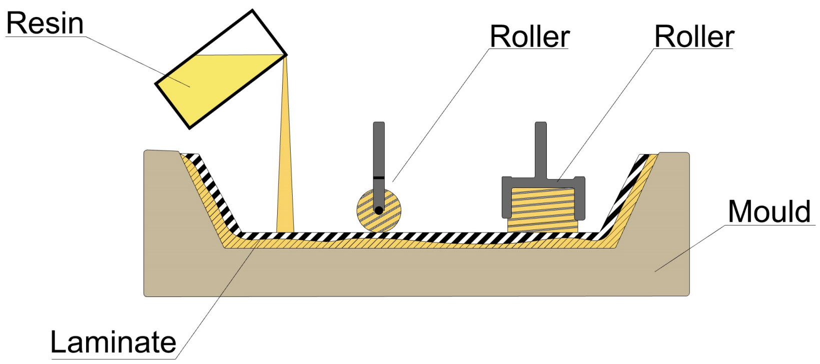


Figure 9. Hand lay-up method. Adapted from Continuous Fibre Composites UNSW Sydney.

5.1.2. Spray-Up

Spray-Up method is similar to the hand lay-up method. First step for this method is identical to the hand lay-up method, applying the gel coat to a high-quality surface. For the next process a special tool is required, a special spray gun with chopper mechanism. The chopper mechanism chops the rowing into small fibers and with the help of spray gun resin is applied to the surface (Figure 10, Spray-Up method). In order to remove the air bubbles below the surface same rollers used in hand lay-up method can be used for this method.

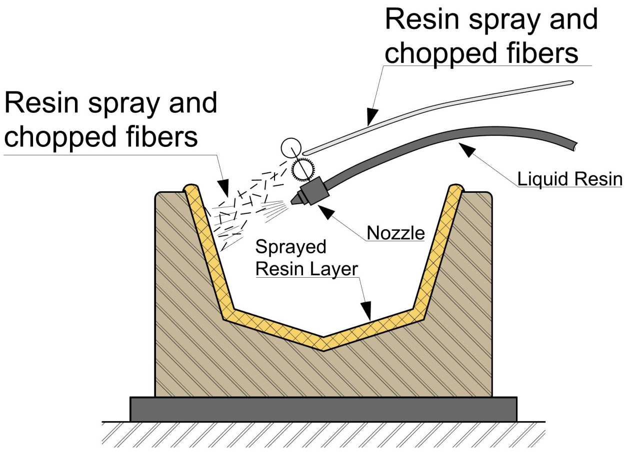


Figure 10. Spray-Up method. Adapted from Hanlon Composites.

5.1.3. Vacuum Bag Molding and Vacuum Infusion Method

Vacuum bag molding is the second complex method between the production methods for GRP. What makes it complex that there is an additional step after the lay-up process. This process requires a flexible film to be placed over the finished lay-up, all sealed up and connected to a vacuum pump with enough hoses. The vacuum pump draws out the air bubbles as well as all the air from the laminate so that the final composite layer is thinner and more durable (Figure 11, Vacuum Bag Molding). The pump also sucks the excessive resin into an overflow tank (Figure 12, Overflow tank), which makes the composite lighter and thinner.

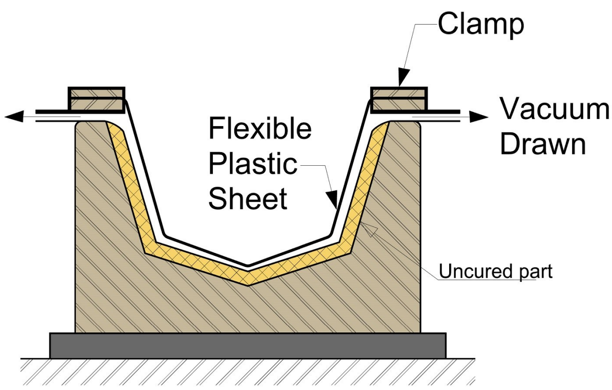


Figure 11. Vacuum bag molding. Adapted from Embryonic Phases of Hard Composites.

Figure 12. Overflow tank. Courtesy of CSC Composites.

Additional to the vacuum bag molding there is another method which is similar but far more complex of all the methods. Vacuum infusion method requires a computer controlled infusion system, which calculates and distributes the resin to the required nozzles which makes the distribution of resin equal all over mold and since the exact amount of resin is injected to the system. With the use of this technology required resin amount becomes lesser and it decreases the waste resin amount. (Figure 13, Vacuum infusion method)

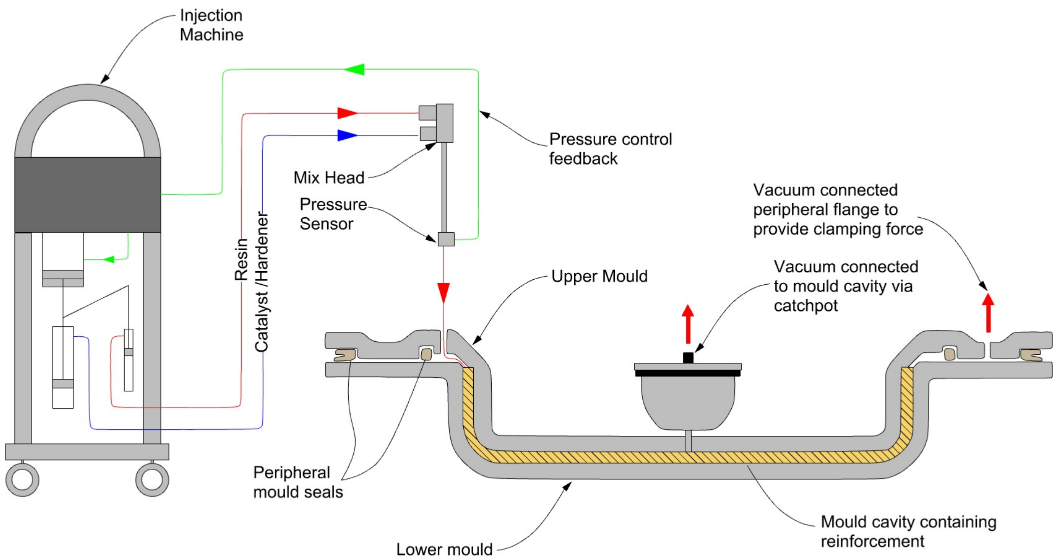


Figure 13. Vacuum infusion method. Adapted from composite-integration.co.uk.

5.2. HDPE

5.2.1. Thermoforming

Thermoforming procedure starts with a sheet of material heated to a softened state, then injected into a mold with a plug, vacuum or air pressure and finally cooled and ejected (Figure 14, Thermoforming Process). This method is perfect for mass production of storage and packaging items (McKelvey, D., Menary, G., Martin, P., & Yan, S., 2017).

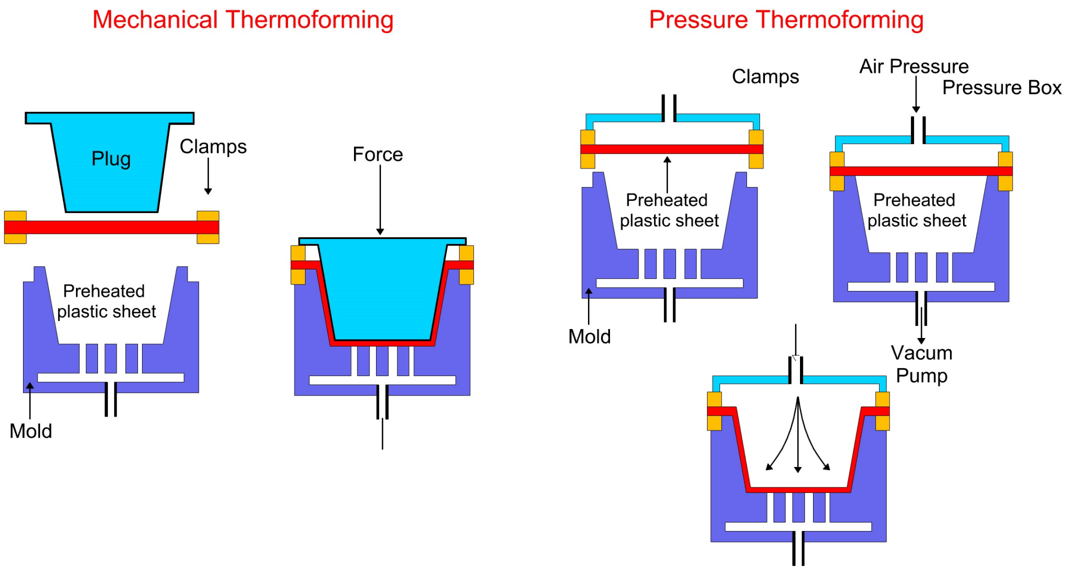


Figure 14. Thermoforming process. Adapted from The Packaging School.

5.2.2. Welding

Another construction with HDPE material is that called butt fusion (HDPE welding). This process is fairly easy compared to thermoforming process. Less tools and equipment is required in order to complete the procedure (Figure 15, HDPE welding process).

Figure 15. Hpde welding process. Courtesy of, Gözüyılmaz Marine Engineering.

HDPE welding process is a thermofusion process which requires both ends of the sheets (which are going to be joined) are simultaneously heated until a molten state. Then those ends are brought back together under controlled pressure for a specific time to cool down and join in a homogenous way (Figure 16, HDPE welding process). The result joint is fully resistant and end loads has comparable performance. (ISO, 2006)

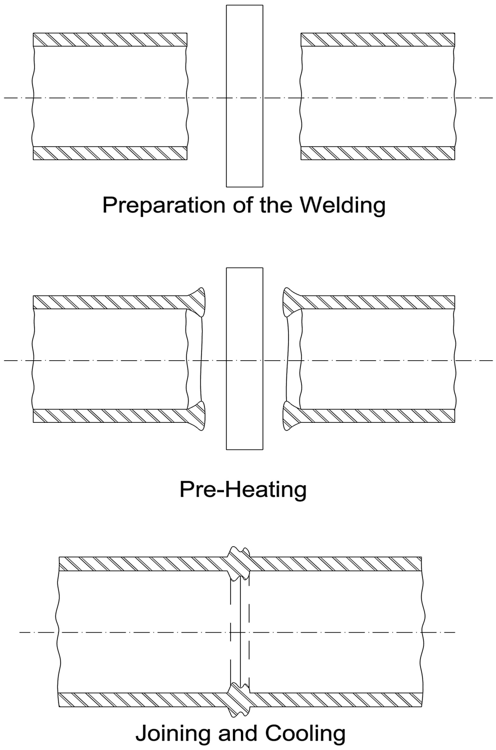


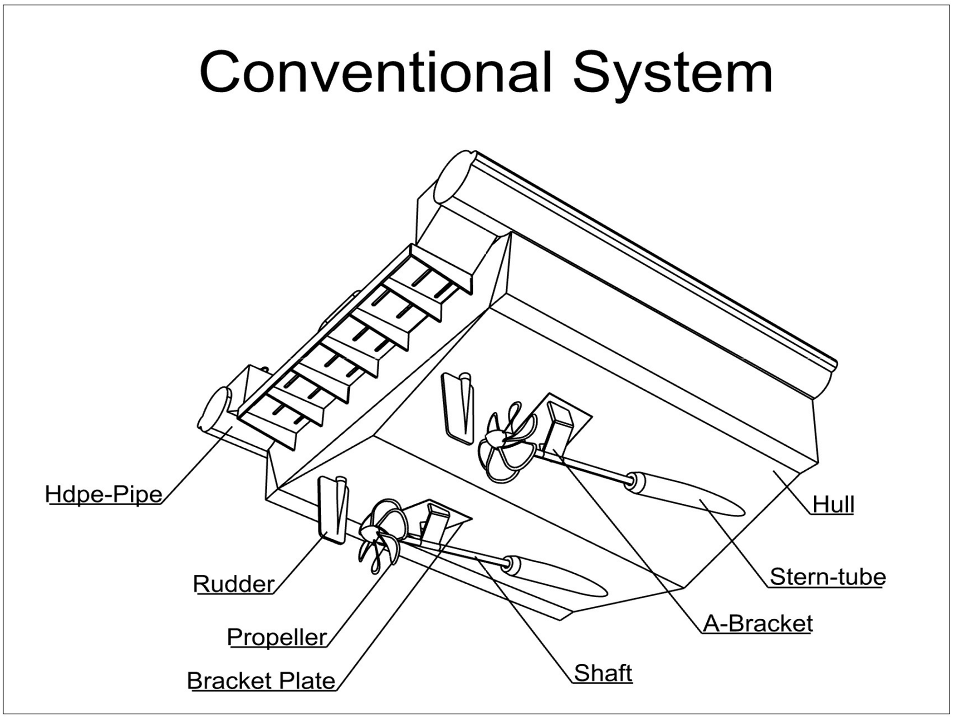
Figure 16. HDPE welding process. Adapted from Polyethylene Jointing – Vinidex Pty Ltd.

Majority of the boat builders use this method in order to construct the vessels. First step is to prepare templates for the HDPE pipes. HDPE vessel construction begins with the pipes welded together, forming the outline of the vessel. Then frames, bulkheads and longitudinal stiffeners are cut with CNC machining. Third step is to put down and weld together the elements (frames, bulkheads and longitudinal stiffeners) on the pipe frame structure (Figure 17, pipes and frames). After the welding is complete from the exterior the vessel is turned upside down and welded from inside. Last step is to construct the deck and superstructure on a flat surface and put the completed parts on top of the hull and weld them together.

Figure 17. Pipes and frames. Courtesy of, Gözüyılmaz Marine Engineering.

5.2.3. Application of Propulsion Systems

There are plenty of propulsion systems used for marine vessels. One of the oldest one is the shaft propulsion. There are some advantages that this propulsion system brings to the industry, however there is a major downside: a high percentage of failure rate. The main reason behind this failures are the alignment between the shaft and the stern tube. Because of the fast rotation speeds and long shafts, there is significant amount of vibration on the system which makes the failure very likely. Since HDPE hulls are not stiff enough and they tend to allow longitudinal bending, this causes shaft to move away from its line and has to be corrected often in order to maintain smoother and effective propulsion (Figure 18, Conventional system and surface drive).



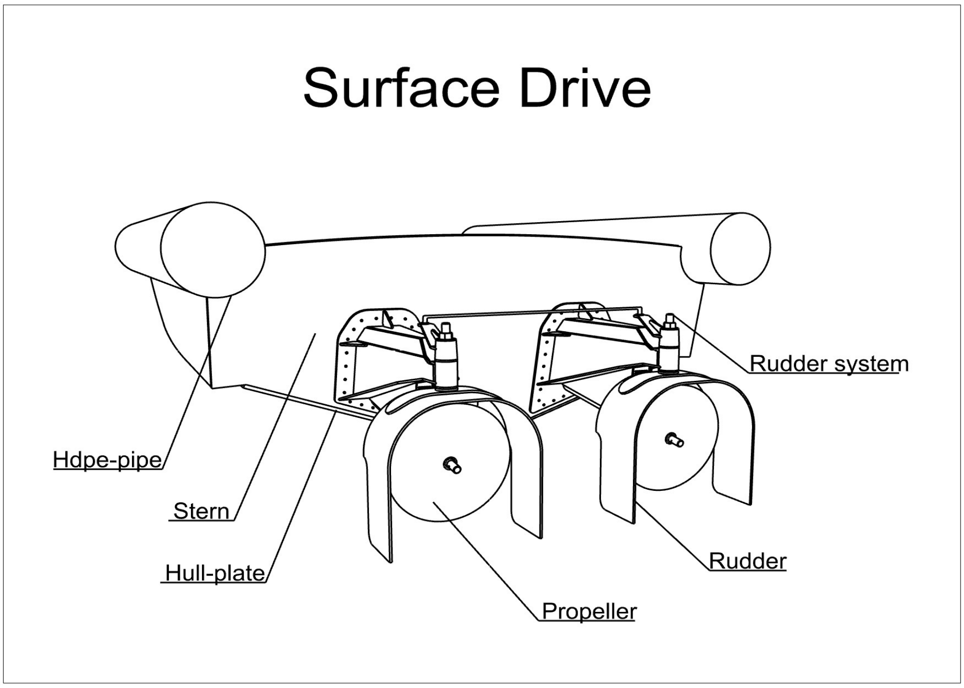


Figure 18. Conventional system and surface drive. Courtesy of, Gözüyılmaz Marine Engineering.

Instead of conventional shaft propulsion, more complicated and expensive systems have to be used in order to avoid this failure. These systems does not require a long shafts to be used, which makes them more reliable when used with HDPE hulls, however they aren't as cost effective as the shaft propulsion. Waterjets and surface drive are the most common systems used with HDPE hulls (Figure 19, Waterjet propulsion installed on HDPE hull). Also installation of these two systems are much easier than installing a stern tube (for the shaft) to the HDPE hull.

Figure 19. Waterjet propulsion installed on HDPE hull. Courtesy of, Gözüyılmaz Marine Engineering.

6. Survey

6.1. Survey Graphs

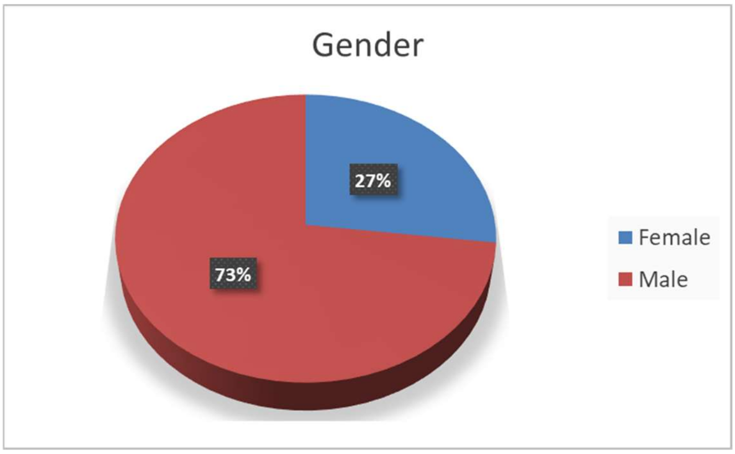


Figure 20. Gender distribution of survey participants

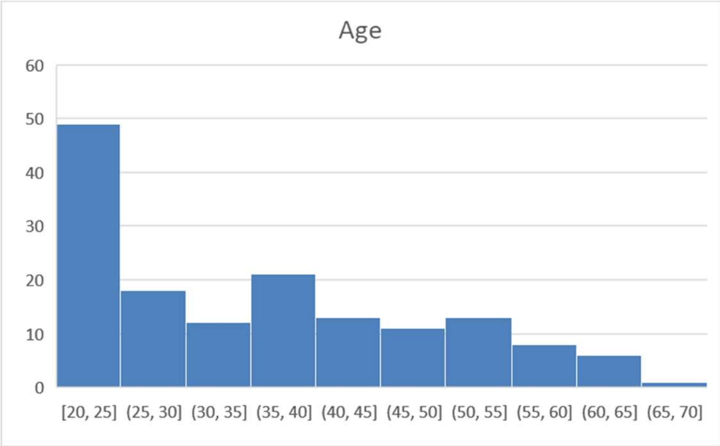


Figure 21. Age distribution of survey participants

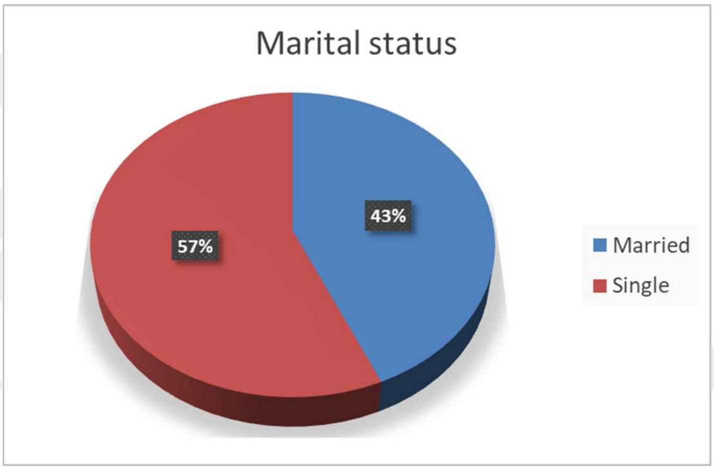


Figure 22. Marital status of survey participants

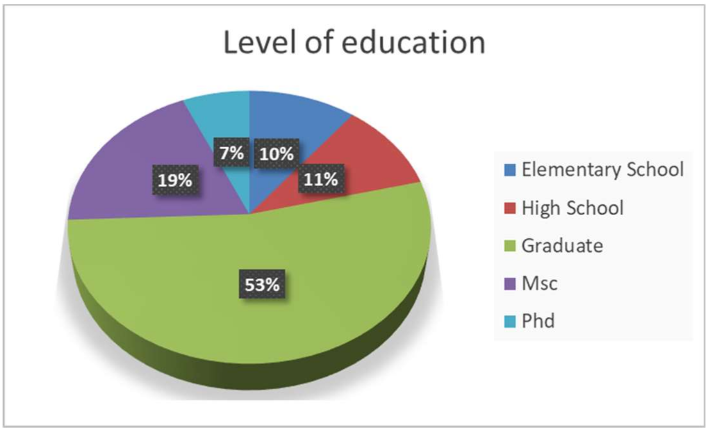


Figure 23. Education levels of survey participants

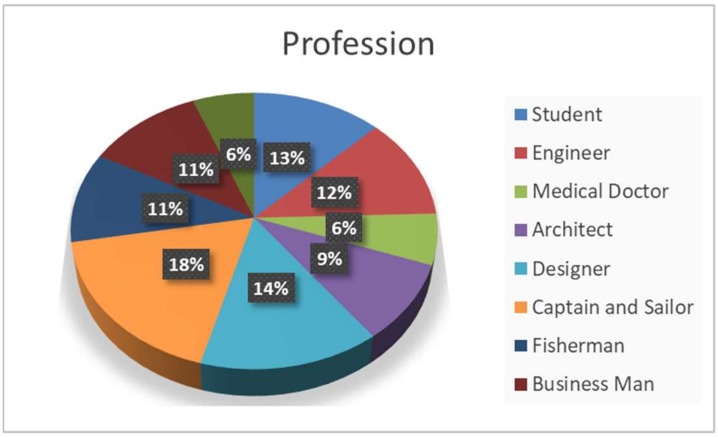


Figure 24. Profession of survey participants

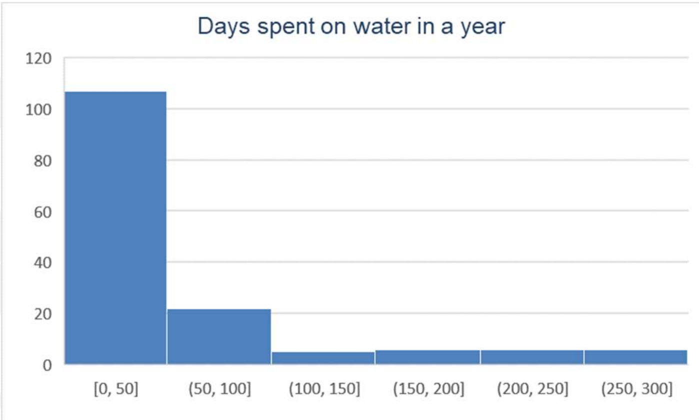


Figure 25. Days per year spent on water of survey participants for a year

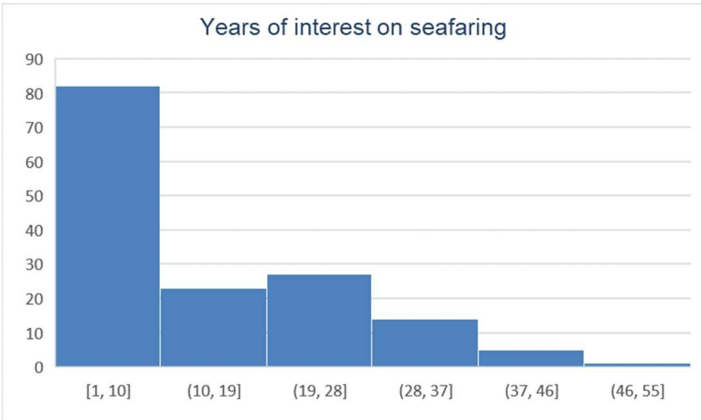


Figure 26. Distribution of years of interest on seafaring of survey participants

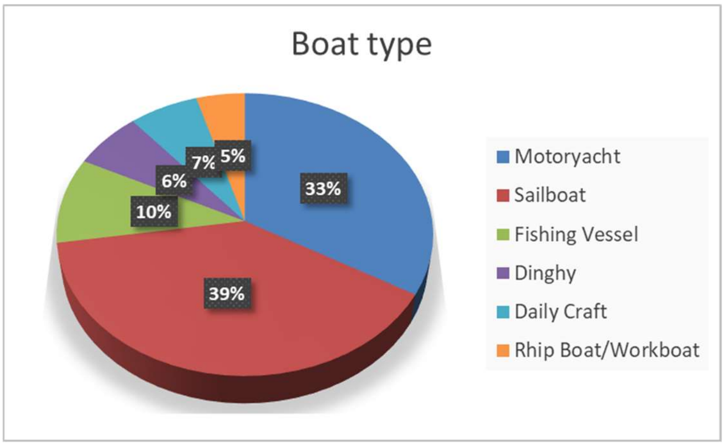


Figure 27. Boat type preference/ownership of survey participants

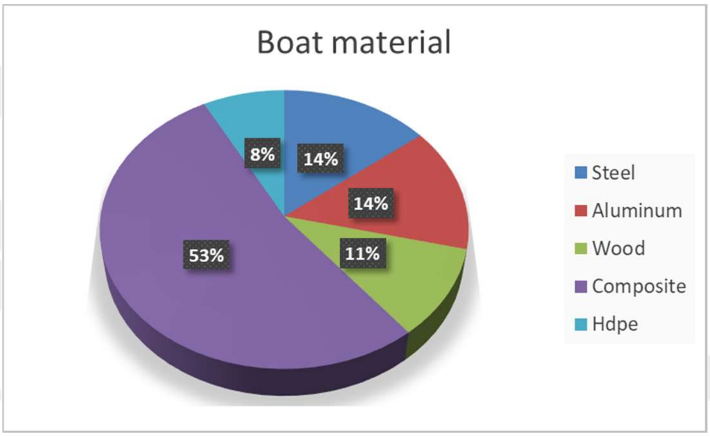


Figure 28. Boat material preference / ownership of survey participants

6.2. Survey Analysis

For the analysis of the survey one-way ANOVA test was chosen. ANOVA (analysis of variance) is a linear modelling method for evaluating the relationship among fields ("Analysis of variance (ANOVA)," n.d.). One-way ANOVA test can compare any number of means. In order to compare two means, an extension of ANOVA test can be used, the t test. One-way ANOVA test and t test procedures are explained below:

1. A hypothesis was created.
2. Overall mean for the continuous field was calculated.
3. The mean square for the explained variance was calculated.

   a) Sum of squares for the explained variance were calculated.

- For each category, overall mean from the category's mean was subtracted.
- Square of each of these results were added together.

   b) Sum of squares for the explained variance were divided by the appropriate degrees of freedom

4. The F value is found by mean square for explained variance was divided by the mean square for the error source. (Ratio of explained variance to unexplained variance)
5. F value is compared to a theoretical F distribution to determine the probability of obtaining the F value by chance, which gives the significance value.
6. If the significance value is less than the significance level, the means are not related.

Table 3. Education level – importance of safety on sea cross tabulation

		Safety on sea is important					TOTAL
		1	2	3	4	5	
Education Level	Phd	0.00%	0.00%	0.00%	20.00%	80.00%	10
	Masters Degree	3.45%	0.00%	6.90%	34.48%	55.17%	29
	Graduate	1.23%	2.47%	6.17%	19.75%	70.37%	81
	High School	12.50%	6.25%	12.50%	12.50%	56.25%	16
	Elementary School	0.00%	0.00%	18.75%	43.75%	37.50%	16
Total		2.63%	1.97%	7.89%	24.34%	63.16%	152

Table 4. Education level – importance of safety on sea ANOVA test

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	7.540	4	1.885	2.313	0.060
Within Groups	119.803	147	0.815		
Total	127.342	151			

Hypothesis 1:

H0: There is no relationship between education and the belief "Safety on sea is important".
H1: There is a relationship between education and the belief "Safety on sea is important".

Since Sigma is greater than the p value (0.060 > 0.05) we accept the H0 hypothesis. According to this analysis there is no relationship between education and the belief "Safety on sea is important".

Table 5. Education level – aesthetic design cross tabulation

		Aesthetic design is important					TOTAL
		1	2	3	4	5	
Education Level	Phd	0.00%	20.00%	20.00%	50.00%	10.00%	**10**
	Masters Degree	0.00%	13.79%	13.79%	51.72%	20.69%	**29**
	Graduate	3.70%	4.94%	18.52%	41.98%	30.86%	**81**
	High School	12.50%	6.25%	12.50%	50.00%	18.75%	**16**
	Elementary School	6.25%	50.00%	31.25%	12.50%	0.00%	**16**
Total		3.95%	12.50%	18.42%	42.11%	23.03%	**152**

Table 6. Education level – aesthetic design ANOVA test

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	27.613	4	6.903	6.784	0.000
Within Groups	149.591	147	1.018		
Total	177.204	151			

Hypothesis 2:

H0: There is no relationship between education level and the boat hulls aesthetic design.
H1: There is a relationship between education level and the boat hulls aesthetic design.

Since Sigma is less than the p value (0.000 < 0.05) we reject the H0 hypothesis. According to this analysis there is a strong relationship between education level and the boat hulls aesthetic design.

Table 7. Education level – caring about the underwater life cross tabulation

		Cares about life underwater					TOTAL
		1	2	3	4	5	
Education Level	Phd	0.00%	0.00%	0.00%	30.00%	70.00%	**10**
	Masters Degree	3.45%	0.00%	3.45%	48.28%	44.83%	**29**
	Graduate	3.70%	3.70%	3.70%	24.69%	64.20%	**81**
	High School	6.25%	12.50%	0.00%	31.25%	50.00%	**16**
	Elementary School	0.00%	0.00%	6.25%	43.75%	50.00%	**16**
Total		3.29%	3.29%	3.29%	32.24%	57.89%	**152**

Table 8. Education level – caring about the underwater life ANOVA test

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	2.958	4	0.740	0.818	0.516
Within Groups	132.910	147	0.904		
Total	135.868	151			

Hypothesis 3:

H0: There is no relationship between education level and caring about life underwater.

H1: There is a relationship between education level and caring about life underwater.

Since Sigma is greater than the p value (0.516 > 0.05) we accept the H0 hypothesis. According to this analysis there is no relationship between education level and caring about life underwater.

Table 9. Boat Type – maximum speed capability cross tabulation

		Maximum speed capabilities of the boat is important					TOTAL
		1	2	3	4	5	
Boat type	Sailing Yacht	3.33%	11.67%	31.67%	36.67%	16.67%	**60**
	Dinghy	10.00%	10.00%	20.00%	60.00%	0.00%	**10**
	Workboat	0.00%	0.00%	16.67%	50.00%	33.33%	**6**
	Motoryacht	3.92%	21.57%	9.80%	33.33%	31.37%	**51**
	Dailycraft	10.00%	30.00%	20.00%	30.00%	10.00%	**10**
	Fisher	13.33%	73.33%	6.67%	6.67%	0.00%	**15**
Total		5.26%	21.71%	19.74%	34.21%	19.08%	**152**

Table 10. Boat Type – maximum speed capability ANOVA test

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	36.336	4	7.267	6.162	0.000
Within Groups	172.183	147	1.179		
Total	208.520	151			

Hypothesis 4:

H0: There is no relationship between boat type and the belief "maximum speed capabilities of the boat is important".
H1: There is a relationship between boat type and the belief "maximum speed capabilities of the boat is important".

Since Sigma is less than the p value (0.000 < 0.05) we reject the H0 hypothesis. According to this analysis there is a strong relationship between boat type and the belief "maximum speed capabilities of the boat is important".

Table 11. Hull aesthetic design – interior planking / veneers cross tabulation

		Cares about interior plankings / veneers					TOTAL
		1	2	3	4	5	
Hulls aesthetic designis important	1	33.33%	66.67%	0.00%	0.00%	0.00%	6
	2	15.79%	36.84%	10.53%	21.05%	15.79%	19
	3	10.71%	10.71%	35.71%	21.43%	21.43%	28
	4	0.00%	4.69%	9.38%	60.94%	25.00%	64
	5	0.00%	0.00%	8.57%	22.86%	68.57%	35
Total		5.26%	11.18%	13.82%	37.50%	32.24%	152

Table 12. Hull aesthetic design – interior planking / veneers ANOVA test

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	57.280	4	14.320	14.525	0.000
Within Groups	144.930	147	0.986		
Total	202.211	151			

Hypothesis 5:

H0: There is no relationship between boat hulls aesthetic design and significance of the interior planking / veneers.
H1: There is a relationship between boat hulls aesthetic design and significance of the interior planking / veneers.

Since Sigma is less than the p value (0.000 < 0.05) we reject the H0 hypothesis. According to this analysis there is a strong relationship between boat hulls aesthetic design and significance of the interior planking / veneers.

Table 13. Hull aesthetic design – practical and large numbers of storage cross tabulation

		Wants practical and large numbers of storage					TOTAL
		1	2	3	4	5	
Hulls aesthetic designis important	1	50.00%	33.33%	0.00%	0.00%	16.67%	**6**
	2	0.00%	21.05%	42.11%	31.58%	5.26%	**19**
	3	0.00%	10.71%	50.00%	17.86%	21.43%	**28**
	4	0.00%	1.56%	14.06%	54.69%	29.69%	**64**
	5	0.00%	2.86%	11.43%	37.14%	48.57%	**35**
Total		1.97%	7.24%	23.03%	38.82%	28.95%	**152**

Table 14. Hull aesthetic design – practical and large numbers of storage ANOVA test

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	71.132	4	17.783	24.644	0.000
Within Groups	106.072	147	0.722		
Total	177.204	151			

Hypothesis 6:

H0: There is no relationship between boat hulls aesthetic design and demand on practical and large numbers of storage.
H1: There is a relationship between boat hulls aesthetic design and demand on practical and large numbers of storage.

Since Sigma is less than the p value (0.000 < 0.05) we reject the H0 hypothesis. According to this analysis there is a strong relationship between boat hulls aesthetic design and demand on practical and large numbers of storage.

Table 15. Hull aesthetic design – deformation of hull issue cross tabulation

		Deformation of hull caused by sun makes the owner unpleasant					TOTAL
		1	2	3	4	5	
Hulls aesthetic designis important	1	33.33%	50.00%	0.00%	0.00%	16.67%	**6**
	2	0.00%	36.84%	31.58%	26.32%	5.26%	**19**
	3	0.00%	0.00%	39.29%	35.71%	25.00%	**28**
	4	1.56%	7.81%	7.81%	51.56%	31.25%	**64**
	5	5.71%	0.00%	2.86%	17.14%	74.29%	**35**
Total		3.29%	9.87%	15.13%	35.53%	36.18%	**152**

Table 16. Hull aesthetic design – deformation of hull issue ANOVA test

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	54.880	4	13.720	16.488	0.000
Within Groups	122.324	147	0.832		
Total	177.204	151			

Hypothesis 7:

H0: There is no relationship between boat hulls aesthetic design and complaint about the deformation of hull caused by sun.
H1: There is a relationship between boat hulls aesthetic design and complaint about the deformation of hull caused by sun.

Since Sigma is less than the p value (0.000 < 0.05) we reject the H0 hypothesis. According to this analysis there is a strong relationship between boat hulls aesthetic design and complaint about the deformation of hull caused by sun.

Table 17. Soft lines and curves – hard lines and edges cross tabulation

		Prefers hard lines and edges					TOTAL
		1	2	3	4	5	
Prefers soft lines and curves	1	4.17%	20.83%	12.50%	8.33%	54.17%	**24**
	2	0.75%	3.76%	5.26%	86.47%	3.76%	**133**
	3	70.25%	3.16%	18.35%	7.59%	0.63%	**158**
	4	5.41%	67.57%	13.51%	10.81%	2.70%	**37**
	5	50.00%	40.00%	0.00%	0.00%	10.00%	**10**
Total		6.58%	28.95%	28.95%	21.71%	13.82%	**152**

Table 18. Soft lines and curves – hard lines and edges ANOVA test

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	57.280	4	14.320	14.525	0.000
Within Groups	144.930	147	0.986		
Total	202.211	151			

Hypothesis 8:

H0: There is no relationship between soft lines and curves preferred and hard lines and edges preferred.
H1: There is a relationship between soft lines and curves preferred and hard lines and edges preferred.

Since Sigma is less than the p value (0.000 < 0.05) we reject the H0 hypothesis. According to this analysis there is a strong relationship between soft lines and curves preferred and hard lines and edges preferred.

6.3. Box Diagram:

Box diagram (or boxplot) is a standardized way of displaying the data distribution. It can tell about if the data is symmetrical, how did the data is spread out, and if and how the data is skewed. Box diagram displays the distribution of the data based on five number summary: maximum, third quartile (Q3), median, first quartile (Q1), and maximum) as shown in Figure 29.

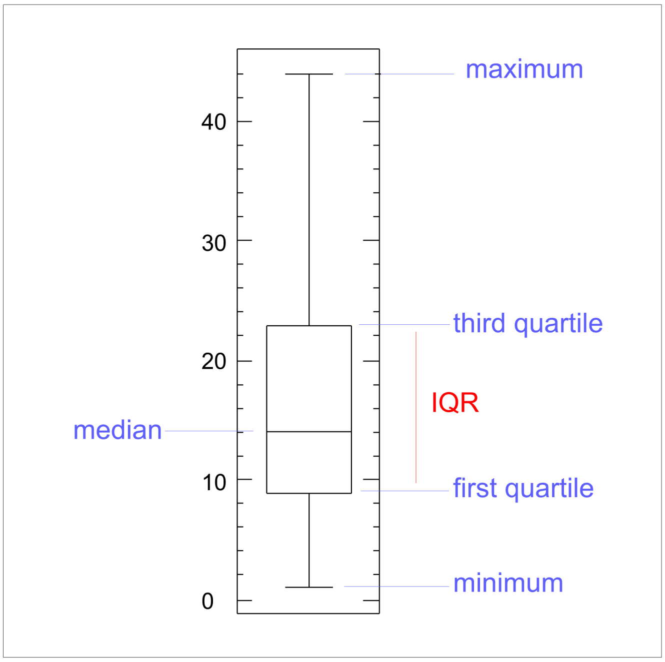
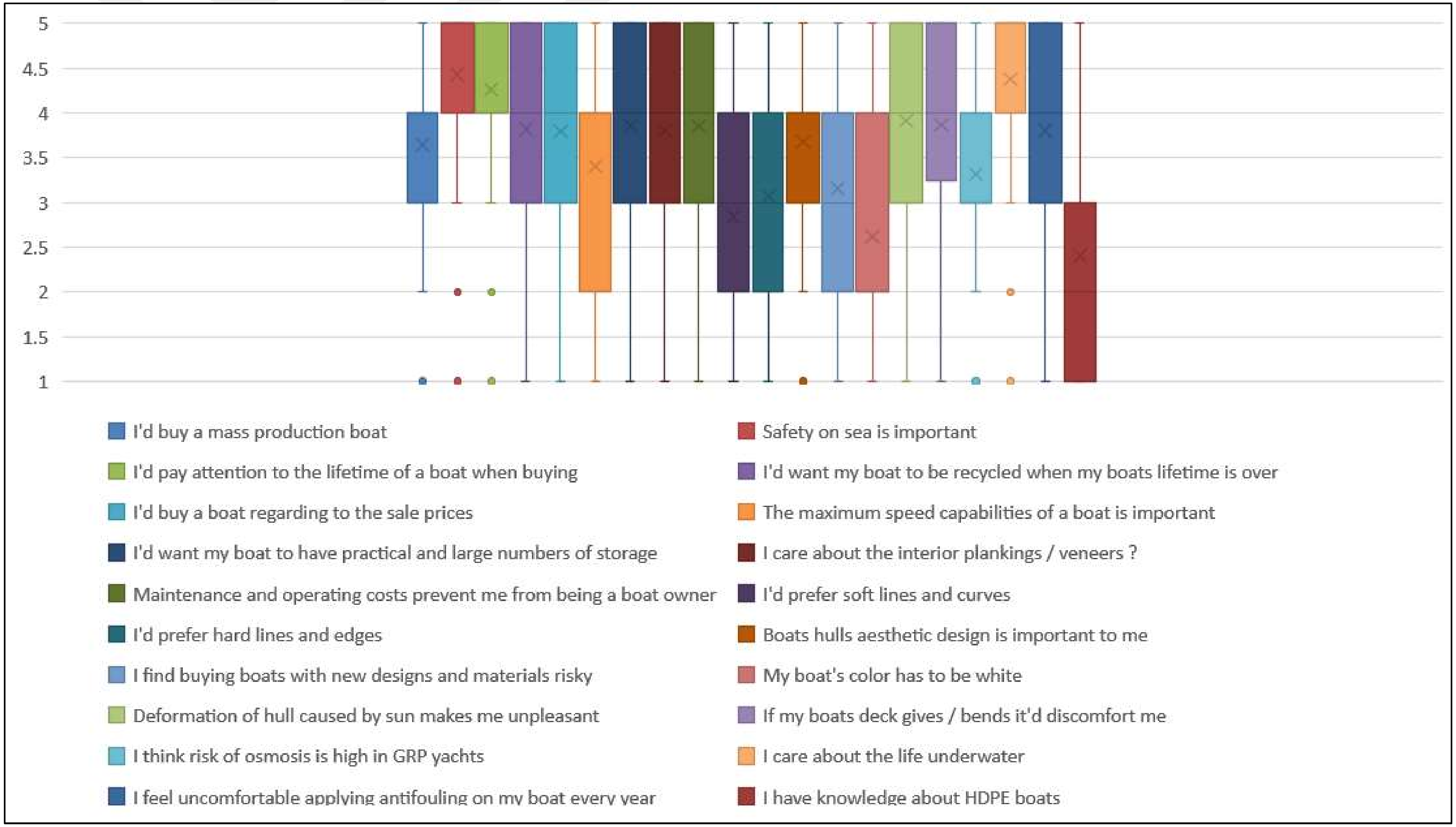


Figure 29. Parts of Box diagram

In this research study box diagram was plotted for the questions which participants ranked 1 to 5. By the help of the box plot, the data obtained from the survey can be easily seen. The majority of the data lies between the first and the third quartile. On the other hand the dots which are not in this area indicate that the contradictory variables. With the use of this graph information about standard deviation can be gathered without any effort. However the mean value can be deceptive if the standard deviation is noticeably high. Therefore, the following box graph is plotted in order to show the answers of the ratable questions in the survey.

Table 19. Box Diagram



6.3. Survey Findings

Notes

Survey was done to boat owners / enthusiasts in Marmaris, Çeşme, Kalamış and Bodrum Marina and also with E.A.Y.K. Race participants. Total of 153 people participated for the survey. Main goal of the survey is to find how much of the problems could be eliminated with the development of joint between HDPE and GRP with the help of this research study.

Results

First three of the ANOVA tests were about education level. In order to determine whether level of education affects the aesthetic perspective of the boat the analysis was made. The result was as expected, the level of education does affect the aesthetic design of the boats hull. The next two tests were between education level and importance of safety on sea and caring about the underwater life. Also the results for these two analyses were not surprising. The level of education does not affect the importance attributed to safety and consideration of underwater life. Next ANOVA test was between boat type and the maximum speed capabilities of the boat. The results were not surprising since the participants who took the survey had idea and some knowledge about yachts and marine industry. For the next three ANOVA tests the goal was to find a relationship between the hulls aesthetic design and the functionality of the boat with interior furnishing. The tests support the idea that not only the people want an aesthetic boat but also a functional one constructed from good quality materials. Last but not least a question was added to the survey in order to check if the participants were answering the questions consciously. People who preferred soft lines and curves on one questions should not choose hard lines and edges and this eliminates the chance that there are some manipulated results. This is a little trick in order to prove that all the questions were answered consciously.

The main reason behind preparing a survey is to support that we need HDPE and GRP joints. Participants, regardless of their education level care about the safety on sea so that HDPE hull stands out from the crowd once more. However, as mentioned in earlier chapters, shaping ability of HDPE is limited and this is a major concern for the participants which have higher level of education. Being incapable of shaping brings another issue on the table, the appeal. When buying or selling the yachts; aesthetic of the boat is an important issue. The need of making the yacht safe and aesthetic can be easily deduced from the analysis of these two questions. This means that adding an appealing GRP structure to a safer HDPE hull would fulfill the majority of the people's needs. Another issue about the aesthetics is the color. HDPE comes with all colors except white. However for the users this was never an issue because of better UV resistance.

Using two materials also brings more advantages to the yacht. HDPE is heavier compared to GRP. Adding a GRP superstructure would also decrease the total weight, increase the maximum speed, lower the center of gravity, and last but not least would increase stability.

From the survey, it can be seen that the participants do care about the life underwater. Since HDPE hulls do not require antifouling treatment, they are friendlier to the underwater environment. Another concern is the lifespan; the participants who want their yachts to have longer lifespans, support our idea that using HDPE hull is more advantageous.

There are also a few disadvantages with HDPE hulls: HDPE is not as stiff as most composite materials used for yachts, so it tends to bend in longer boats. Another issue is that because of the lack of know-how there are only few boatyards which can produce HDPE hulls. This is a disadvantage because this causes lack of competition. For this reason, price range is limited and finding a boatyard which constructs HDPE hulls nearby could be difficult.

7. Joining HDPE and GRP

7.1. Specimen Testing

Regardless of all the advantages, the most important issue is the joining process of HDPE and GRP. If the joints cannot fulfill the safety requirements the two material boat construction cannot be realized. For joining the structures or the frames. There are several options in the marine industry to join the two structures. However for joining HDPE and GRP materials, chemical or mechanical bonding alone won't be the solution, both have to be used. For the mechanical connection metric 10 bolts and nuts (Stainless steel 316) were used and for chemical bonding marine adhesive was used between HDPE and GRP (Figures 30, 34, and 38).

In this thesis research three specimen types were tested. For each type three samples were constructed. The reason behind this is to do the test multiple times and get reliable mean values on the results. There are several possible causes for variation in properties including variation in raw materials, manual operations, and environmental variables such as temperature and humidity.

Each specimen contains two main parts, GRP and HDPE. Lamination of specimens were done by hand lay-up method (tables 21, 22, and 23). For the HDPE part of the specimen 30mm HDPE (table 20, technical specifications of HDPE) was used. Construction of the HDPE parts took approximately 10, 20, and 40 minutes for Type 1, Type 3, and Type 2 respectively.

To test the specimen tensile load of 2 kN was applied during the testing process. In order to begin the tests the specimen has to be fixed; however because of the form of the specimen it was not possible to fix it with simple clamping. A holding construction has to be crafted specifically for the specimens (Figure 61). After the holder is completed the experiments could be run without any hesitation.

Table 20. Technical specification of HDPE

Test Report EN 10204-2.2			
Results from random tests			
Property	**Value**	**Unit**	**Test Method**
Specific gravity, RT	0,9622	g/cm^3	DIN EN ISO1183
Notched impact strength, RT	22,7	kJ/m^2	DIN EN ISO 179 EAI
Oxidation Induction Time, 210^0C	0,502	min	DIN EN 728
Carbon content, RT	2,558	%	DIN EN ISO 11358
Melt flow rate (MFR), 5 kg, 190^0 C	0,27	g/10min	DIN EN ISO 1133
Yield strain, RT	8,95	%	DIN EN ISO 527
Yield stress, RT	26,69	N/mm^2	DIN EN ISO 527
Thermal properties, along, 110^0C	0,27	%	DIN EN ISO 14632
Thermal properties, transverse, 110^OC	0,27	%	DIN EN ISO 14632
Tensile modulus, RT	1.31	N/mm^2	DIN EN ISO 527
*According to manufacturer data			

One of the specimen type was designed according to Neşer (2009). The other two were designed considered to the past researches (Hildebrand M, Hentinen M., 1998, Wright PNH, Wu Y, Gibson AG., 2000). As mentioned before, in order to join HDPE and GRP metric 10 bolts and marine adhesive was used. For each specimen, strain gauges were placed on them and specimens were tested in Dokuz Eylül University Labs. Three specimens of three types were pulled with 2 kN load. For the results, cracks and strain gauge stress values can be seen as plotted individually and together in the next section.

Table 21. Lamination table of part 1

#	Material	Glass to Resin Ratio	Thickness [mm]	Density
1	Chopped Strand Mat	34%	0,92	450 gr/m²
2	Chopped Strand Mat	34%	1,22	600 gr/m²
3	Woven Fiberglass Mat	34%	1,05	800 gr/m²
4	Chopped Strand Mat	34%	0,92	450 gr/m²
5	Chopped Strand Mat	34%	1,22	600 gr/m²
TOTAL			5,32	
6	Polyurethane Foam		15,00	60 kg/m³

Table 22. Lamination table of part 2

#	Material	Glass to Resin Ratio	Thickness [mm]	Density
1	Chopped Strand Mat	34%	0,92	450 gr/m²
2	Chopped Strand Mat	34%	1,22	600 gr/m²
3	Woven Fiberglass Mat	34%	1,05	800 gr/m²
4	Chopped Strand Mat	34%	0,92	450 gr/m²
5	Chopped Strand Mat	34%	1,22	600 gr/m²
TOTAL			5,32	
6	Polyurethane Foam		15,00	60 kg/m³

Table 23. Lamination table of part 3

#	Material	Glass to Resin Ratio	Thickness [mm]	Density
1	Chopped Strand Mat	34%	0,92	450 gr/m²
2	Chopped Strand Mat	34%	1,22	600 gr/m²
3	Woven Fiberglass Mat	34%	1,05	800 gr/m²
4	Chopped Strand Mat	34%	0,92	450 gr/m²
5	Chopped Strand Mat	34%	1,22	600 gr/m²
TOTAL			5,32	
6	Polyurethane Foam		15,00	60 kg/m³

The first three tests were held with specimens 1, 2, and 3 (Type 1, Figure 58). This type was adapted from Neşer (2009). The specimens were tested for 2 kN tensile load. As a result of the first three tests, the specimens cracked around the same point (Figure 31, 32, and 33). ANSYS analysis of the deformation has predicted the crack around the same areas for the type 1 specimens (Figure 53). Figures 42, 43, and 44 the force-strain graphs were plotted from the 5 strain gauges which were placed on the specimens (Figure 30). In the first experiment the crack started at around 2000 N load (Figure 42) where a little bump could be noticed. However for the experiment 2, the crack occurred at just above 1000 N load (Figure 43). This is another indication of the different outcomes of hand lay-up method. The durability of the GRP is not always the same and it could change according to various parameters. On the other hand with Experiment 3 there was a different problem. While the testing, at 800 N load there was an unexpected crack (Figure 44). The crack happened around the predicted area, yet it was bigger than the first two experiments, which again proves that with hand lay-up method it is not possible to get same durability on grp structures.

The following three tests, experiments 4, 5, and 6 were completed with Type 2 joints (Figure 59). This connection type is one of the most common joints in the marine industry. HDPE side of the structure has a bracket for extra durability and for the GRP side the same fillet was used in Type 1. Type 2 was also tested for 2 kN tensile load. ANSYS results for Type 2 specimens showed three critical areas (red colored), and which the results of these three experiments cracks occurred around two of these three critical areas (Figure 34). In experiments 4 and 6 the cracks happened just above 1000 N load while cracking in experiment 5 occurred at 1500 N load (Figures 45, 46, and 47). At the beginning of experiment 5, the connection cable for Strain Gauge 5 was disconnected and because of that, throughout the experiment no data could be gathered (Figure 46).

Last three tests, experiments 7, 8, and 9 involved the third type of specimen. Specimen Type 3 looks like Type 2; however with a slight change, no bracket was used on the HDPE side of the structure. This is to test whether the bracket on HDPE is necessary for the structure or not. The tests indicate that the crack the bracket was necessary because of the cracks happened around the corner on HDPE side (Figure 38). ANSYS analysis showed that the corner of HDPE has the most deformation which matches up with the cracks happened in the experiments (Figure 39, 40, and 41). It is not clear when the crack started in Experiment 7 because of no visual indication in the strain-force graph (Figure 39); on the other hand it is clear that cracking started around 2 kN load in Experiment 8 (Figure 40). While the tensile load was being applied to the specimen in Experiment 9 the clamp which was holding the specimen has slipped and made the test invalid around 600 N load (Figure 41).

7.1.1. Drawings and photos of cracks

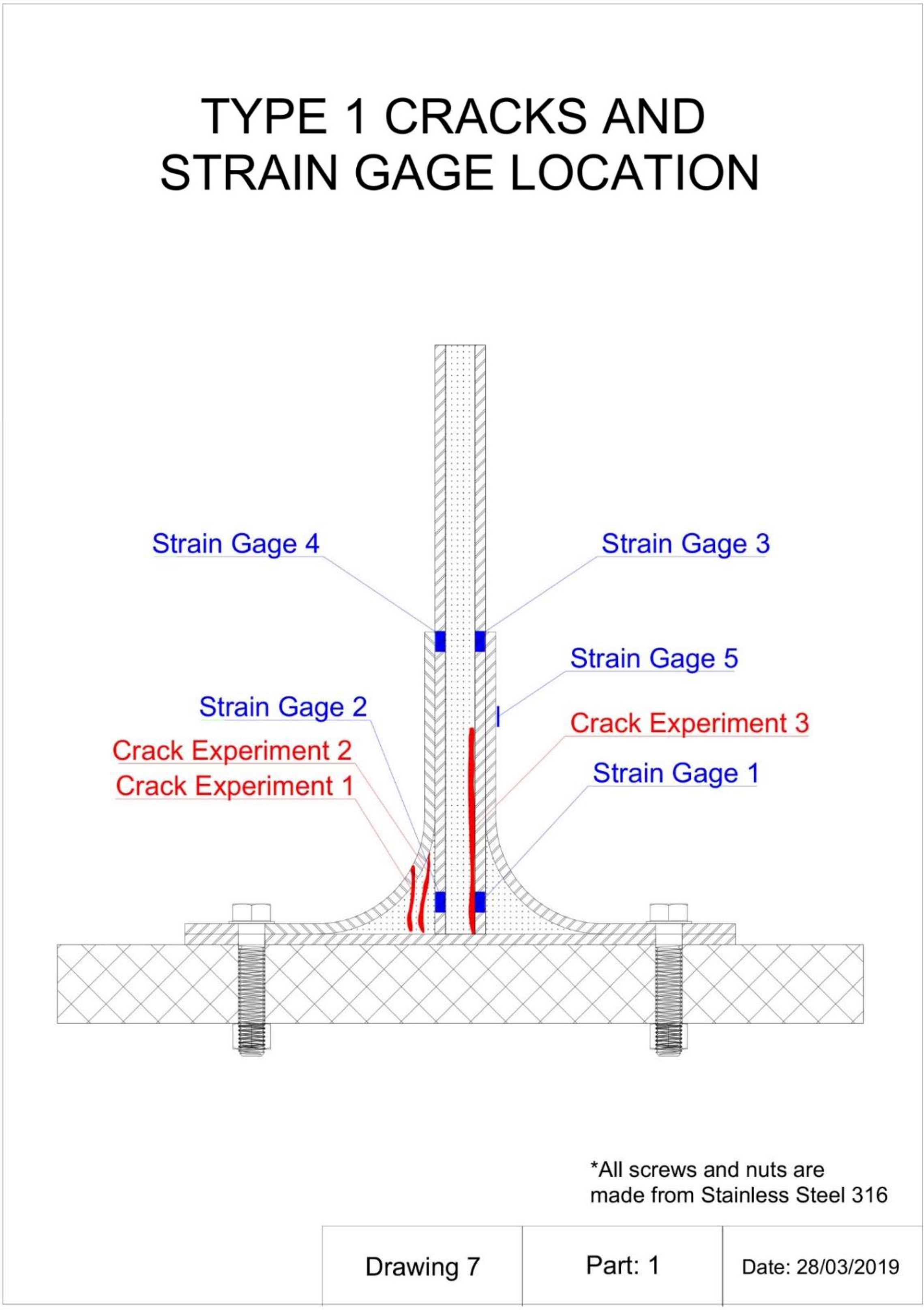


Figure 30. Cracks and Strain Gauge Locations of Type 1 Specimens

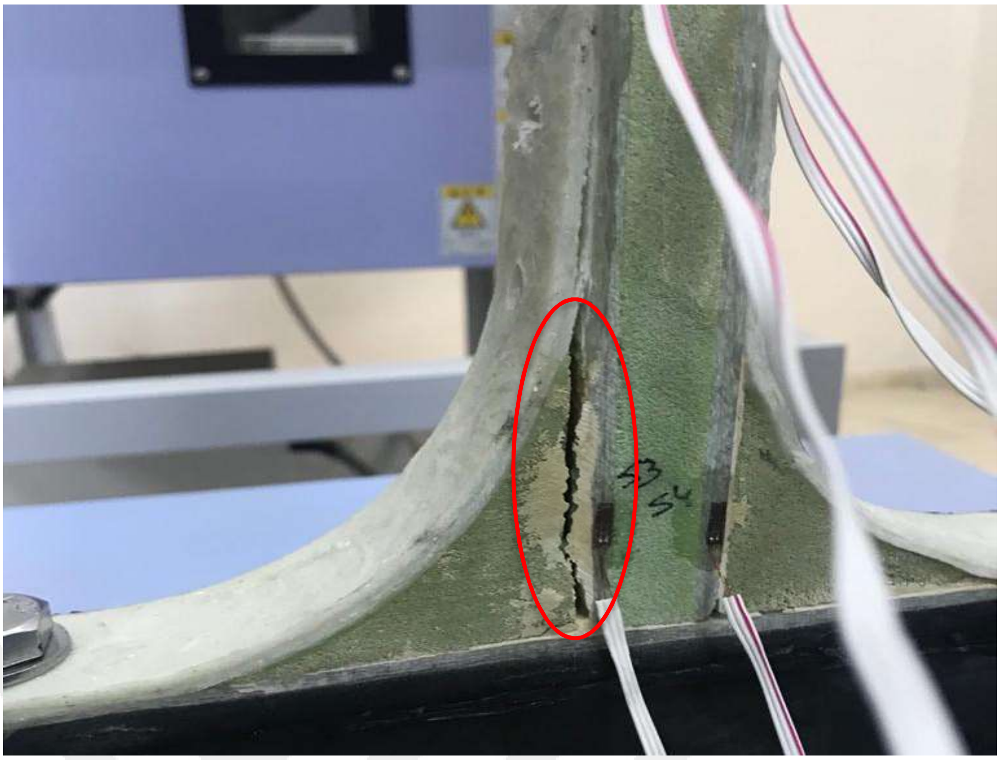


Figure 31. Experiment 1, Type 1

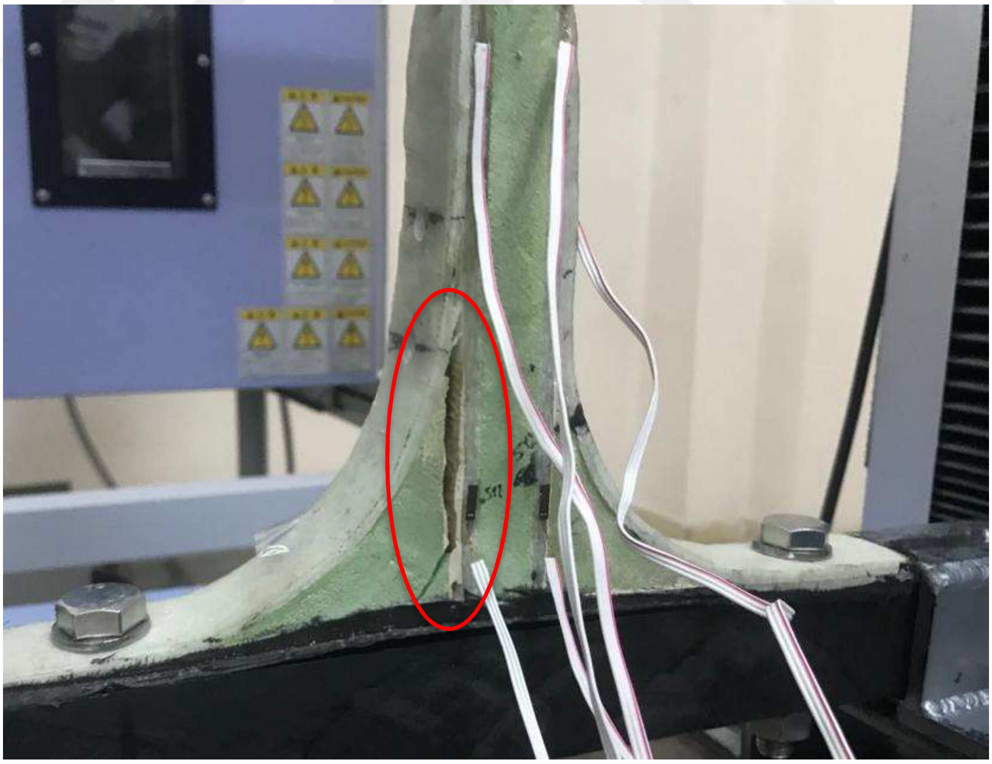


Figure 32. Experiment 2, Type 1

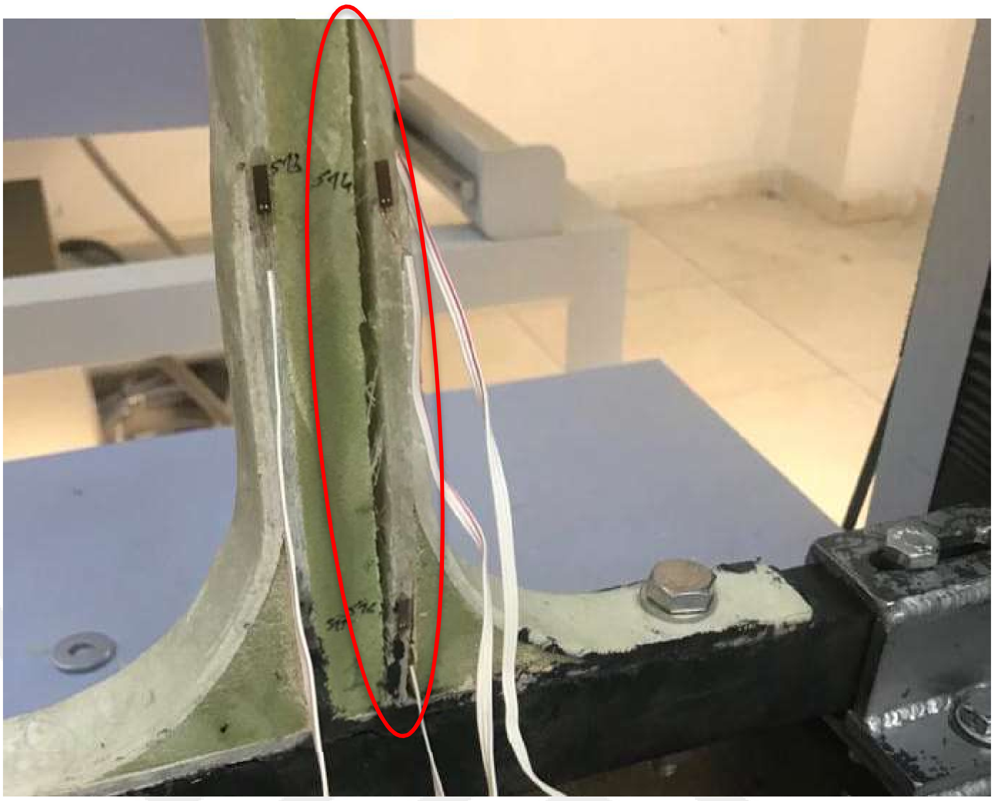


Figure 33. Experiment 3, Type 1

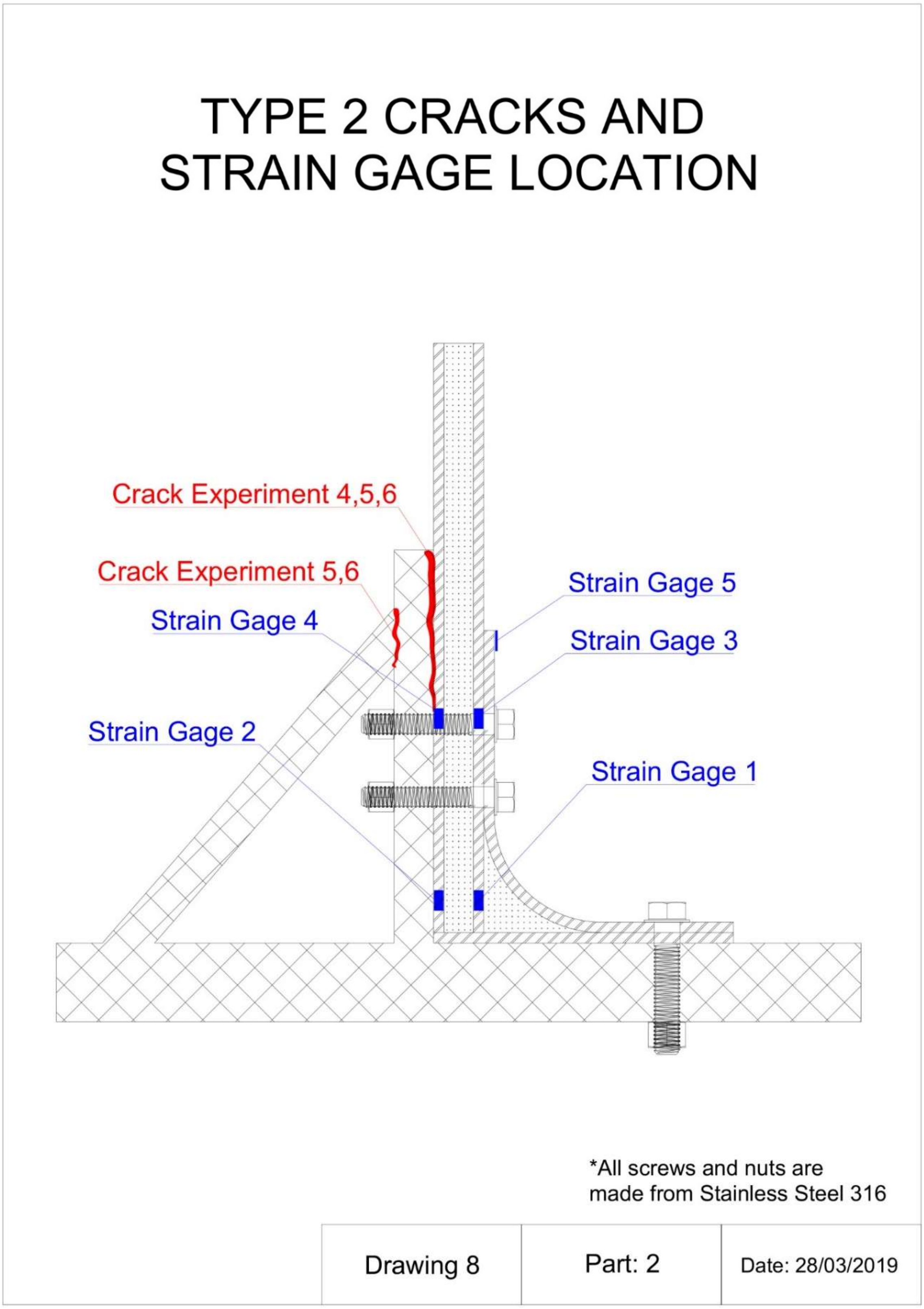


Figure 34. Cracks and Strain Gauge Locations of Type 2 Specimens

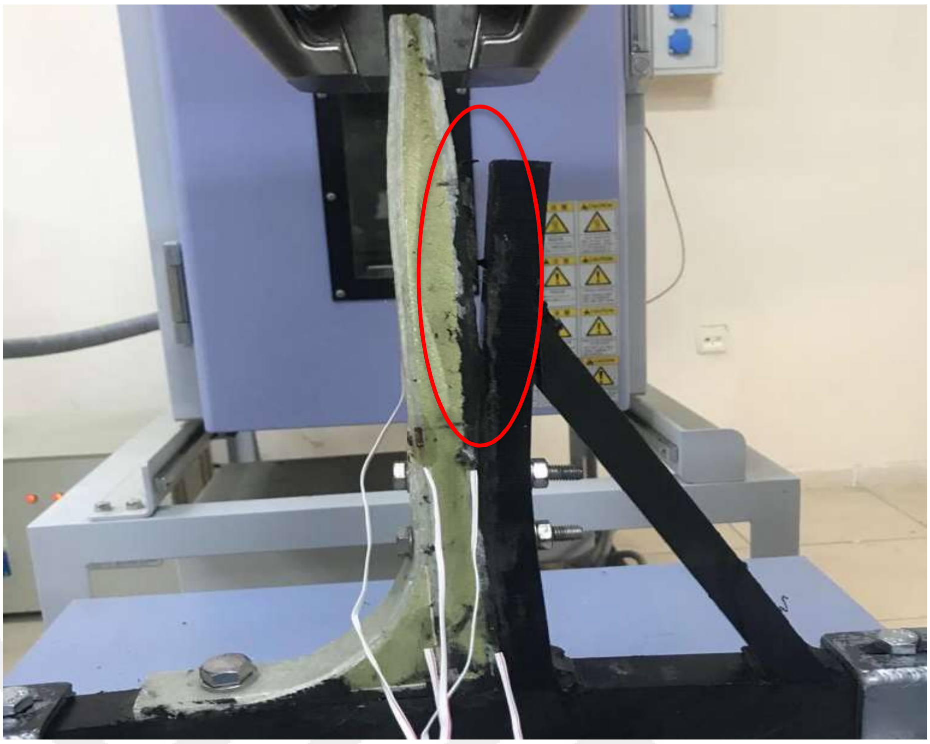


Figure 35. Experiment 4, Type 2

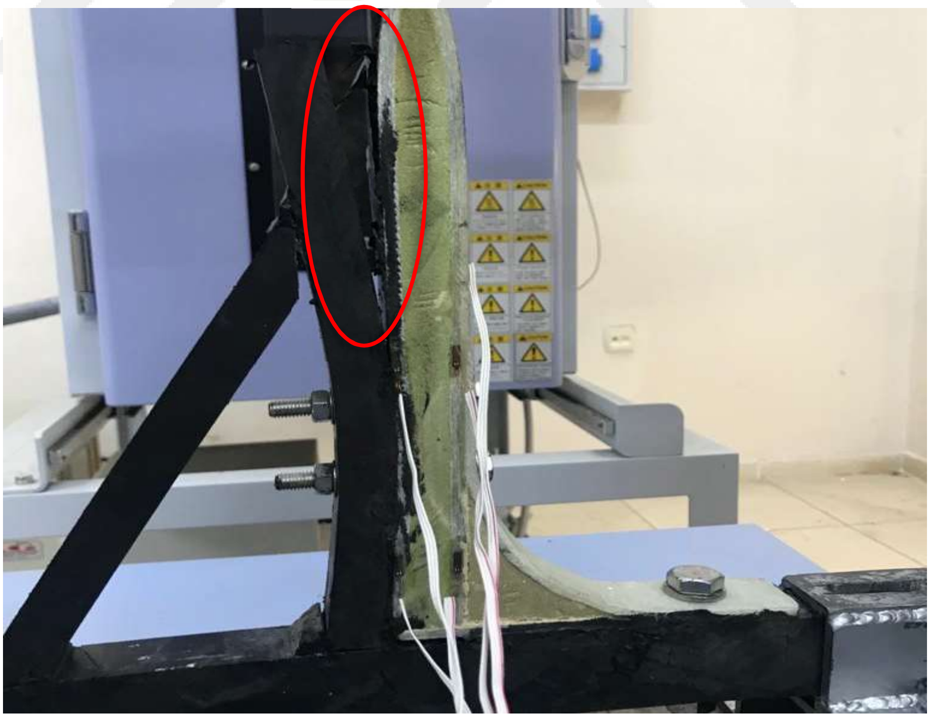


Figure 36. Experiment 5, Type 2

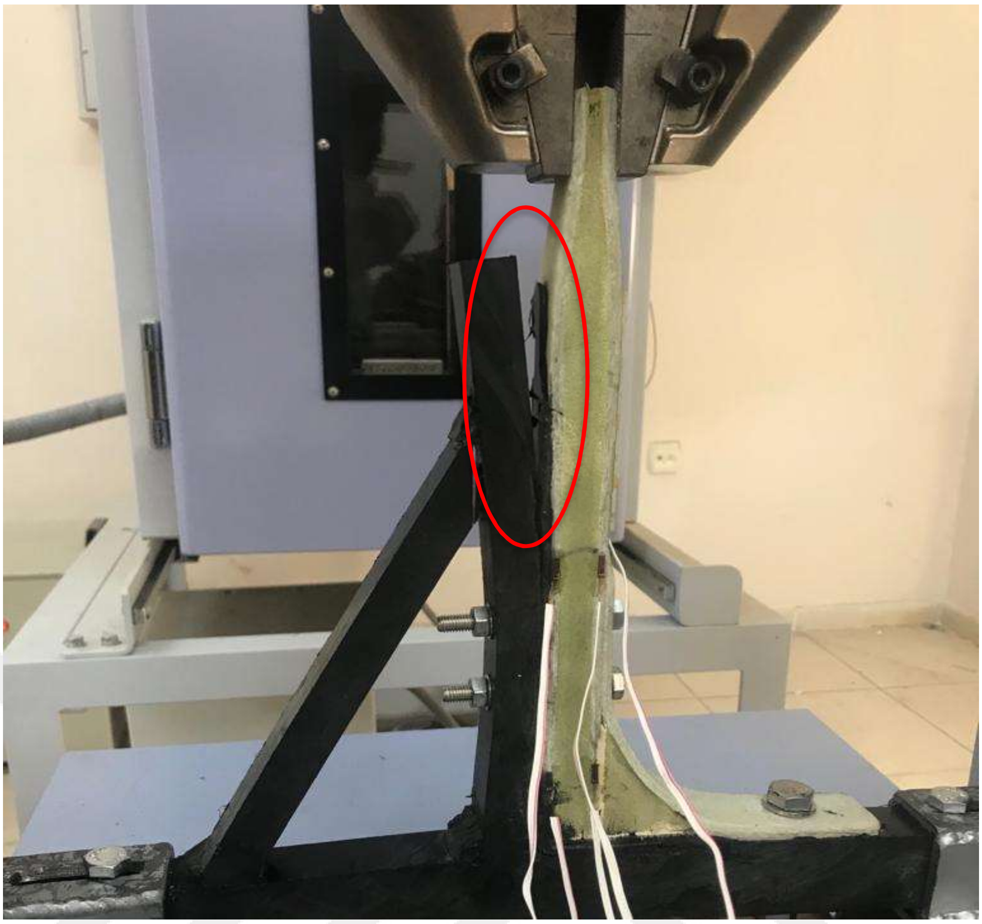


Figure 37. Experiment 6, Type 2

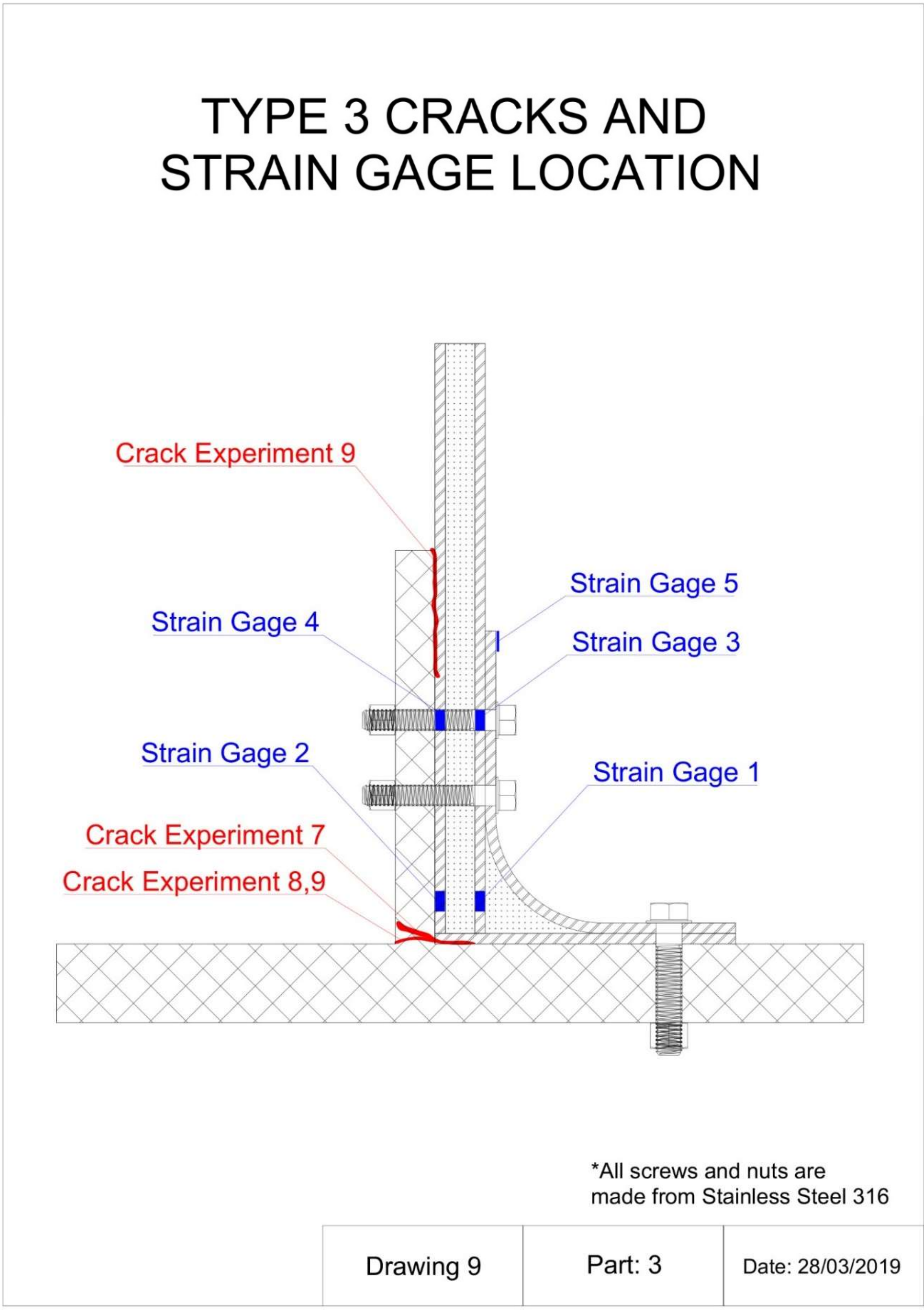


Figure 38. Cracks and Strain Gauge Locations of Type 3 Specimens

Figure 39. Experiment 7, Type 3

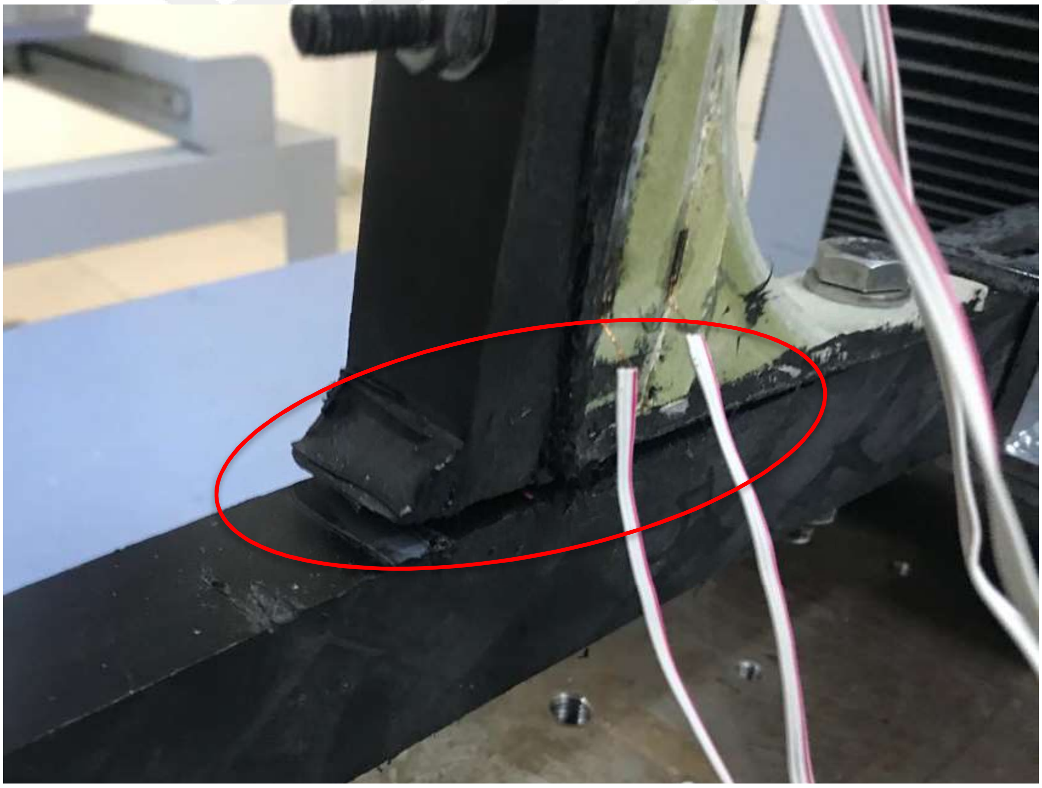


Figure 40. Experiment 8, Type 3

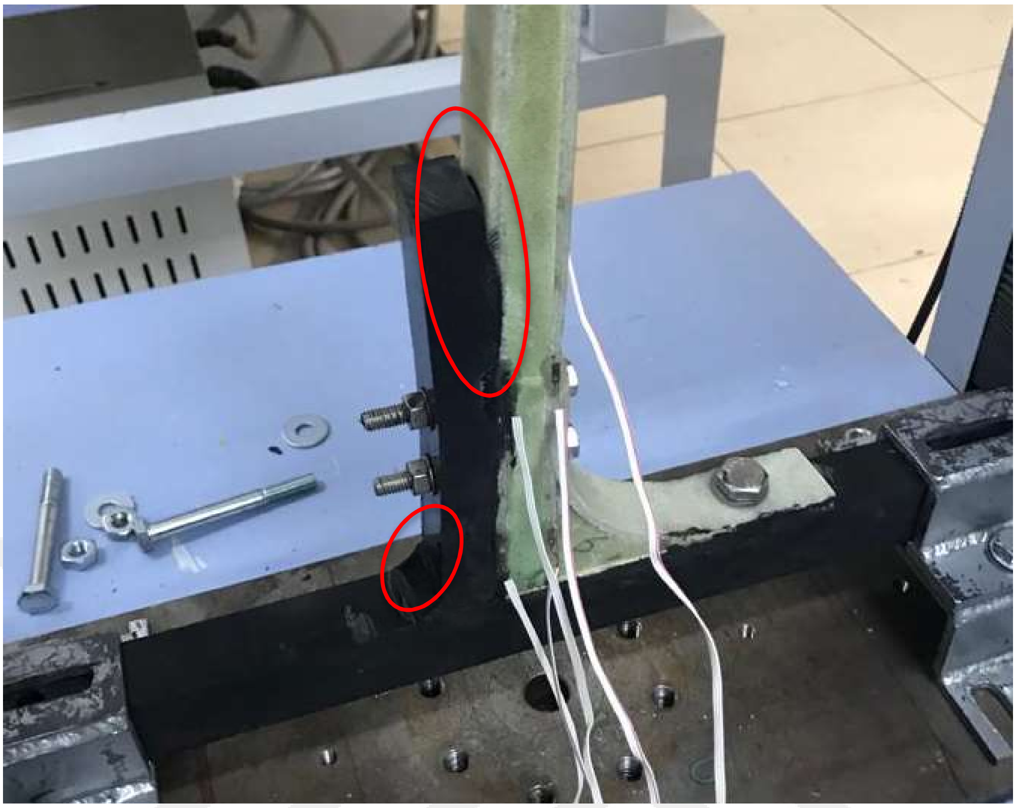


Figure 41. Experiment 9, Type 3

7.1.2. Strain Gauge Results

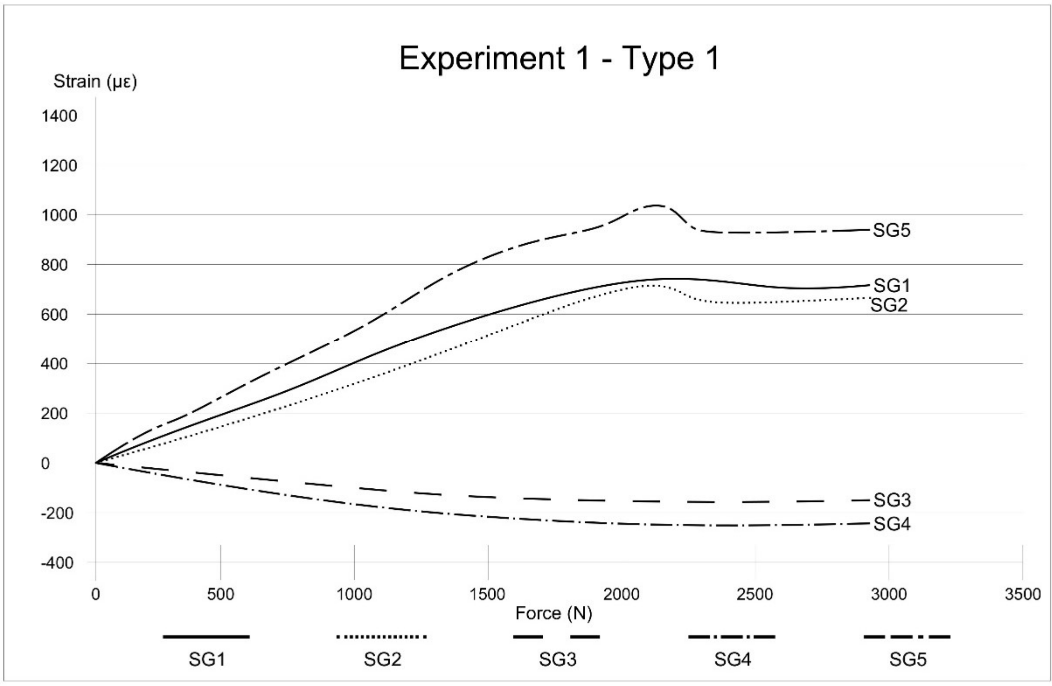


Figure 42. Strain - Force Graph of Experiment 1 Type 1

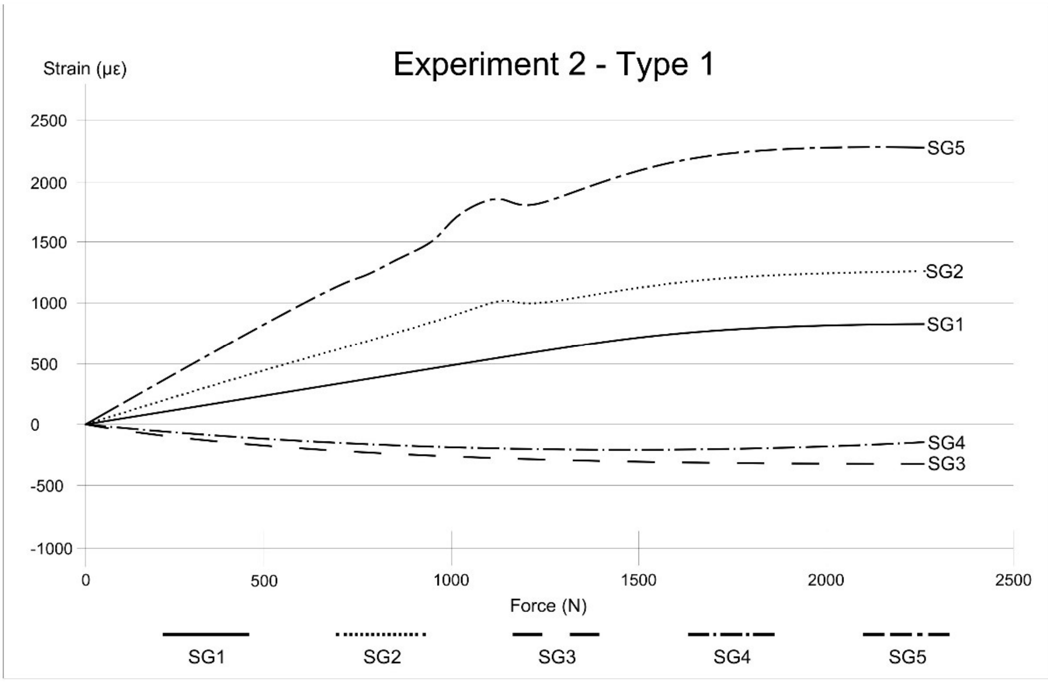


Figure 43. Strain - Force Graph of Experiment 2 Type 1

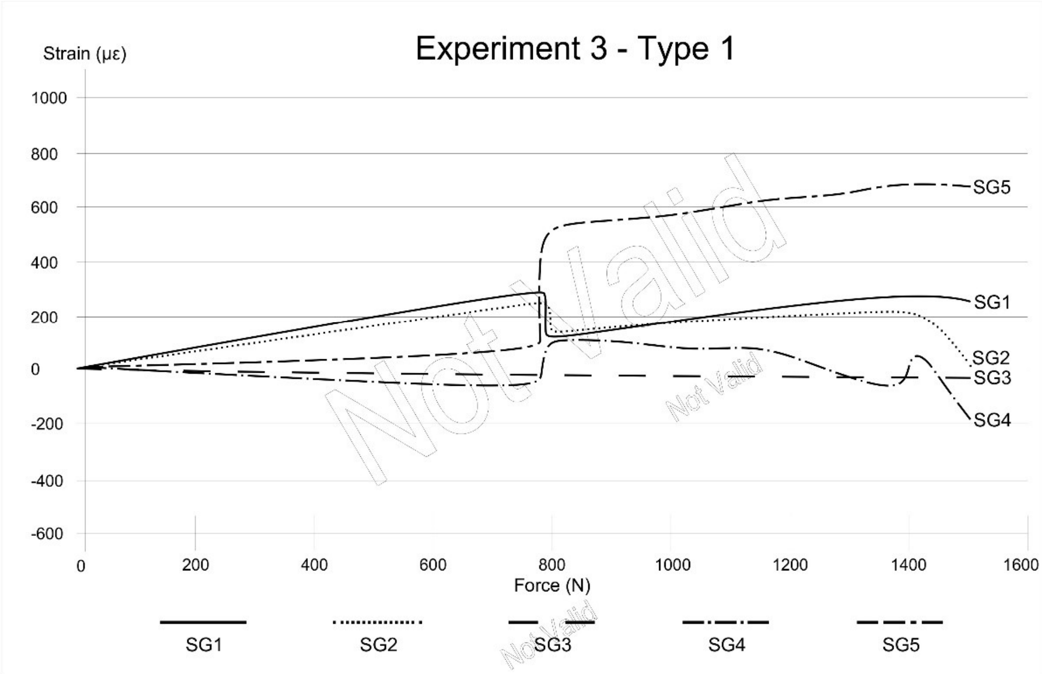


Figure 44. Strain - Force Graph of Experiment 3 Type 1

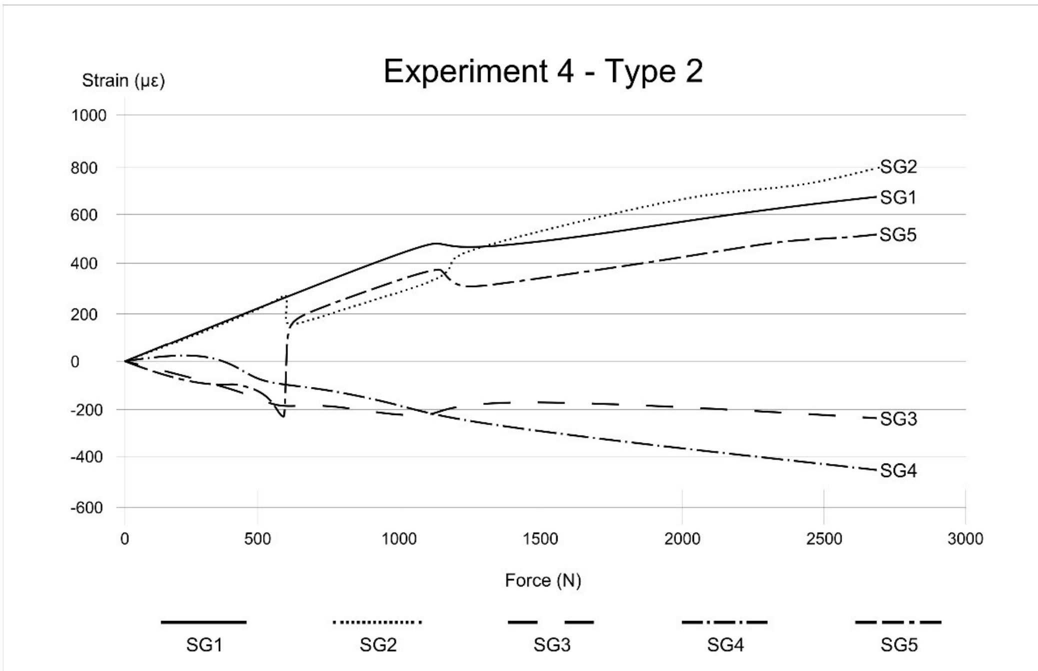


Figure 45. Strain - Force Graph of Experiment 4 Type 2

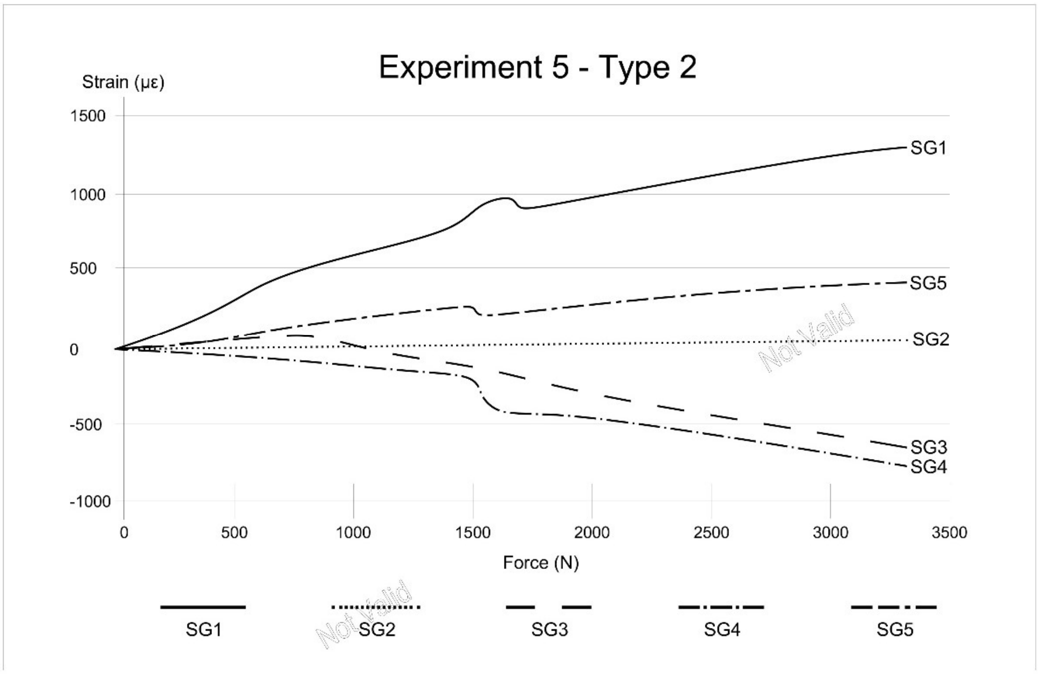


Figure 46. Strain - Force Graph of Experiment 5 Type 2

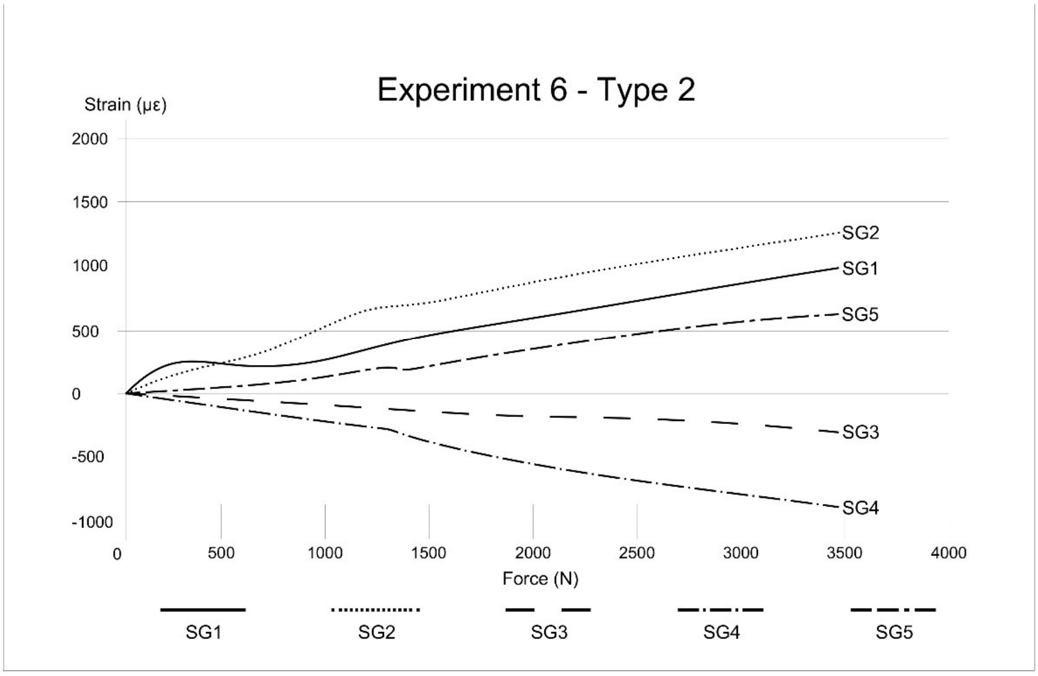


Figure 47. Strain - Force Graph of Experiment 6 Type 2

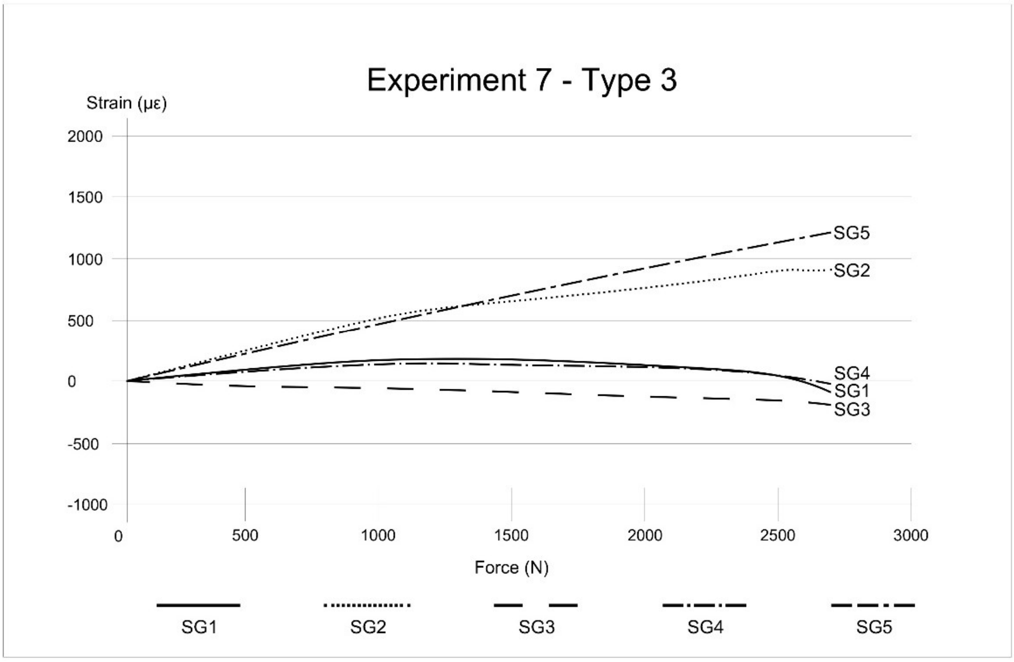


Figure 48. Strain - Force Graph of Experiment 7 Type 3

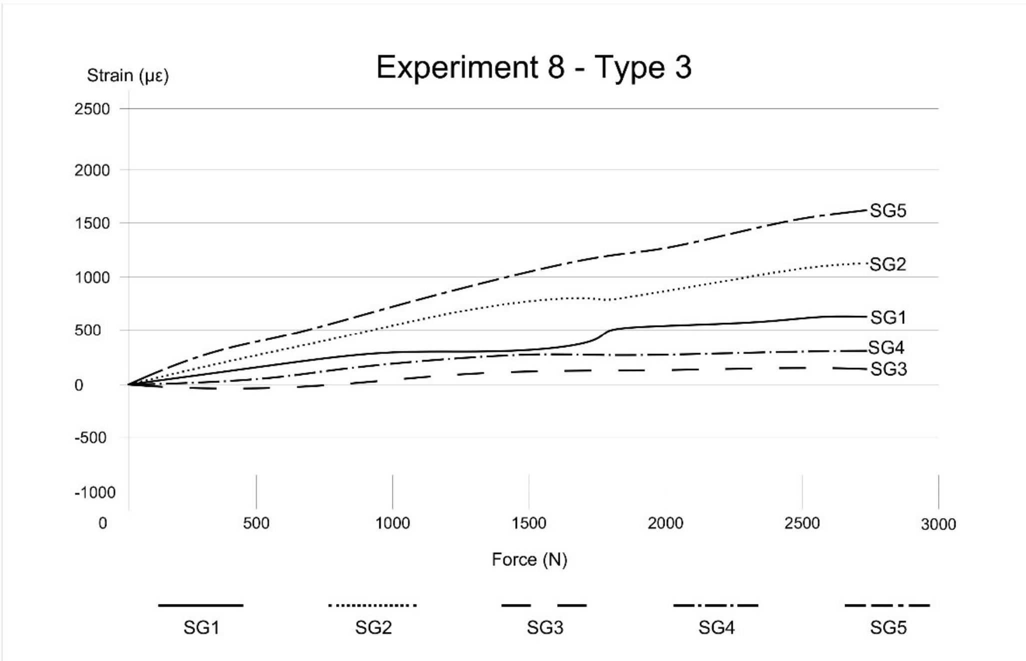


Figure 49. Strain - Force Graph of Experiment 8 Type 3

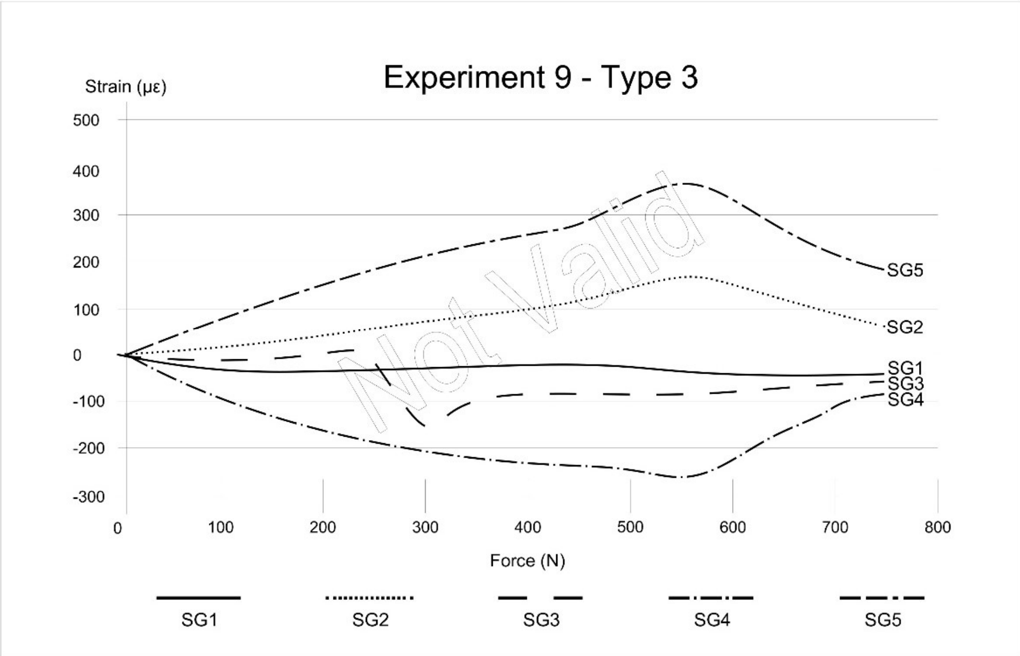


Figure 50. Strain - Force Graph of Experiment 9 Type 3

All Experiments

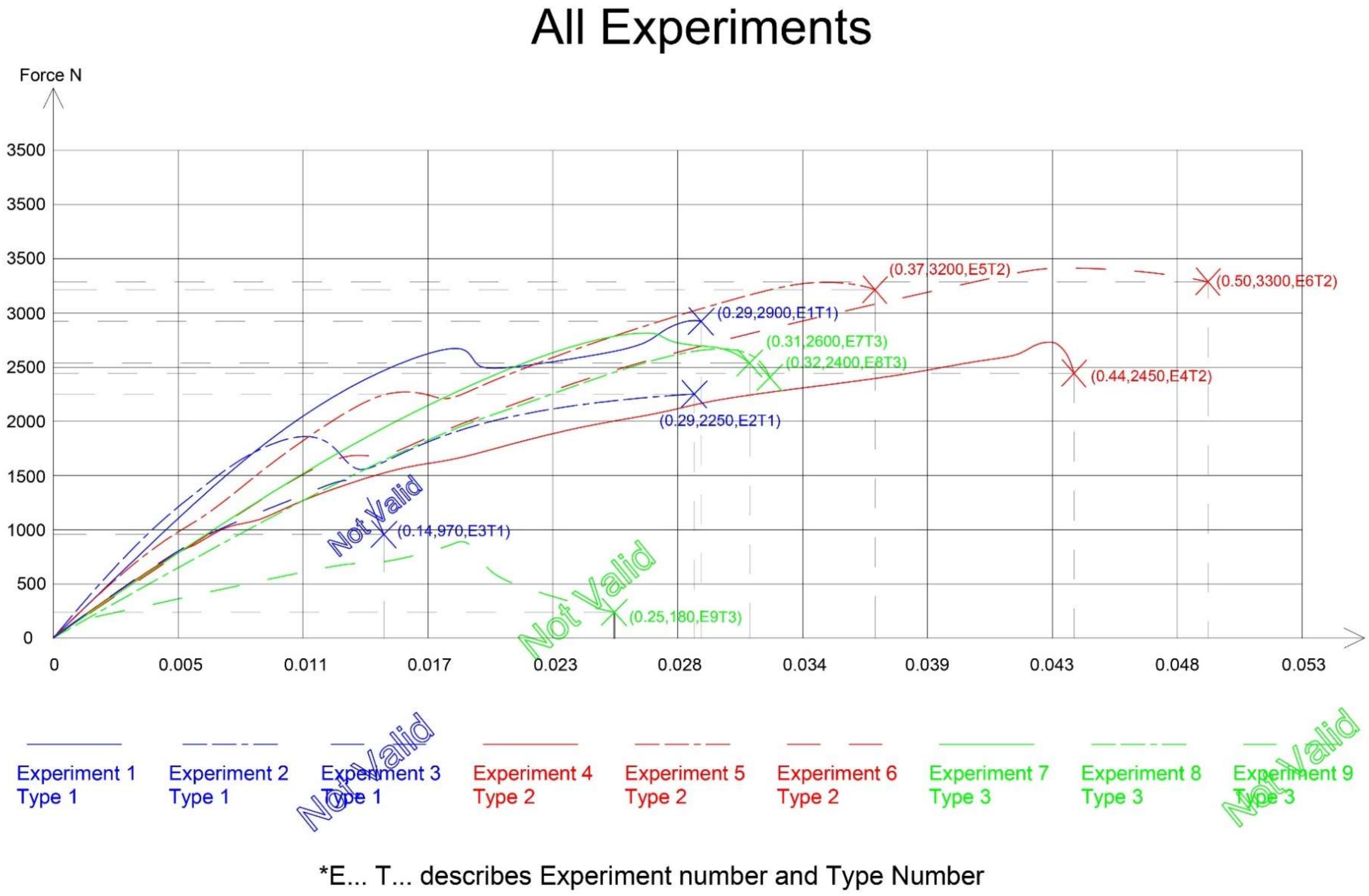


Figure 51. Strain - Force Graph of All Experiments

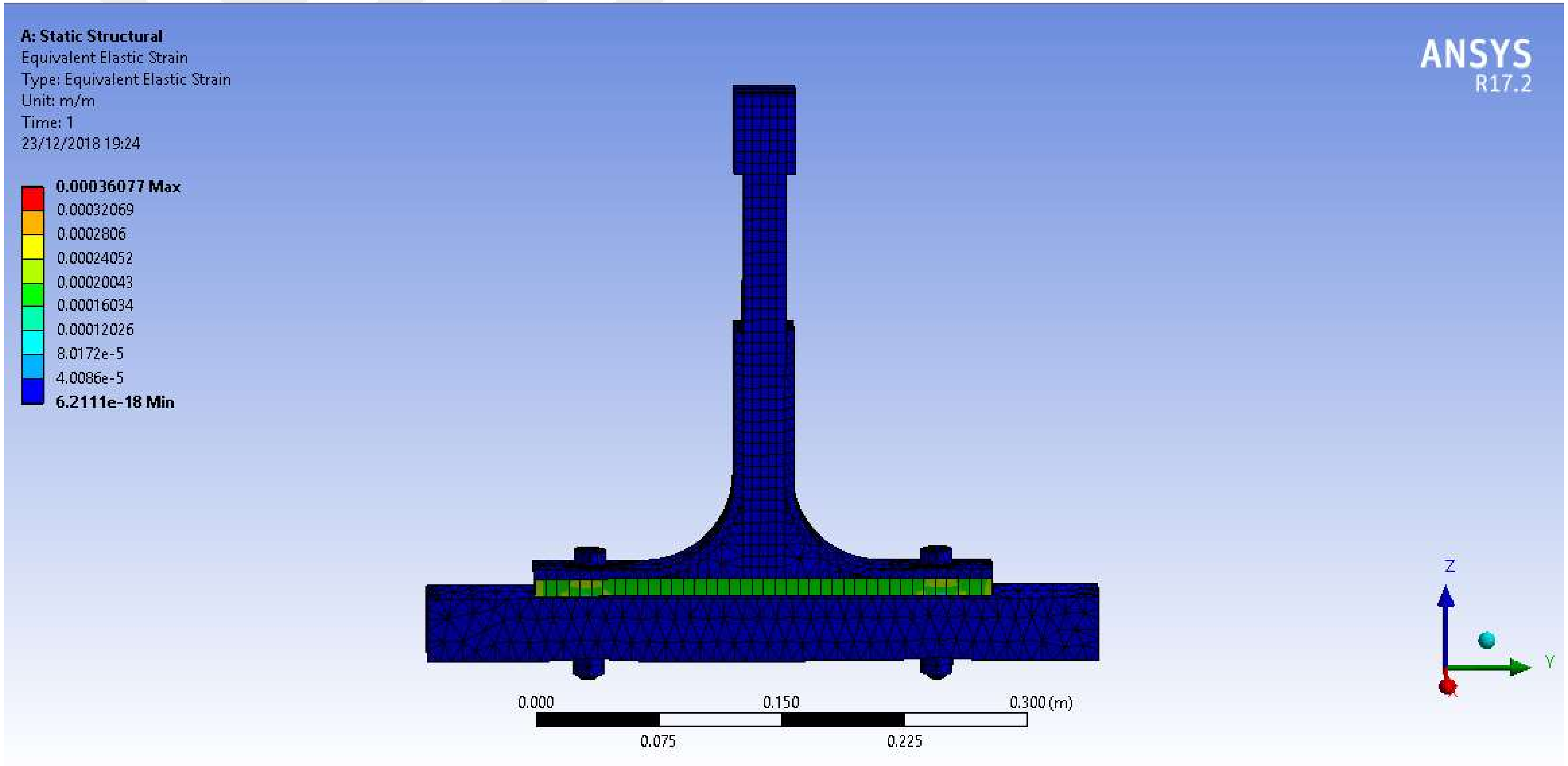


Figure 52. Specimen 1, Elastic Strain

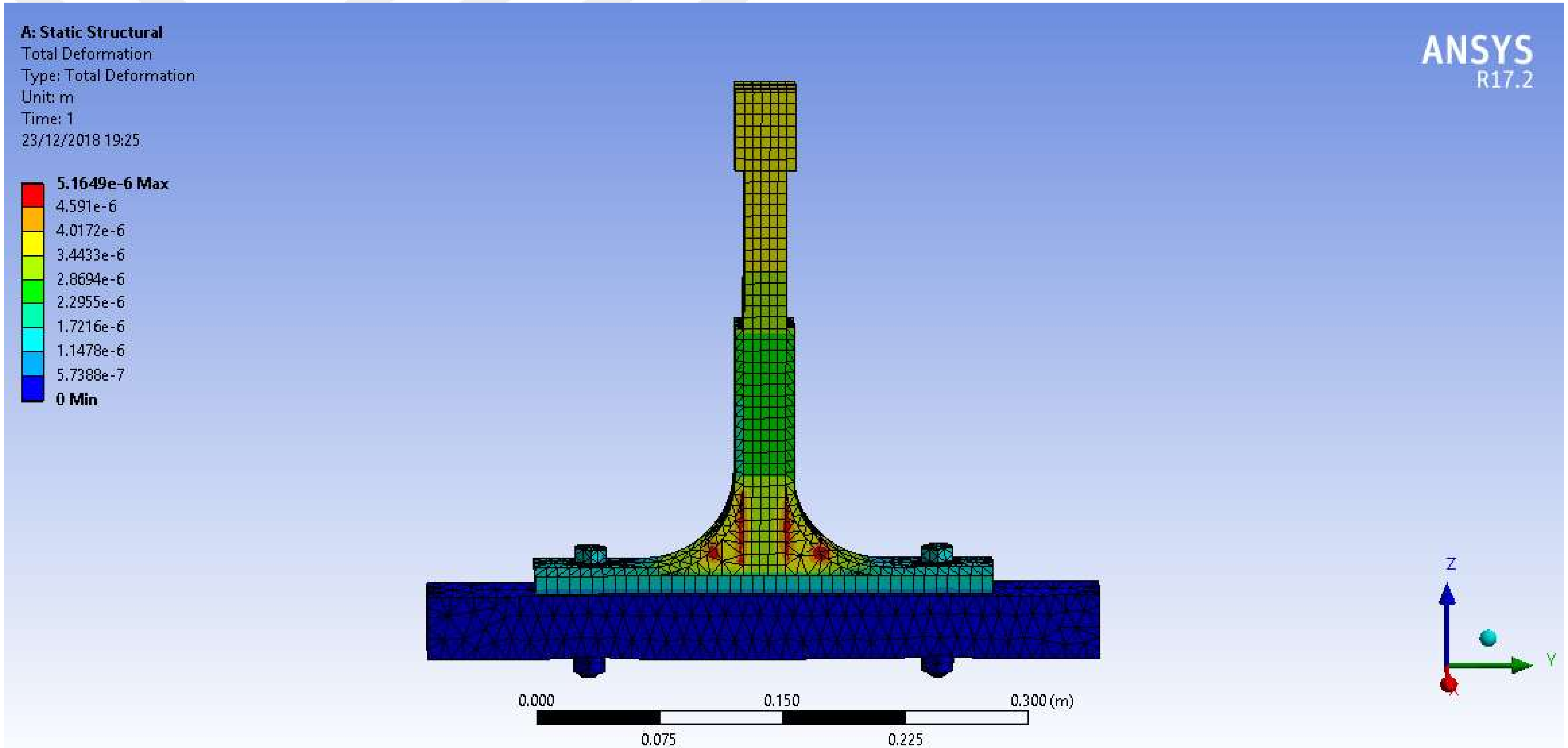


Figure 53. Specimen 1, Total Deformation

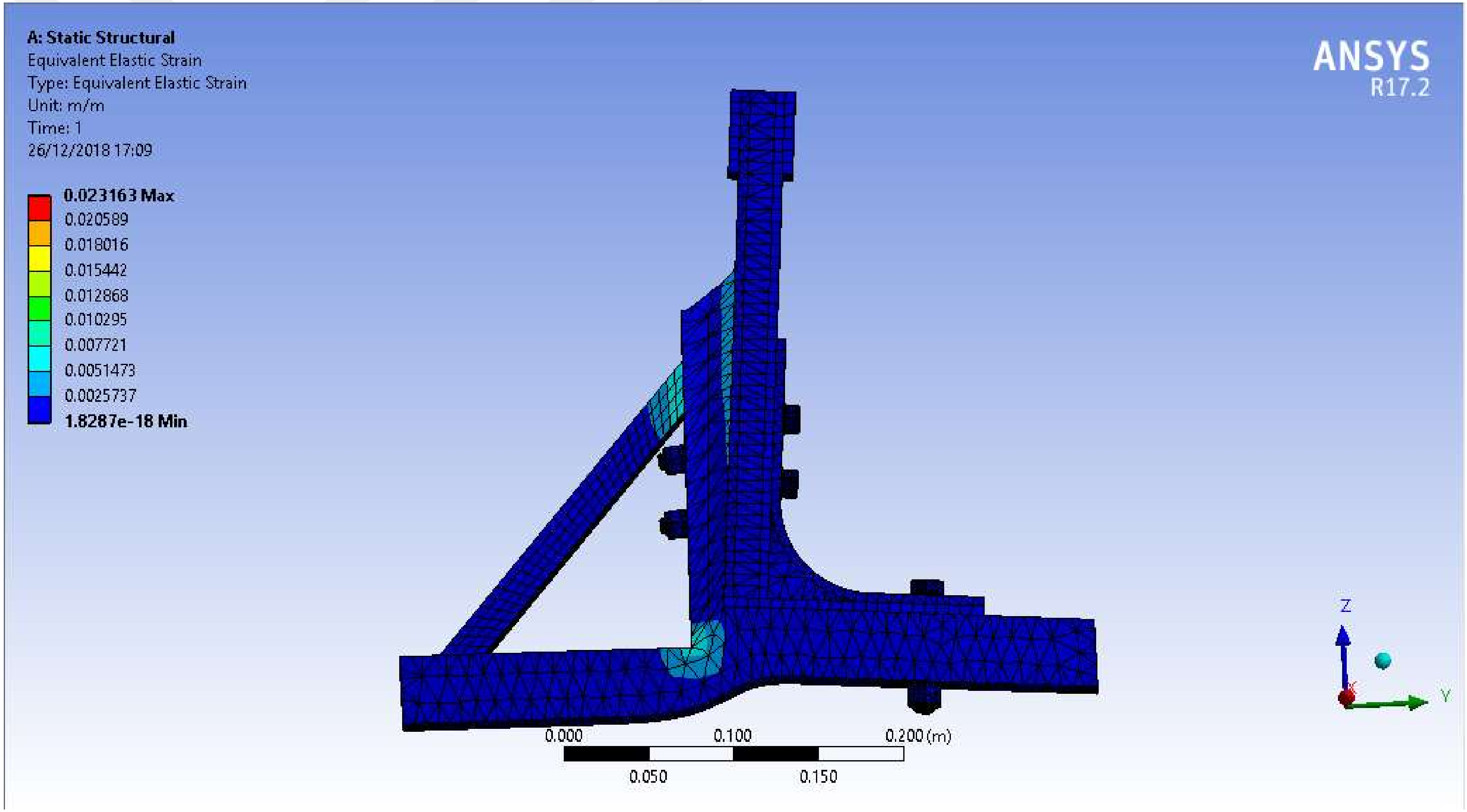


Figure 54. Specimen 4, Elastic Strain

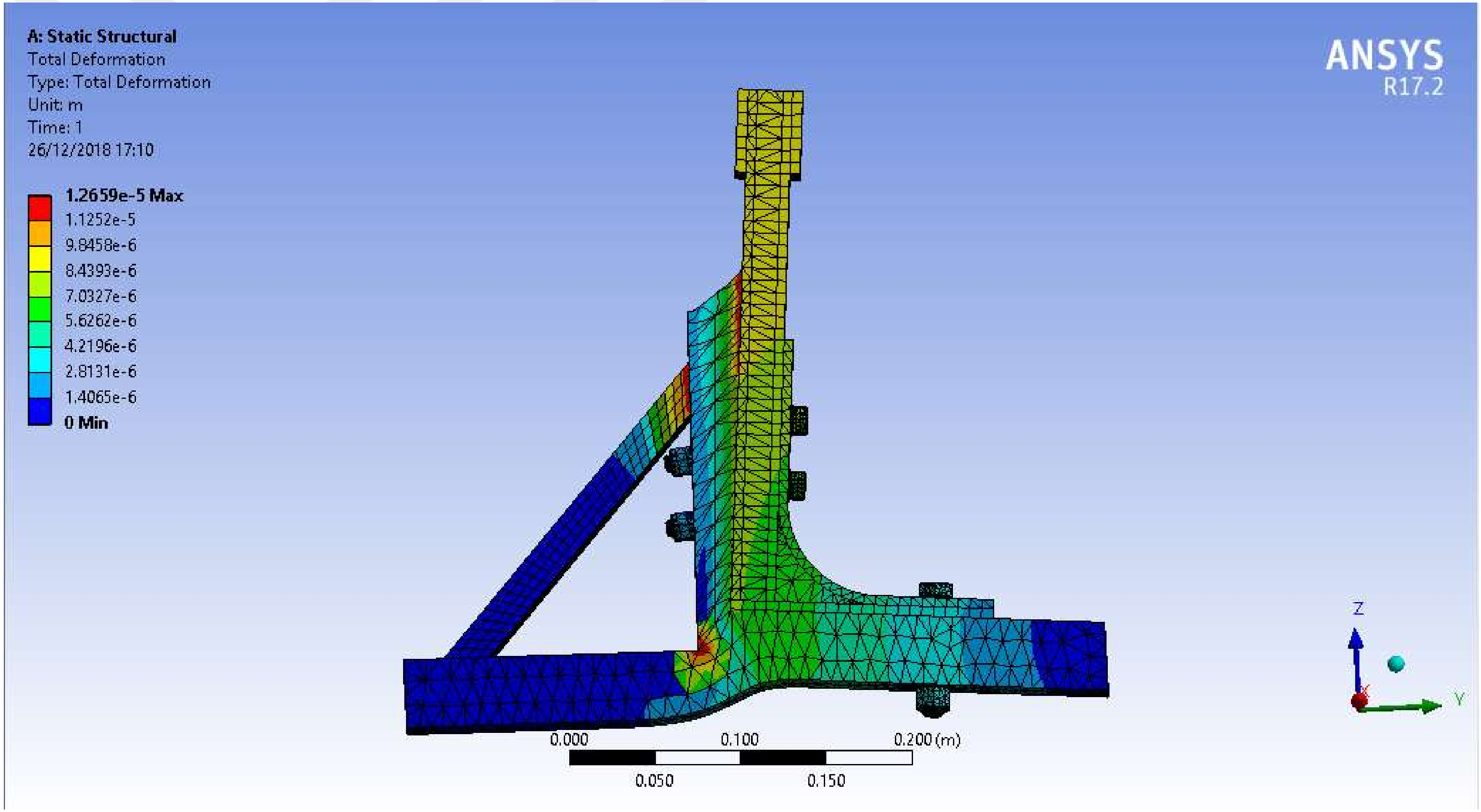


Figure 55. Specimen 4, Total Deformation

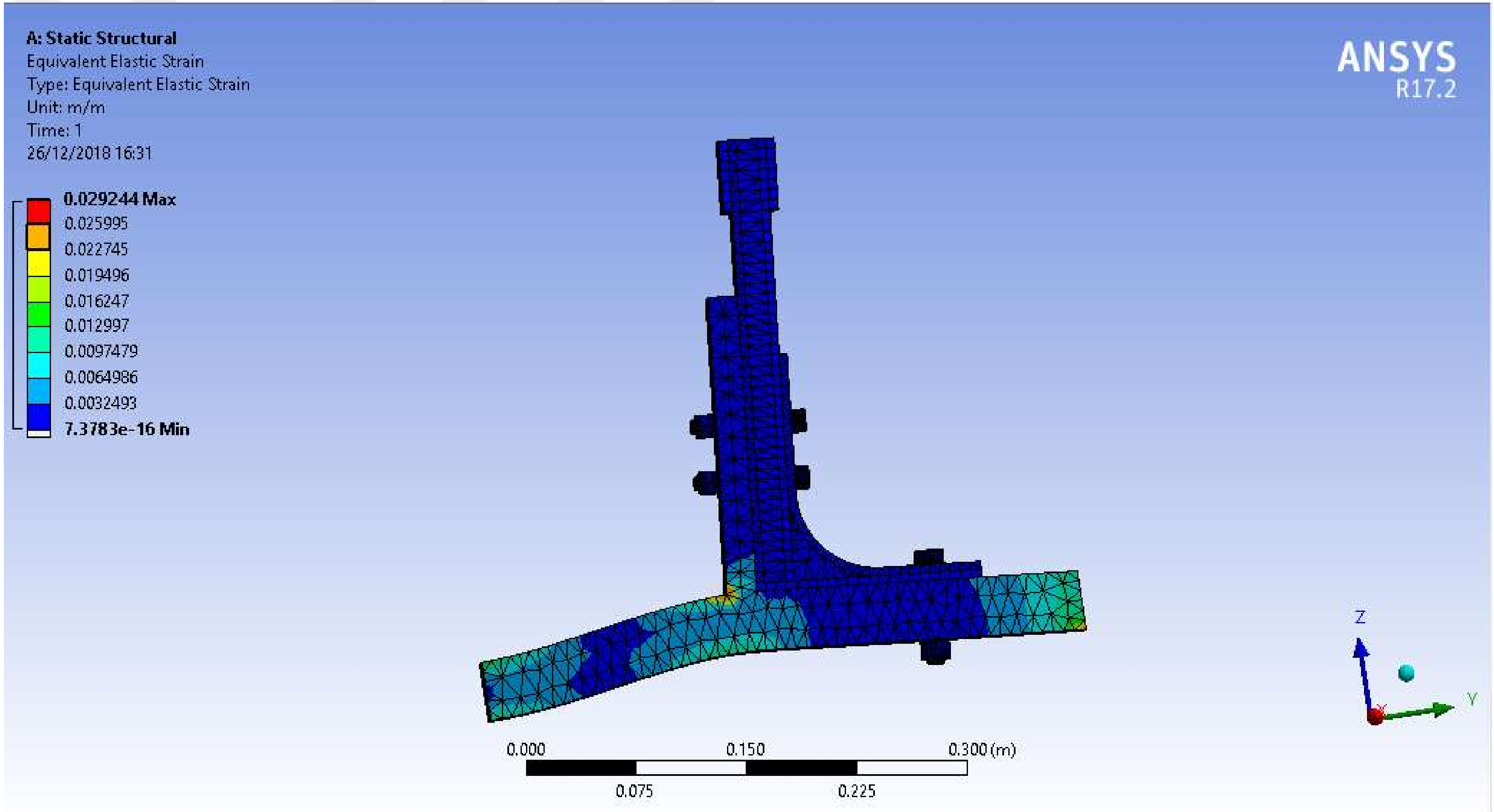


Figure 56. Specimen 7, Elastic Strain

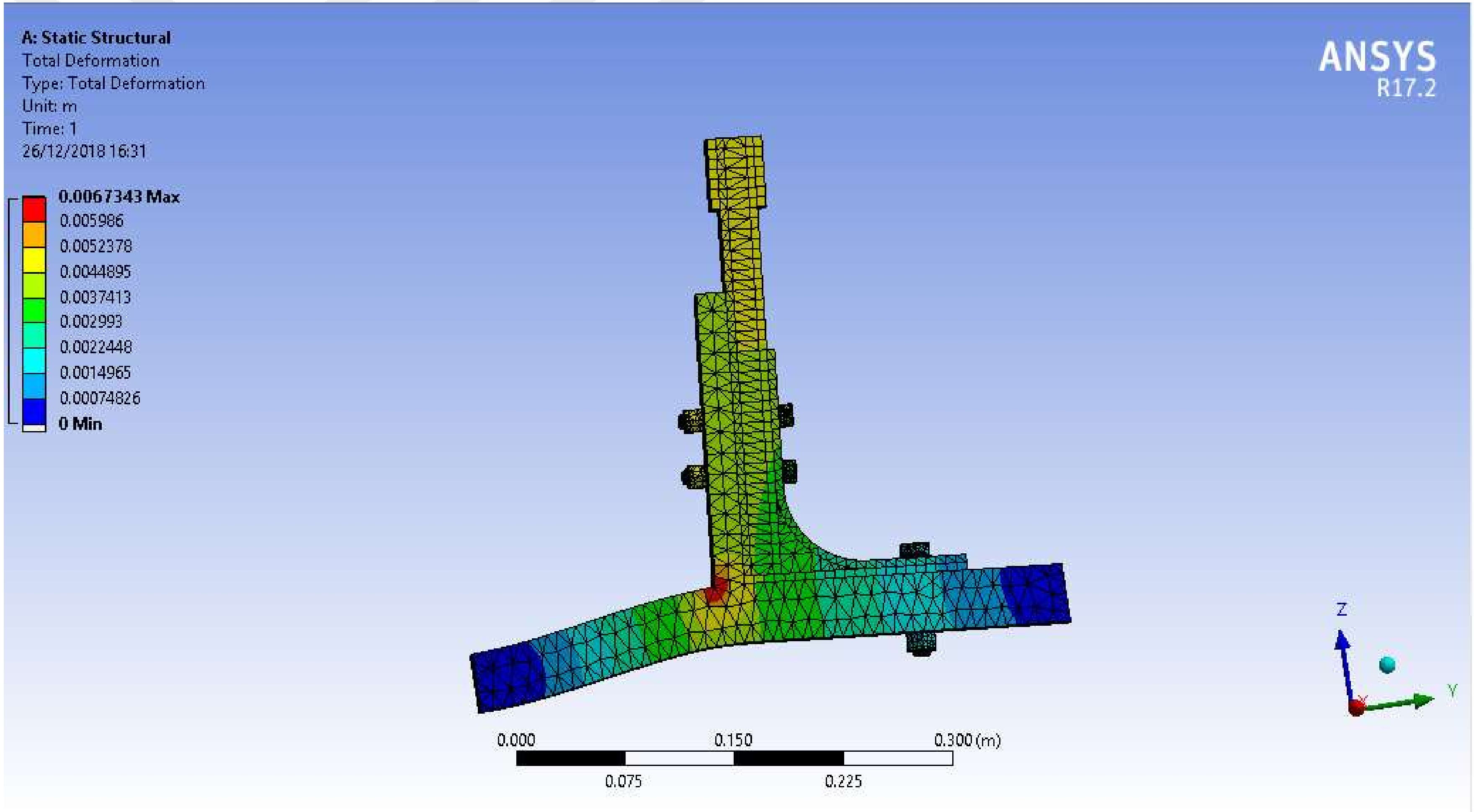


Figure 57. Specimen 7, Total Deformation

8. Conclusion

The comparison table 2 gives a brief information about the hull materials and its basic parameters. HDPE hull stands out as a better candidate compared to the other materials in many cases. It is easily recyclable, environmental friendly, requires less maintenance, has longer lifespan, lighter, has great UV resistance, easily produced, etc. There are few downsides along those advantages; such as the aesthetics. One of the main reason of this research study is to overcome that issue by designing a composite yacht by adding a GRP superstructure to make the whole boat design more appealing. This makes HDPE material for hull construction a better decision.

This research study also includes a 31 question survey. As previously mentioned one of the main goal besides the safety and recyclability is the design factor. Since design is not measurable fact, opinion of people about boats design is the way to proceed. The survey asks people what they want from their vessel, on what type of boat they would spend their money on, how much time they're willing to spend on it, how aware they are about yachts and materials. According to the survey there were some common answers. People want safer, more environmental friendly, longer lasting and most importantly appealing boats.

The lab test results showed once more that even the GRP structures were constructed in the same environment, they differ one to the other. Because of various parameters (humidity, temperature, the mix of resin components, the saturation of resin to the fiberglass at certain points, chemical reaction, etc.) same results from GRP should not be expected. Between three specimen types "Type 2" has the highest ultimate strength value of all. It could stand more strain than the other types. "Type 1" was the second competitor. Type 1 also requires more hand lay-up work on the GRP side compared to the other types which makes the whole process bit more complex and time consuming. To conclude Type 2 has the best crack resistance and the lowest shear concentration effect of all although the construction process is complex and difficult.

ANSYS results for all the specimens were very similar to the specimen testing. The force was used on the meshes were 2 kN load, which is logical since the strain gauges plotted force values around 1000-2000 N load before the two parts separate or crack. Also exaggerated deformation graphs are almost identical to experiments. Which proves that with the help of computer software it is easily possible to pinpoint the weak spot of a structure.

For the future studies, this thesis leads a path with a joint method between HDPE hulls and GRP superstructures. The main goal is not inventing or creating a better design, it's about providing flexibility to the existing designs. By the use of these two materials, more environmental friendly, safer, more appealing HDPE boats with GRP superstructures could be constructed. This means that we don't have to sacrifice the safety or purity of sea water for aesthetics. Development and future research would ease the joining process so that more boatyards would be interested to produce HDPE hulls. Thus marinas, and sea surfaces could be filled with recyclable, easy to maintain and operate yachts which are still great to look at.

For the future development of the joint, adding a flexible seal would be a better option for making the joint last longer. Since the HDPE and GRP have different modulus of elasticity, in order to prevent shear between the two materials in longer terms a flexible seal would be the best option. Also an alternative to the marine adhesive which was used in the experiments could be considered. The marine adhesive was one of the best options for a consumer grade; however for better bonding between two materials, better alternatives could be used or developed. Future development of this hybrid structure can be tested further by tensile loading more specimens. To prevent the cracking in further experiments thicker HDPE and higher density foam core could be used, and also because of low reliability of the hand lay-up method vacuum infusion would be a better option for GRP construction. Additionally resin type can be changed for increased stiffness and strength. The long term durability of the suspected hybrid boats remains to be analyzed after their construction and use in the future.

Appendix

Questionnaire

Demographic Questions
1) Gender A) Male B) Female
2) Age ……………………………………
3) Marital Status A) Married B) Single
4) Level of Education A) Primary School B) High School C) Bachelors Degree D) Masters Degree E) Phd
5) Profession ……………………………………
6) Salary (Monthly) ……………………………………

Maritime Questions	
7)	**How familiar are you to seafaring ?**
A)	I own a boat
B)	I rent boats
C)	I'm a sailor
D)	I'm just curious about seafaring
E)	Other ....
8)	**How many days do you spend on water in a year ?**
	....
9)	**How many years do you have the interest on seafaring ?**
	....
10)	**Which type of sea vessel are you interested or do you own ?**
A)	Motoryacht
B)	Sailing Yacht
C)	Fishing Boat
D)	Dinghy
E)	Fun Boat
F)	Rib / Inflatable / Zodiac
G)	Other ....
11)	**What is your boat made of ?**
A)	Steel
B)	Aluminium
C)	Wood
D)	Composite
E)	HDPE

Design and Seafaring Questions	Totally Disagree	Somewhat Disagree	Not Sure	Somewhat Agree	Totally Agree
11) I'd buy a mass production boat	☐	☐	☐	☐	☐
12) Safety on sea is important	☐	☐	☐	☐	☐
13) I'd pay attention to the lifetime of a boat when buying	☐	☐	☐	☐	☐
14) I'd want my boat to be recycled when my boats lifetime is over	☐	☐	☐	☐	☐
15) I'd buy a boat regarding to the sale prices	☐	☐	☐	☐	☐
17) The maximum speed capabilities of a boat is important	☐	☐	☐	☐	☐
18) I'd want my boat to have practical and large numbers of storage	☐	☐	☐	☐	☐
19) I care about the interior plankings / veneers ?	☐	☐	☐	☐	☐
20) Maintenance and operating costs prevent me from being a boat owner	☐	☐	☐	☐	☐
21) I'd prefer soft lines and curves	☐	☐	☐	☐	☐
22) I'd prefer hard lines and edges	☐	☐	☐	☐	☐
23) Boats hulls aesthetic design is important to me	☐	☐	☐	☐	☐
24) I find buying boats with new designs and innovative materials risky	☐	☐	☐	☐	☐
25) My boat's color has to be white	☐	☐	☐	☐	☐
26) Deformation of hull caused by sun makes me unpleasant	☐	☐	☐	☐	☐
27) If my boats deck gives / bends it'd discomfort me	☐	☐	☐	☐	☐
28) I think risk of osmosis is high in GRP yachts	☐	☐	☐	☐	☐
29) I care about the life underwater	☐	☐	☐	☐	☐
30) I feel uncomfortable applying antifouling on my boat every year	☐	☐	☐	☐	☐
31) I have knowledge about HDPE boats	☐	☐	☐	☐	☐

Questionnaire Answers

1) Gender

Male: 111

Female: 41

2) Age

Mean: 36

Standard Dev.: 12.627

3) Marital Status

Married: 66

Single: 86

4) Level of Education

Elementary School: 16

High School: 16

Graduate: 81

Msc: 29

Phd: 10

5) Profession

Student: 19

Engineer: 18

Medical Degree: 9

Architect: 14

Designer: 22

Captain / Sailor: 27

Fisherman: 17

Lawyer: 9

6) Salary (Monthly, TL)

Mean: 10,249

Standard Dev.: 14,107

7) Days spent on water in a year

Mean: 60.066

Standard Dev.: 75.836

8) Familiarity to seafaring

Boat owner: 47

Competitive Sailor: 27

Charter business: 20

Enthusiast: 32

Captain or Sailor: 27

9) Years of interest on seafaring

Mean: 13.763

Standard Dev.: 10.799

10) Type of sea vessel owned

Motor yacht: 51

Sailboat: 60

Fisher: 15

Dinghy: 10

Daily craft: 10

Rib / Workboat: 7

11) Material of the boat owned

Steel: 22

Aluminum: 22

Wooden: 16

Composite: 81

HDPE: 12

12) Prefers mass production boat

Mean: 3.645

Standard Dev.: 0.979

13) Safety on sea is important

Mean: 4.434

Standard Dev.: 0.918

14) Would pay attention to the lifetime of the boat when buying

Mean: 4.263

Standard Dev.: 0.882

15) Would want his / her boat to be recycled after the lifetime is over

Mean: 3.822

Standard Dev.: 1.042

16) Would buy a boat regarding to the sale prices

Mean: 3.796

Standard Dev.: 1.038

17) Believes that the maximum speed capabilities of the boat is important

Mean: 3.401

Standard Dev.: 1.175

18) Would prefer to have his / her boat to have practical and large numbers of storage

Mean: 3.855

Standard Dev.: 0.986

19) Cares about interior plankings / veneers

Mean: 3.803

Standard Dev.: 1.163

20) Maintenance and operating costs have prevented him / her to be a boat owner

Mean: 3.855

Standard Dev.: 1.057

21) Prefers soft lines and curves

Mean: 2.842

Standard Dev.: 1.157

22) Prefers hard lines and edges

Mean: 3.072

Standard Dev.: 1.151

23) Believes that the hull of the boats aesthetic design is important

Mean: 3.678

Standard Dev.: 1.083

24) Finds buying boats with new designs and materials risky

Mean: 3.158

Standard Dev.: 1.134

25) Prefers his / her boats color to be white

Mean: 2.618

Standard Dev.: 1.121

26) Feels unpleasant if his / her boats hull is deformed because of sun

Mean: 3.914

Standard Dev.: 1.098

27) Would feel discomfort if the boats deck gives / bends

Mean: 3.868

Standard Dev.: 1.126

28) Thinks the risk of osmosis is high for GRP yachts

Mean: 3.316

Standard Dev.: 0.938

29) Cares about life underwater

Mean: 4.382

Standard Dev.: 0.949

30) Feels uncomfortable applying antifouling to the boat every year

Mean: 3.803

Standard Dev.: 1.122

31) Has knowledge on HDPE boats

Mean: 2.408

Standard Dev.: 1.329

Technical Drawings of Parts and Assembly's

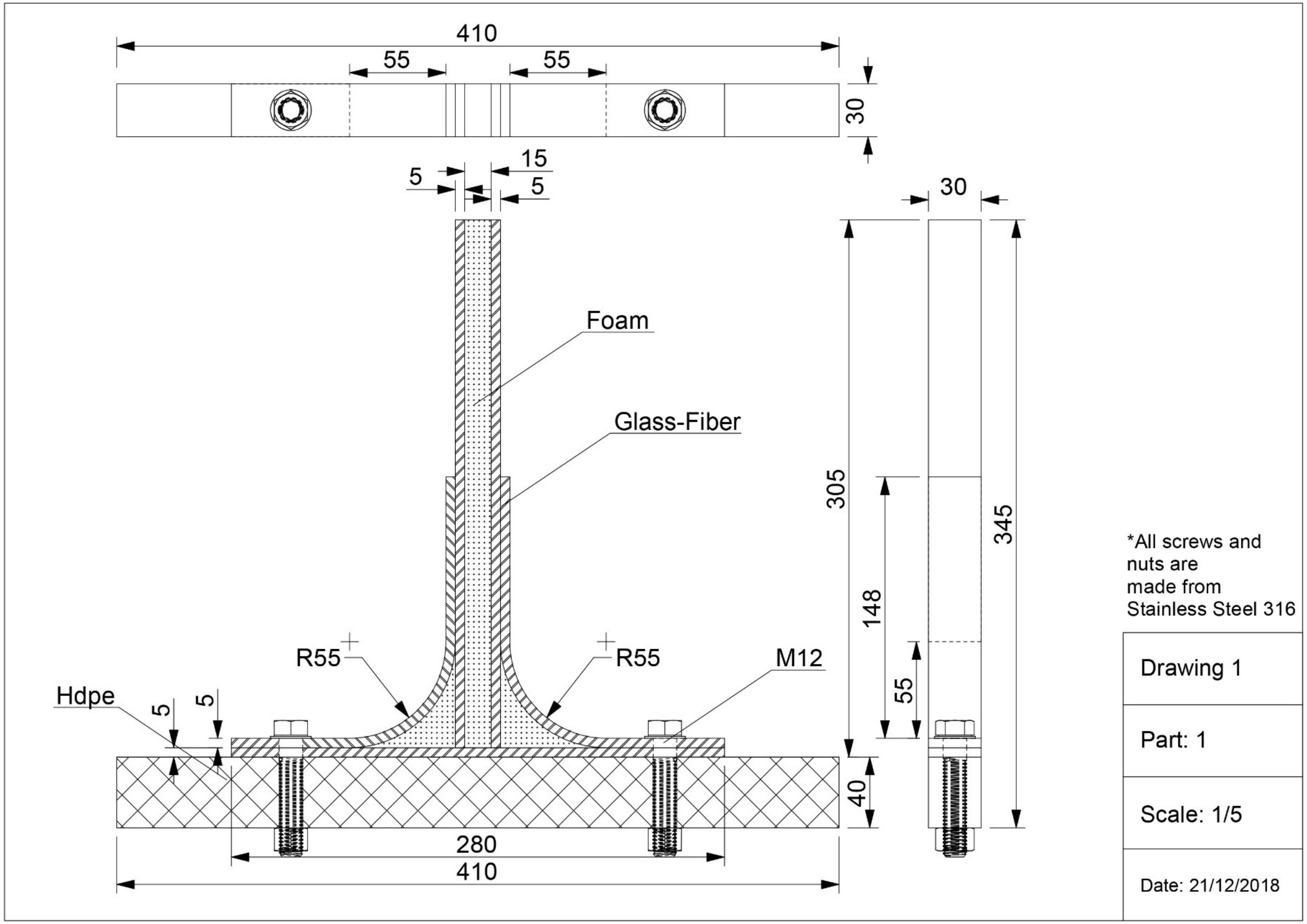


Figure 58. Drawing 1, Part 1

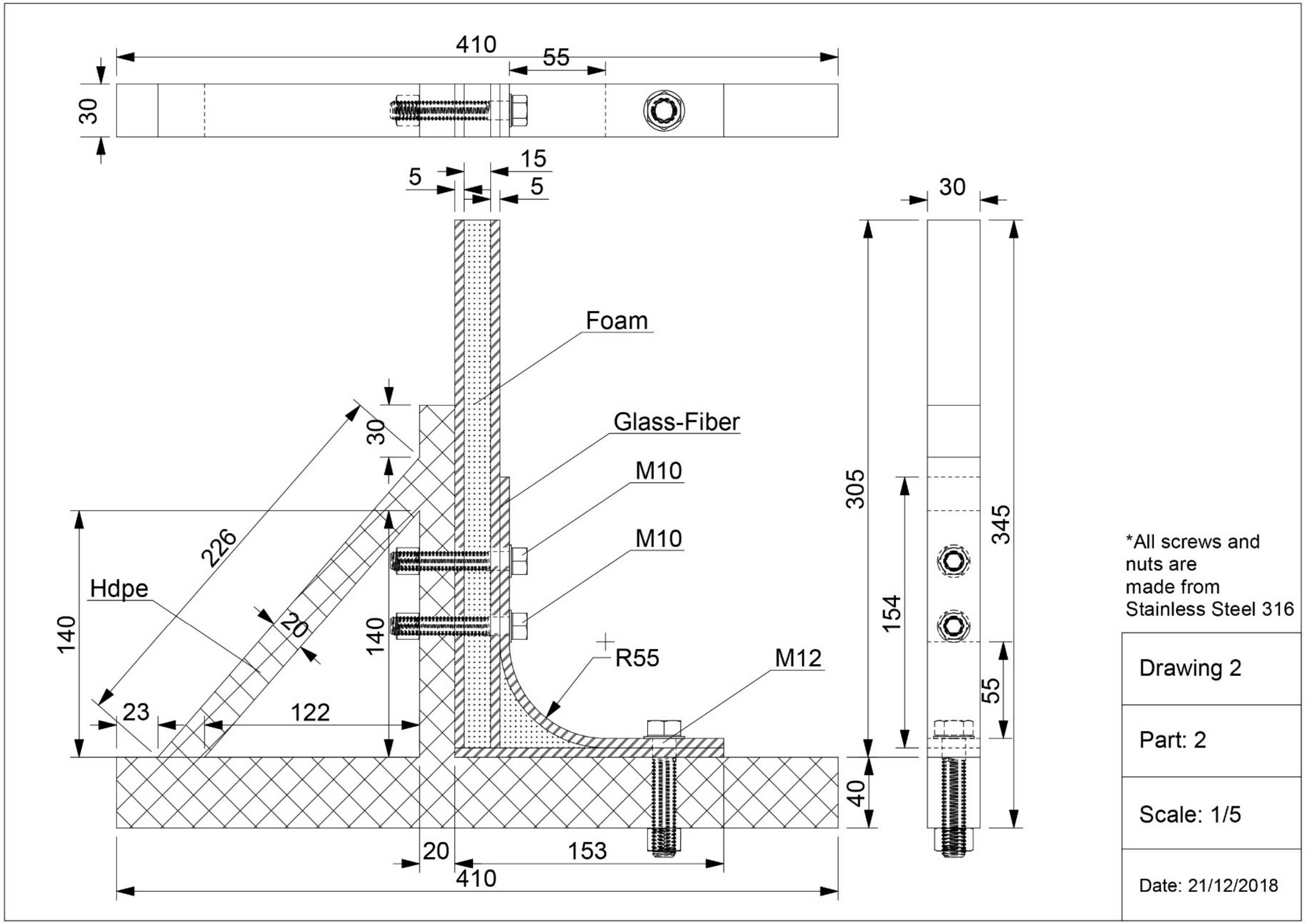


Figure 59. Drawing 2, Part 2

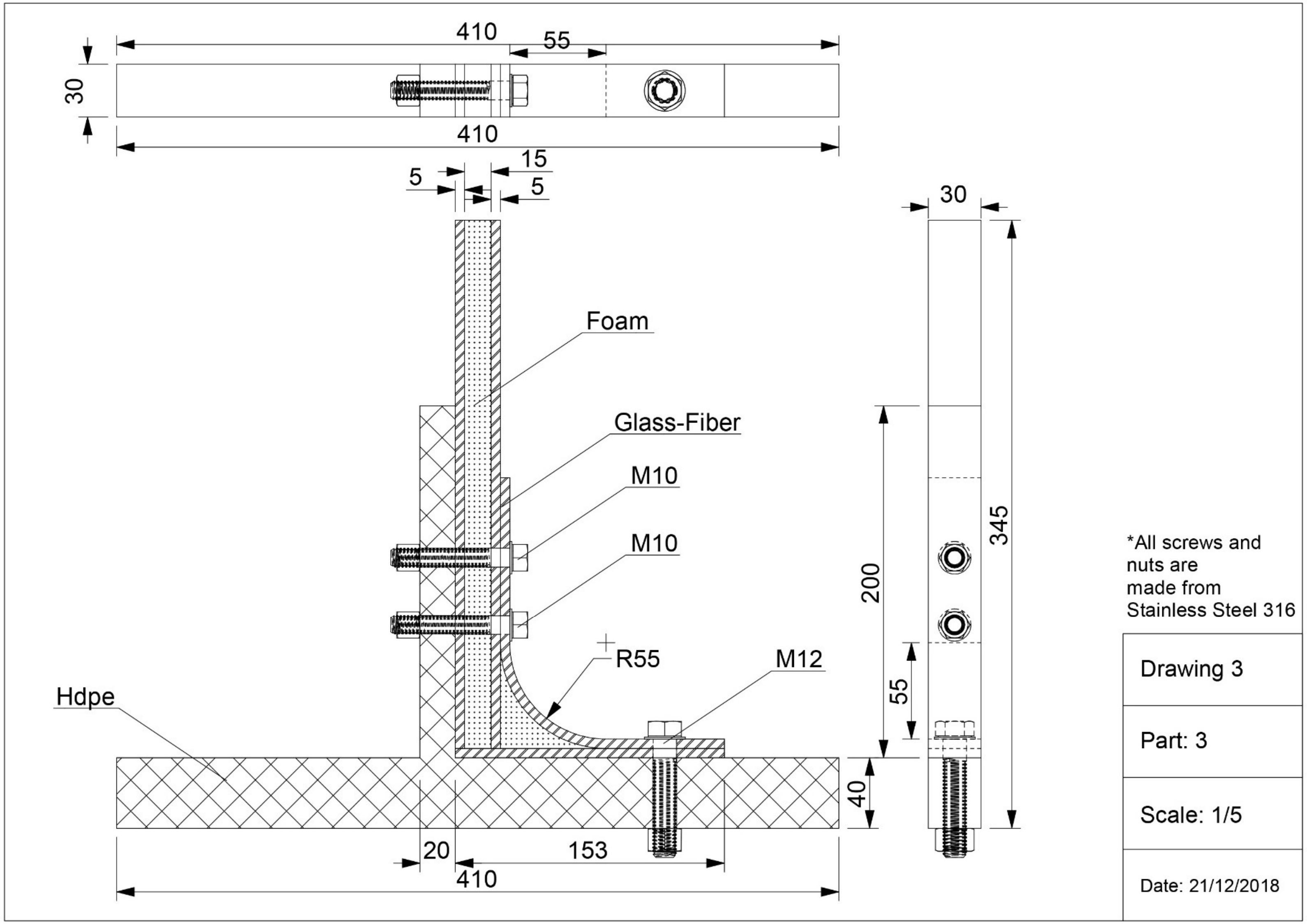


Figure 60. Drawing 3, Part 3

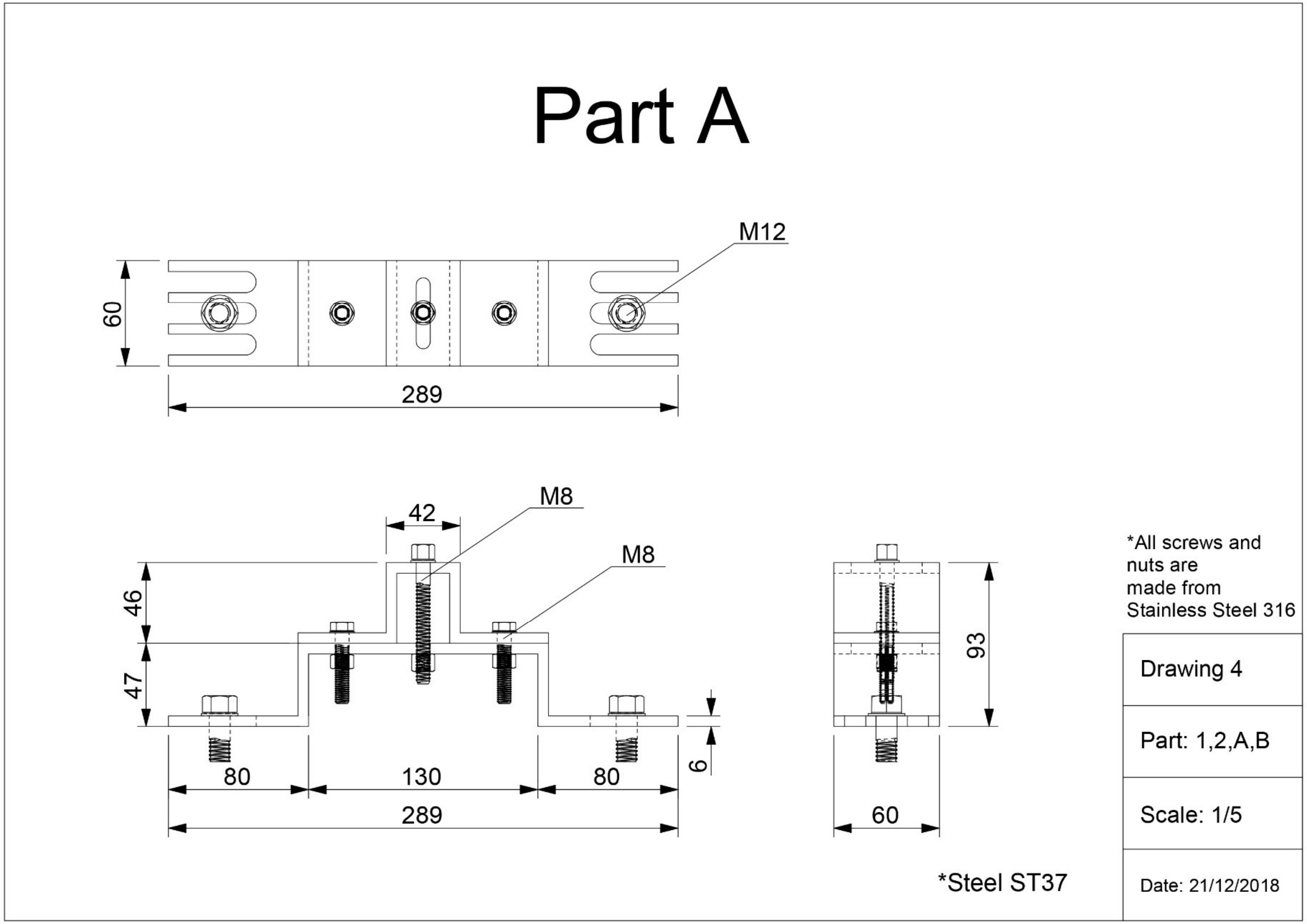


Figure 61. Drawing 4, Part A

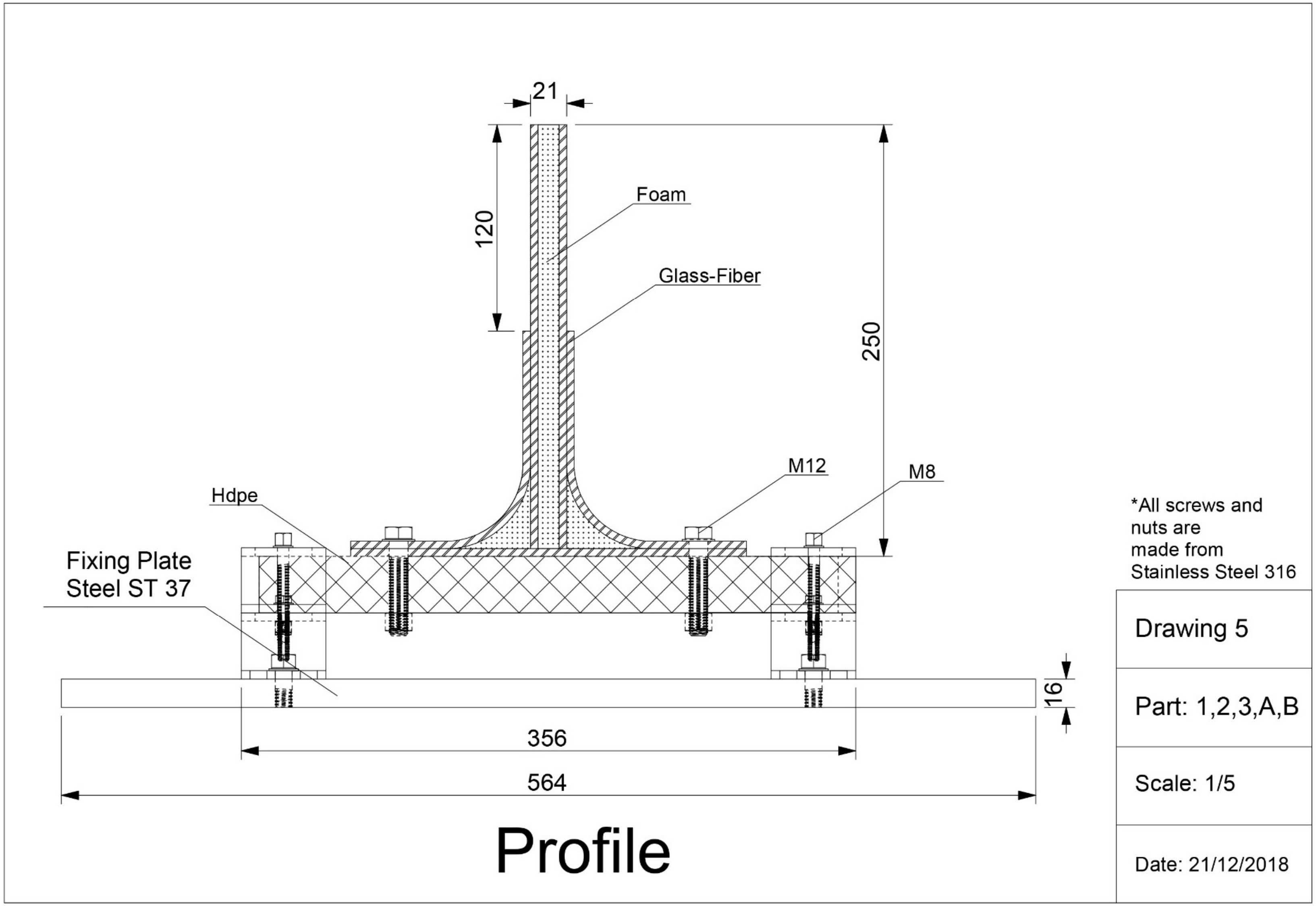


Figure 62. Drawing 5, Profile View

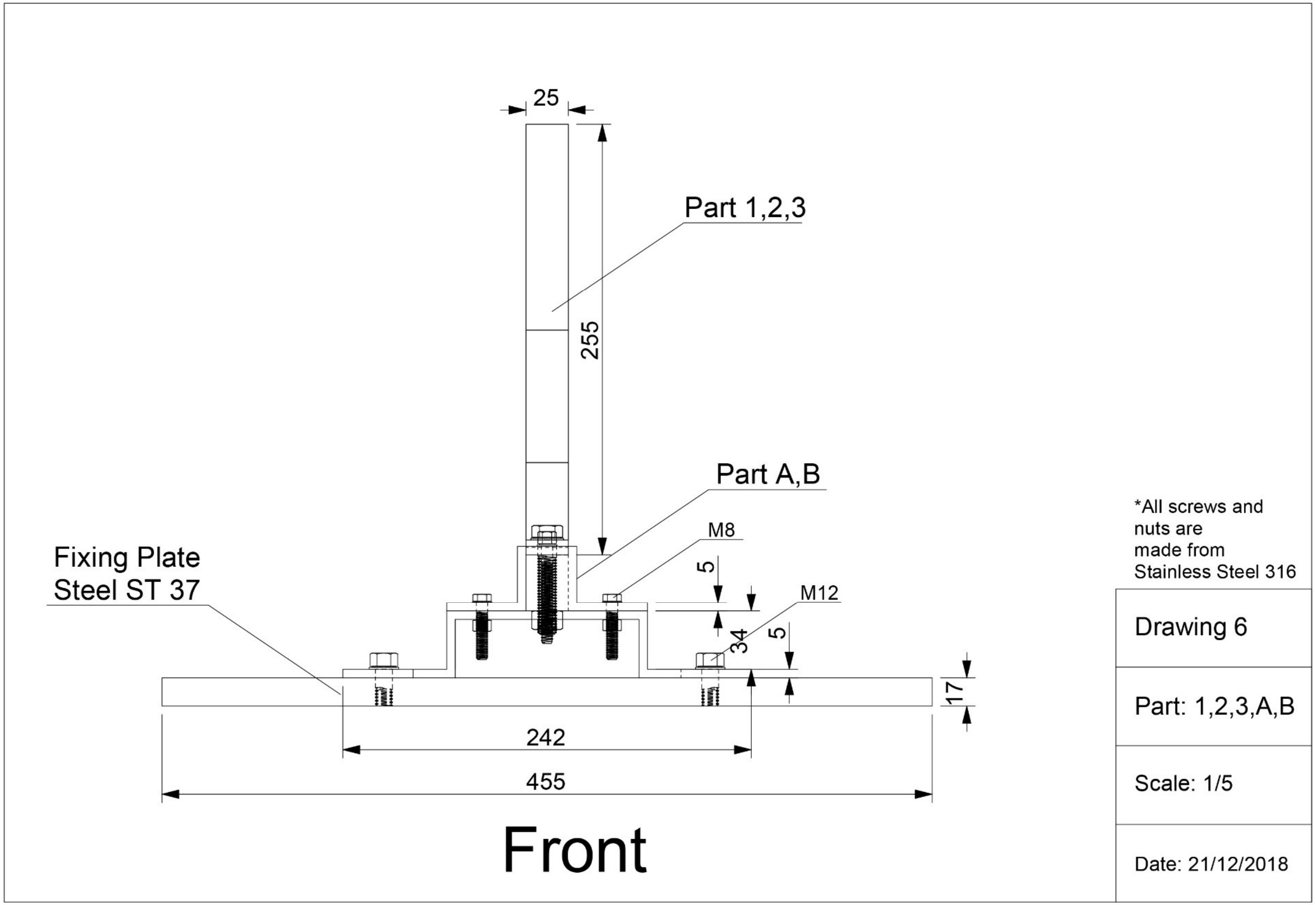


Figure 63. Drawing 6, Front View

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