Multi-material 3D-printing of hard-soft interfaces
The additive manufacturing of biomimetic functionally graded materials

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Abstract

An abrupt connection between hard and soft materials will be susceptible to failure, due to the inherently different properties between the two materials. Nature provides solutions to this problem, for many natural hard-soft interfaces possess both great strength and toughness. In this study, the hard-soft interface as it is often found in nature, possessing a gradient transition zone, is used as an inspiration. 64 Specimens were 3D printed using additive manufacturing. These specimens were designed with different values for two parameters: The transition zone width and the percentages of each material in the interface. The specimens were subjected to fracture testing, tensile testing and digital image correlation, in order to discover how the two parameters influence their intrinsic properties. It is shown that introducing a gradient transition zone can improve the fracture and tensile properties of the hard-soft interface, relative to an abrupt hard-soft transition.

FGM	**Functionally Graded Materials**
AM	**Additive Manufacturing**
DIC	**Digital Image Correlation**
$\rho_h - \rho_{h'}$	**Gradient difference**
W10-60-40	**Width in % - ρ_h - $\rho_{h'}$**
HS	**Hard-soft abrupt interface**

1 Introduction

The mechanical properties of hard and soft materials differ. Hard materials are mostly described as strong and brittle, while soft materials are described as mechanically weak but with high elasticity. Due to the significant difference in mechanical properties, an abrupt hard-soft interface will exhibit a non-uniform deformation when exposed to external loads [1]. These non-uniform deformations are a result of regions of high stress concentration. Therefore, those regions are susceptible to failure when subjected to external loads [2]. Due to the high prospect of failures, there is a need for optimization of the hard-soft interface, with special focus on strength and toughness.

Nature offers some inspiration in the hard-soft interfaces which display high toughness and high strength. A few of the most known examples are tendons, the connective tissue between bone-to-muscle interaction, and cartilage, the connective tissue between bone-to-bone interaction [3]. These interfaces have different characteristics throughout the human body. The function of the interface dictates the gradient of the materials in the transition zone in terms of tissue structure, hierarchical organization, and chemical composition [1]. The appropriate grading is thus dependent on the specific role the functionally graded material (FGM) has to fulfill [4]. The gradient can be influenced by manipulating the underlying arrangement, distribution, size, type and orientation, of the building blocks

[5] [1]. Earlier studies have reviewed FGM's in the terms of thermal conductivity and the influence the orientation, size and distribution, of the building blocks, have on the mechanical properties of the FGM's. However, there are still a lot of unanswered questions on the functionality of FGM's in the biomedical field.

The aim of this study is to generate new knowledge that supports the design and manufacturing of artificial hard-soft interfaces. The study will focus on the optimization of the values of the width and gradient of the transition zone, for which the hard-soft interface reaches the mechanical properties of high strength and high toughness. The approach will involve the design, printing and testing of several horizontal distributions on multiple length scales.

After providing an introduction on the topic and stating the aim for the project, the study will supply some background information on the topic. Furthermore, it will include a description on the method used to design the specimens, to conduct the experiments and to compute the data analysis. The results will be stated and at last a discussion and a conclusion will be provided. This research has been conducted as a part of the Bachelor End Project for Mechanical Engineering students at the TU Delft in the third year of their bachelor studies.

2 Theory

Hard-soft interfaces have a high influence on the mechanical properties of a composite material [6][7]. A functionally graded interface effectively transfers stress between the different materials, and thus minimizes the formation of stress concentration. Therefore, the functionally graded interface promotes interaction between the building blocks. [2] [8].

2.1 Strength versus Toughness

The hard-soft interface should be both strong enough to withstand high loads and tough enough to allow some damage under load. Strength is defined as the resistance of a material to deform irrecoverably. Toughness is defined as the resistance of the material to fracture [9][10]. An ideal material has both strength and toughness, but they are often at the expense of each other [11]. In synthetic materials, strength and toughness are mutually exclusive, one property must be chosen at the expense of the other [1][12] [13]. Natural structural materials often contain both unique properties [5]. Therefore the biomedical field has a high interest in the biomimicking of natural structures which possess both these qualities.

2.2 Nature

As mentioned above, many types of soft-hard interfaces can be found in nature, for instance the transition from bone to tendon or ligament, also known as the enthesis [2] [14]. The structure of the enthesis varies from the function of the ligament or tendon and even between the different ends of the ligament or tendon [15] [16]. The interface between bone and soft tissue contains a large difference in mechanical properties on a relatively small scale [1]. However, the interface shows high strength and toughness [17].

The difference in elastic modulus in the enthesis ranges from 0.4 GPa in the tendon to 20 GPa in the bone [5]. The length scale of the enthesis can differ from 100μm till 1 mm and it consists of four distinct zones, see Figure 1 [3] [9] [5]. The first region corresponds with tendon and consists of mostly collagen type I fibres, micro fibrils, fibrils and fascicles. The second zone is formed by a network of collage type II and III. Furthermore, the third zone also consists of a network of collagen type II and III. However, Hydroapatite (HA) is embedded in the collagen II fibres, and thus the HA results in an increase in mineralization. At last, the fourth zone which corresponds with bone, is formed of HA platelets and collagen type I [18] [19][20].

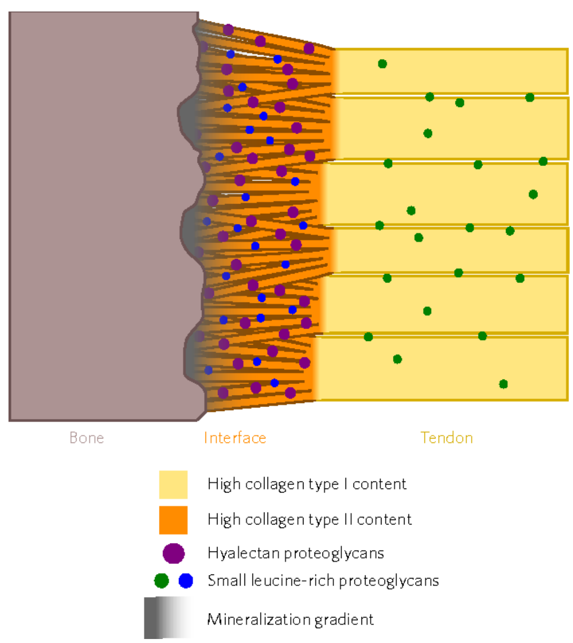

Figure 1: Composition of the enthesis[19]

The organization of collagen fibres is directly related to the stiffness of the interface, while the molecular changes relate to the toughness [21] [22]. Furthermore, an increase in the mineralization content has been associated with higher mechanical properties [23], as the increase of the Young's modulus. This mineralization content varies over the transition zone in almost a linear way [24] [17]. The transition of the elastic modulus in the enthesis is shown in Figure 2. At first, there is a decrease in the elastic modulus caused by the entanglement of the collagen fibres. Yet after this small decrease, the elastic modules displays a non-linear graded transition comparable to a sigmoid-like function [19] [12].

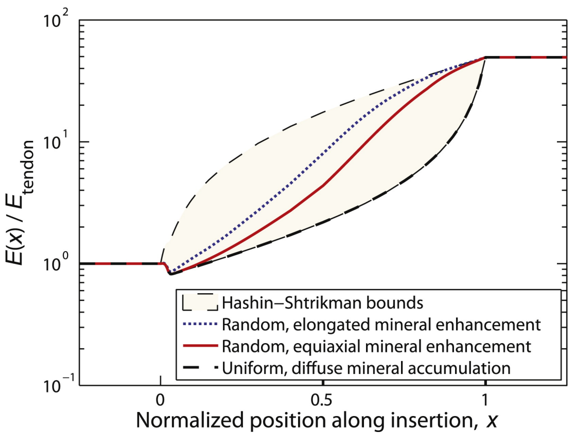

Figure 2: The E-modulus curve in the enthesis[18]

By changing the interface, the mechanical properties of the composite can be changed; The differences in the Young's moduli, the Poisson's ratio and the shear moduli between materials play, among others, a big part in reducing edge stresses around the transition zone [18]. It is proposed that, for optimal results, the values of the engineered material should closely match those of the native human tissue [3].

2.3 3D printing

Several manufacturing processes can be used to mimic the hard-soft interface, such as additive manufacturing, foaming and laser engraving. Additive manufacturing (AM) techniques are mostly used in the bio-engineering field. AM is an innovative method for the fabrication of complex designs [25]. AM is a technique that builds 3D objects by adding layer-upon-layer of material [26]. The technique used in the study is a Voxel-based additive manufacturing technique. This technique enables a high resolution of printing, as well a enabling the manufacturing of 3D objects with two materials and shows a high control on the location placement of the different type of materials [25]. Voxel-based 3D printing uses bitmap level to control the desired pattern [27].

The printer used in the study is the Voxel-based additive manufacturing printer, the Objet350 Connex3 3D printer. The printer uses photopolymer and UV curing. This type of 3D printing is seen as an effective method to design a hard-soft interface with a gradient structure, because it can print at a minimal size of $40\mu m$ x $80\mu m$ x $30\mu m$ [27]. The hard and soft materials used, are respectively VeroBlack and Agilus Clear, both manufactured by Stratasys.

3 Method

This chapter will focus on the methods used to develop and to test the specimens. Firstly, the Matlab code and the design of the specimens will be discussed. At last, the method of the experiments will be provided with the corresponding data analysis.

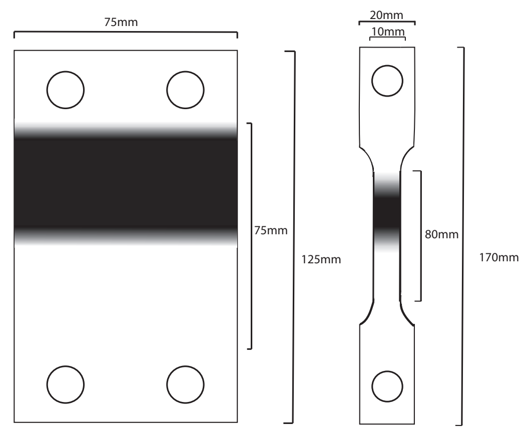

Figure 3: The dimensions of a fracture specimen and a tensile specimen

3.1 Specimens

As seen in Figure 3, there are two different types of specimens; fracture specimens and tensile specimens. The orientation of the gradient in all specimens was chosen as hard-soft-hard with a horizontal transition. The gradient is heterogeneous and anisotropic. The independent values in the specimens are the distribution of the gradient and the length scale of the transition zone. The fracture specimen has an initial crack, which spans 20 percent of the original width of the specimen, thus 15mm, and is roughly 0.7 mm wide. The initial crack is placed at the weakest point of the structure to promote crack propagation. The fracture specimen is provided with grippers to ease the attachment to the testing machine. The tensile specimens are dog bone shaped. Due to this shape, the stress concentration occurs in the middle of the specimen. This causes rupture to occur in the middle of the specimen away from the grippers and thus the composition material can reach its maximum tensile strength. The dog bone specimens are also provided with grippers to ease the attachment to the testing machine.

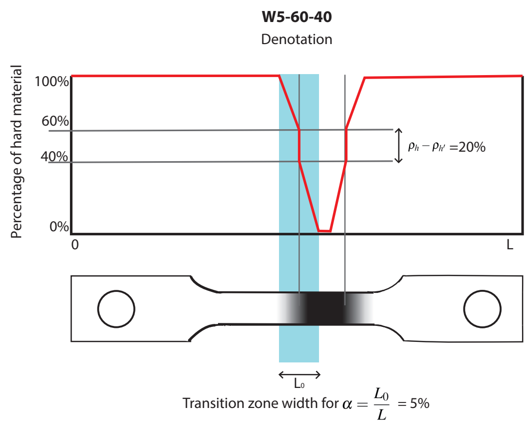

Figure 4: Visualisation of the gradient of the W5-60-40 specimen.

The transition zone has a 2-step linear gradient, (Figure 4), which corresponds to the linear increase of mineralization and the elastic modulus sigmoid function. The first independent value, the gradient distribution was chosen based on earlier research conducted. This earlier research stated that the fracture toughness of a specimen can be increased by keeping complementary material ratios on both sides of the interface [28]. This means that the distribution ranges from 100-to-0 percent until 50-to-50 percent. Therefore, to grasp the full range of the gradient distributions of 90-to-10 percent, 80-to-20 percent and 60-to-40 percent were selected (App. B, Fig. 6).

Secondly, the independent value of the length of the transition zone [L_0] is dependent on the total length of the specimen [L].

$$\alpha = \frac{L_0}{L}$$

With α being either 2, 5, 10 or 15 percent. These values were based on preliminary research, which concluded that a transition zone above 20 percent does not contribute to the mechanical properties of the interface. Therefore, the constraints of the length scale of the transition zone were between the 0 and 20 percent.

In total 64 specimens were printed, for every different type of specimen three or four random distributions were printed. The 5 percent and the 10 percent transition zones were constructed with three different gradients; 90-to-10, 80-to-20 and 60-to-40. The 2 percent and the 15 percent transition zone with only the 90-to-10 gradient (App. B, Table 1). The specimens were labeled by first their width, followed by their gradient on each side.

3.2 Matlab Code

The additive manufacturing method uses binary bitmap files to compose a specimen with a 3D printer. In these binary bitmap files each material is assigned a value of 0 or 1 [27] [11]. The binary bitmap images are generated with a Matlab file. The Matlab code computes a greyscale image with a transition zone which has a random linear distribution. Thus, the strength of each category will not depend on the alignment of the hard and soft particles in the interface. These greyscale images are subjected to halftoning methods. These halftoning methods use algorithms to create the illusion of a continuous toning with only using white and black dots [29]. The halftoning method we used in the Matlab code was random dithering.

Each layer of the specimen corresponds to a different bitmap file. Each material has its own bitmap file, which are complementary to each other, wherein each pixel location of each material has to be deposited indicated with a pixel value of 1 or 0. These material files are used to 3D print the specimens (App. G).

3.3 Data Gathering

The experimental setup is shown in Appendix A 5. As mentioned above 64 specimens were printed. Both the fracture and tensile specimens were printed and tested 3 times for all gradient and transition zone combinations. Furthermore, specific fracture and tensile specimens were printed a fourth time and were analysed with digital image correlation (Appendix B, Table 1). The fracture and tensile tests were performed on the Lloyd tensile test machine (LR5K). The testing machine uses a 5 kN load cell for the fracture test and a 100 N loadcell for the tensile test, to measure the load applied to the specimen. The preload is set on 0.1 N and the extension rate is set on 2.00 mm/min. The upper part of the specimen is subjected to the extension, while the lower part of the specimen remains static. The specifics of the digital image correlation testing machine will be explained below.

Fracture Testing

The fracture specimens were subjected to fracture testing. The specimen remains under load until it is is completely fractured. The machine collects data on the time, load and deflection of the specimen. 200 data points are collected during the test. These variables can be used to obtain multiple fracture properties:

- Normal stress [σ], the stress in axial direction.
- Strain [ε], the relative displacement with respect to the initial length.
- Stiffness [E], also known as the elastic modulus
- Fracture stress [σ_f], the stress at the moment of crack propagation, which is the maximum stress.

- Fracture toughness [U], defined as the area under the stress-strain graph
- Strain at fracture [ε_f], also at the moment of crack propagation.

These fracture properties will be realised using the computer software Rstudio (App. F).

Tensile Testing
The tensile specimens are subjected to the tensile testing. The tensile specimen will also be subjected to a load until it completely fractures. The machine collects data on the time, load and deflection of the specimen. Again, this is done for 200 data points spread out over the whole test. The results can be used to obtain multiple tensile properties:

- Normal stress [σ], the stress in axial direction.
- Strain [ε], the relative displacement with respect to the initial length.
- Stiffness [E], also known as the elastic modulus.
- Ultimate strength [σ_{Ult}],defined as the maximum stress.
- Toughness [U], defined as the area under the stress-strain graph.
- Strain at fracture [ε_f], strain at the moment of complete failure.

These tensile properties will be realised with using the computer software Rstudio (App. F).

Digital Image Correlation Testing
The remaining specimens will be tested with digital image correlation (DIC). With DIC, the specimens are analysed with respect to the strain distribution and the crack propagation. This technique will display the topography of the interface of the specimen and will give more insight in the composition created by the 3D printer.

In this test, the specimens are painted white and then speckled with black dots. The speckle size used is 0.007". During the tests, two cameras continuously take pictures of the specimen until it breaks. After the test, the way the speckle pattern changes during the test is analysed using the specialised Vic3D software. This makes the strain distribution in the specimen visible.

DIC is used as a validation of the result found in the fracture and tensile testing. For the fracture tests, the maximum strain is supposed to be concentrated directly in front of the crack, because this is naturally the weakest point. If the DIC shows high amounts of strain somewhere else on the specimen, it means the fracture test is not implemented correctly. For the tensile tests, DIC can provide insight in the fracture pattern of the specimens, because areas subjected to high strain are prone to fracture.

4 Results

The data retrieved from the fracture and tensile testing, is the time, load and extension. All properties are evaluated for both independent values, the transition width and the gradient difference.

4.1 Fracture Test

The data analysis is focused on the difference in stiffness, fracture toughness, the fracture stress and the strain at fracture. These properties were calculated using the cross-sectional area of the specimen, minus the initial length of the crack. Each of these parameters are shown in the graphs and data sets in Appendix C.

Stress-strain properties
In the stress- strain plot a representative of every specimen is shown that has portrayed the highest fracture stress (Figure 7). Every specimen is marked in the legend by first its transition width [%] and subsequently by its transition gradient [%]. The plot also includes the control value, the abrupt hard-soft transition (HS). The stress-strain results show that notably the 10% transition zone width achieves a highest stress level, going over 0.40 ± 0.03 MPa, while the control value does not surpass 0.33 ± 0.009 MPa. However, the fracture strain is lower, the wider the transition zone is.

Fracture properties
A design with a gradient does not necessarily withstand higher stresses. The highest fracture stresses were shown at the 20% gradient difference, which was for the 10% width 20% gradient difference 1,2 times higher. (Figure 10) The smaller this gradient difference, the higher the fracture stress. Regardless of the gradient, the 2% and 5% transition width do not show a higher mean fracture stress than the control values in the abrupt soft-hard interface (Figure 9). There is a nonlinear increase in the fracture stress with an increase in the transition length. The wider the transition length, the higher the fracture stress.
In all cases the mean strain at fracture is lower than it was the case at the abrupt hard-soft interface (Figure 11 and Figure 12). The mean strain at fracture is defined as the strain at the highest stress. The mean strain decreases linearly for all transition lengths with exception of the 15% width. At this width the strain increases again. The mean strain differs between 0.27 ± 0.02 and 0.22 ± 0.01 , between the 2% and 10% width respectively. The 15% width has a strain of 0.24 ± 0.009.

The mean fracture strain, unlike the fracture stress, differs less between different transitions widths when the gradient difference smaller (Figure 12). When $(\rho_h - \rho_{h'}) =$ 20 % and $(\rho_h - \rho_{h'}) = 60\%$, the difference is 0.0040 ± 0.02

and 0.0015 ± 0.03 between different widths respectively, which is minuscule . However, at a higher gradient difference the strain difference is higher; 0.029 ± 0.03 at $(\rho_h - \rho_{h'})$ = 80%. The abrupt soft-soft interface has a mean fracture strain of $0.35 \pm 6 * 10^{-2}$, which lies relatively close to the mean fracture strains of the specimens with a gradient. The hard-hard interface has a mean fracture strain of $0.045 \pm 4 * 10^{-3}$.

The fracture toughness, the resistance to fracture [5], is in all cases lower than the control value of 0.071 ± 0.01MPa (App. C, Fig.13 and Fig.14). The differences in toughnesses is small, 0.011 ± 0.01 MPa between all graded materials. The specimens that come the closest to the control value's toughness are the 10% widths with $(\rho_h - \rho_{h'})$ = 60% and $(\rho_h - \rho_{h'})$ = 20%. They have a fracture toughness of 0.068 ± 0.003MPa and 0.069 ± 0.007MPa respectively.

Stiffness is strongly related to the Young's Modulus, which specifies the force needed for elastic deformation [5]. The Young's Modulus increases almost linearly with the transition length. (App. C, Fig.15) The width of 2% has a mean Young's Modulus of 1.4 ± 0.03 MPa, which has a neglectable difference with the hard-soft abrupt interface specimen. A width of 15% percent has the highest mean Young's Modulus of the specimens of 1.8 ± 0.04 MPa.

Regarding the interface gradient, there is a nonlinear correlation between the percentage of hard material and the Young's Modulus. (App. C, Fig.16). Within the 5% and 10% width the Young's Moduli differ 0.12 ± 0.1 MPa, 0.17 ± 0.02 MPa and 0.23 ± 0.02 MPa for the 80 %, 60% and 20% $\rho_h - \rho_{h'}$ respectively.

The wider the transition zone, the higher the elastic modulus. Even though the elastic modulus goes up, there is a neglectable change in fracture toughness. As the gradient difference decreases, the mean fracture toughness and fracture stress both increase (App. C, Fig.17).

4.2 Tensile Test

The data analysis is focused on the difference in stiffness, toughness, the ultimate strength and the strain at fracture, evaluated for both transition length and gradient. Each of these parameters are shown in the graphs and data sets in Appendix D.

Stress-strain properties

In the stress-strain plot a representative of every specimen is shown that has portrayed the highest ultimate strength (Appendix D, 19). The control values with the soft-soft and hard-hard transitions were not included in the graph, for it would make the graph unreadable. It is notable that the values for the fracture strain are almost equal between specimens with a wider transition zone (10% and 15% width) and between specimens with a smaller one (0%, 2% and 5% width).

Tensile properties

The ultimate strength is highest for the 5% and 15% transition lengths, and relatively low for both 2% and 10%. All specimens with a gradient have a higher ultimate strength than the abrupt hard-soft interface (HS). This can be interpreted as a non-linearity (App. D, Fig.21). When comparing the ultimate strengths with the transition gradient, it becomes clear that the difference in ultimate strength between the 5% and 10% width specimens increases as the percentage of hard material in the interface $(\rho_h - \rho_{h'})$ decreases (App. D, Fig.22).

The fracture strain seems to have an optimum for small transition lengths (2% and 5%). A small interface width has a higher fracture strain than the abrupt hard-soft interface, however wider interfaces (10% and 15%) perform worse than the control specimen (App. D, Fig.23). Just as the ultimate strength, the difference in strain between the 5% and 10% width increases as the percentage of hard material in the interface $(\rho_h - \rho_{h'})$ decreases (App. D, Fig.24).

The toughness increases from a 2% to 5% transition length, but drops to a minimum for 10% and increases again for a 15% transition length. All gradients have a higher toughness than the control specimen. This may also be interpreted as a nonlinear correlation (App. D, Fig.25). The toughness values for the 0%, 2%, 5%, 10% and 15% are respectively $0.028 \pm 0.26 * 10^{-2}$ MPa, $0.036 \pm 0.15 * 10^{-2}$ MPa, $0.038 \pm 0.26 * 10^{-2}$ MPa, $0.032 \pm 150.28 * 10^{-2}$ MPa and $0.033 \pm 0.21 * 10^{-2}$ MPa. Unlike the ultimate strength and fracture strain, the difference in toughness, for the specimens with a 5% and 10% transition width, does not significantly change as the values for the gradient change (App. D, Fig.26).

The Young's modulus clearly increases as the transition length increases (App. D, Fig.27). Yet again, the difference in Young's modulus between the specimens of 5% and 10% width increases as the percentage of hard material in the interface $(\rho_h - \rho_{h'})$ decreases (App. D, Fig.28).

The 5% width 20% gradient difference specimen has the highest Ultimate strength, along with the 15% width 80% gradient, but the 5% width 20% gradient has a higher toughness. Overall, the 5% width 20% gradient has the best tensile properties. The 10% width specimens perform worst in both categories. (App. D, Fig.29)

4.3 DIC results

Using the DIC testing method, the Von Mises strain of the specimens has been made visible for the entire fracture and tensile tests.

Fracture Test
First of all, different stages of the fracture test for one specimen will be considered. Secondly, specimens with different gradients and transition zone widths will be compared.

Different stages of the fracture test

- The beginning of the test. The strain is relatively high throughout the entire soft material. Especially from the crack to both corners of the soft material on the other side.
- The opening of the crack. The maximum strain is concentrated around the crack tip, but the corners of the soft material opposite to the crack are also subjected to high strain. The strain in the centre of the soft material has decreased.
- Maximum force. At the moment of maximum force, a similar pattern can be observed. It can also be noted that the hard material shows absolutely no strain, even at maximum force. At this point the crack has already propagated through the gradient.
- After maximum force. After the moment of maximum force, the soft material tears with increasing speed. The crack does not follow the direction of the soft-hard interface, but it always propagates downwards through the gradient into the soft material and then through to the other side.

It should also be noted that, while the purely hard material does not show any strain, the transition zone does. The strain increases along the gradient from the hard to the soft material during the entire test (App. E, Fig.32).

Different fracture specimens at crack propagation
Different specimens are compared at the moment of crack propagation, meaning the frames were taken when the crack opens and just starts to propagate through the gradient. The specimens can be compared in several ways to find out how different compositions affect the strain distribution:

Firstly, we can compare specimens with the same transition zone and different gradients. For instance, the strain is distributed more evenly over a specimen with the 60-40 gradient than the 90-10 gradient with the same width of transition zone. This difference is however less apparent for the 80-20 and 90-10 gradient with a 5% transition zone (App. E, Fig.33).

Secondly, a comparison between specimens with the same gradient and a different transition zone can be made. The specimens with transition zone widths of 2%, 5%, 10% and 15% are all tested with the gradient of 90% to 10% hard material. It is clear that the strain is more concentrated for specimens with a smaller transition zone (App. E, Fig.31).

Tensile Test
The strain in a single specimen, 5% width and 60% gradient, will be examined at several moments in the test (App. E, Fig.34). All specimens will be compared at the half extension stage of the test.

Different stages of the tensile test

- Beginning of the test. The strain is highest in the middle of the soft material, decreasing through the edges of the soft material and the gradient and is zero in the hard material.
- Half extension. The maximum strain is distributed over the entire soft material. It decreases to zero through the interface.
- Maximum force. Because the whole soft material is strained to the same extent, fractures appear on both sides and over the entire length of the soft material. It needs to be noted that the specimens fracture in the soft material and not at the transition zone.
- After maximum force. Once a fracture starts to propagate to a larger extent than the others, the maximum strain is concentrated around its crack tip. The specimen breaks quickly hereafter.

Comparison of different specimens at half extension
All specimens show the same strain distribution: The strain is zero in the hard material, increases through the interface and is equally high for the entire soft material. This explains why fractures appear all along the soft material. Only the W2 specimen showed fractures along the interface, this was however not the weakest point, because it broke somewhere in the pure soft material.

4.4 Discussion of Results

Based on the fracture test, the transition width hardly makes a difference on the fracture strain. With a higher gradient difference, so when the difference between the hardness ratio's in the transition zone is higher, comes a higher strain. Although the difference still is neglectable. The bigger the transition zone, the smaller the fracture strain. A gradient does not necessarily give a higher fracture stress. The highest fracture stresses were seen in the 20% gradient difference. They increase non-linearly along with the width. This suggests that greater transition length gives higher fracture stresses. In the tensile test, the strain versus the transition zone showed characteristics of a sigmoid function, which shows that a smaller transition zone allows for higher strains. A transition zone smaller than 6% of the width, would give a significantly higher fracture strain. The DIC testing of the fracture test showed that the maximum strain was right in front of the crack. It also showed that the strain is progressively less concentrated for specimens with a wider transition zone and a smaller gradient difference. In both the tensile and fracture tests, the strain increases along the gradient from the hard to the soft material. It needs to be noted that all the tensile specimens fractured in the soft part and not at the transition zone. Only the 2% width showed cracks along the interface. This means that the transition interface has higher tensile properties than the soft material.

Furthermore, the tensile test showed that a decrease in gradient difference, increases the difference between the 5% and 10% width, regarding the ultimate strength, fracture strain and Young's modulus. The Young's modulus in the fracture tests behaved the same as in the tensile test, the smaller the gradient difference, the more impact the transition width has on the Young's Modulus. (App. C, Fig.15). The stiffness increases with a wider transition zone.

It is always difficult to have both high strength and toughness in a material. For this aspect the 10% width, 20% gradient gives the best results in the fracture test. (App. C, Fig.17). In the tensile test the 5% width, 20% gradient difference has the best tensile properties, the 10% width specimens have the lowest tensile properties, regarding the ultimate strength and toughness (App. D, Fig.29).

Based on (App. C, Fig.17), and (App. D, Fig.29), a gradient can give the material higher fracture stresses and ultimate strengths, with a small difference in (fracture) toughness. The fracture toughness was in all cases lower than the control values in the fracture test. This could mean that bringing (only) a gradient into the material does not necessarily give it better resistance to fracture than an abrupt interface does.

The fracture toughness also may not give conclusive data, as we have used the entire area under the stress-strain graph as our definition of the fracture toughness. The material may have such an extension, caused by the crack propagating at lower stresses already, that the strain enlarges substantial. The curves generated in the stress-strain graphs almost all have the same area underneath them. Thus, the fracture toughness differs insignificantly as well. In a future data analysis, the data could be analysed with a different definition of the fracture toughness: the toughness up until the point of fracture/ crack propagation. This would give a more significant difference.

5 Discussion

In this section we will touch on parts of the study that raised concern, or could have been done differently in order to yield clearer results. First of all, the specimens used in this study were designed on microscale. However, to fully grasp the complex mechanical properties of hard-soft material interfaces, research should happen on a mesoscale. This means that the hard-soft interface should be designed on nano-, micro- and macroscale, which is also seen in nature, as the structures of natural hard-soft interfaces are built on all these length scales [5].

Another point for discussion are the control values for the tensile tests of the hard-soft interface without gradient. These specimens were tested before this study took place with another load cell. The first problem with this is that the load cell used for the control specimens generates a lot more noise, because it is meant for higher forces than the load cell used for the tensile specimens: 5 kN compared to 100 N, respectively. The high amount of noise makes it hard to compare it with the other specimens. The second problem is that the testing of the control specimen may have gone differently than the testing of the tensile specimens, because they were tested separately. Also, it is not known if the tensile and the control specimens were made of the same material. Materials of the same type, for example 'Agilus30' or 'Vero', can have different properties if they have another colour. However, these differences in properties are most significant between the transparent and opaque variants and we know that all specimens were made with opaque material. The properties of the material used for all specimens are therefore assumed to be equal.

Lastly, the composition of the specimens introduces another variable that might have influenced the results. The aim for both the fracture and tensile specimens was to keep the hard and soft phase equal for all specimens, so the percentage of hard material over the entire specimen should be 50%. This does not include the clamps. In reality, the percentage of hard material increased as the transition zone got wider. This is because of the gradient near the clamp: The hard and soft material have equal length, so without gradient the amount of hard material is 50%. However, when a gradient is introduced the amount of soft material decreases, because the gradient near the clamps brings hard material into the otherwise soft phase. For a 2% transition zone, this gives 51% hard material. A 5% transition zone gives 52% hard material. A 10% transition zone gives 55% hard material. And a 15% transition zone gives 58% hard material. Because of this variation, the effective length of the soft material is shorter for specimens with a wider transition zone, this introduces a new variable that needs to be taken into account when interpreting the data. There are two ways to ensure a 50/50 hard-soft ratio in the specimens, while keeping all specimens the same length. The first way is to simply shift the middle transition zone towards the hard material, making it shorter and the soft phase larger. The second approach is to shift the transition zone near the clamp into the clamp. This will make the soft phase longer, but it may affect the properties of the clamp.

6 Conclusion and Recommendations

Introducing a transition zone and/or a gradient will increase certain intrinsic properties when compared to the abrupt hard-soft interface. The tensile and fracture properties have the same behaviour regarding the strength, strain and Young's Modulus. These can all be increased by inserting a gradient.

The wider the transition zone and the smaller the gradient difference, the higher the stress. A 5% transition width can have around the same strength as a 15% transition width, changing the gradient from $\rho_h - \rho_{h'}$ = 80% to $\rho_h - \rho_{h'}$= 20%. The ultimate strength is always higher than the control value, the fracture stress only when the transition zone is wider than 10%. The effect of differentiating the width of the transition zone has roughly the same effect as differentiating the gradient. Both increase with a power of 1.1 in the tensile test and in the fracture test it increases times 1.2 for the width, versus 1.3 times for the gradient. A small transition zone (2% and 5%) will also increase the fracture strain by 1.2 times for the 2% in the tensile test. However, using a wider transition zone (10% and 15%) will decrease the fracture strain without gaining additional strength. In the fracture test, the fracture strain is always lower than the control value, diminishing in the best-case scenario, for the 2% width, with 8%. The gradient has negligible effect on the strain. The Young's Modulus increases along with the transition width. The 15% transition zone has an increase with a power of 1.3 for both the tensile as the fracture test, with respect to the control values of the abrupt hard-soft interface. A decrease in $\rho_h - \rho_{h'}$ causes an increase in Young's Modulus. For both the tensile and the fracture test, the Young's Modulus also increased with a factor of 1.3 for the $\rho_h - \rho_{h'}$= 20%. The fracture toughness may not give conclusive data, as mentioned in the 'Discussion of Results'. The differences in toughness were both in the tensile and fracture tests minor and it was hard to distinguish a trend. In the fracture test, the fracture toughness went down in respect to the hard-soft material. In the tensile test, the toughness went up. If we exclude the fracture toughness, the other parameters mentioned above show similar changes in the fracture and tensile properties.

In conclusion: using a gradient can increase the tensile and fracture properties. The transition zone width has more impact on the strain than the gradient difference. The width and gradient both change the strength and Young's Modulus of the material and have about the same impact, steadily increasing it. The fracture toughness did not change that much, not clearly showing a bigger influence by either the width or the gradient.

For further research, we would recommend to look at the reason the 5% width outperforms the 10% width in both ultimate strength and strain in the tensile test and if there is an optimum for samples with a small transition zone width. The recommendation would also be to conduct further research with the $\rho_h - \rho_{h'}$= 20%, because it has the highest fracture properties. In making samples for further research it would advised to consistently make the average percentage of hard material in the specimen 50%, as to diminish the influence of it on the Young's Modulus, shear modulus and Poisson's ratio of the composite material.

The average fracture toughness of a specimen with gradient, was closer to the soft-soft interface than to the hard-hard interface by a power of 5.3. This makes sense because the crack propagates towards the soft material and afterwards, for a large parts, goes through the soft material. Further implementation of more crack resistance mechanisms could heighten the fracture toughness. The fracture toughness could be increased by keeping the crack within the transition zone, by for example changing the brick and mortar structure [5]. Along with using a harder soft material. Also, we would recommend to look more into using nanoscale and bringing patterns and alignments within the material in combination with FGM's. That might give results which could surpass the abrupt interface in toughness.

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A Experimental Approach

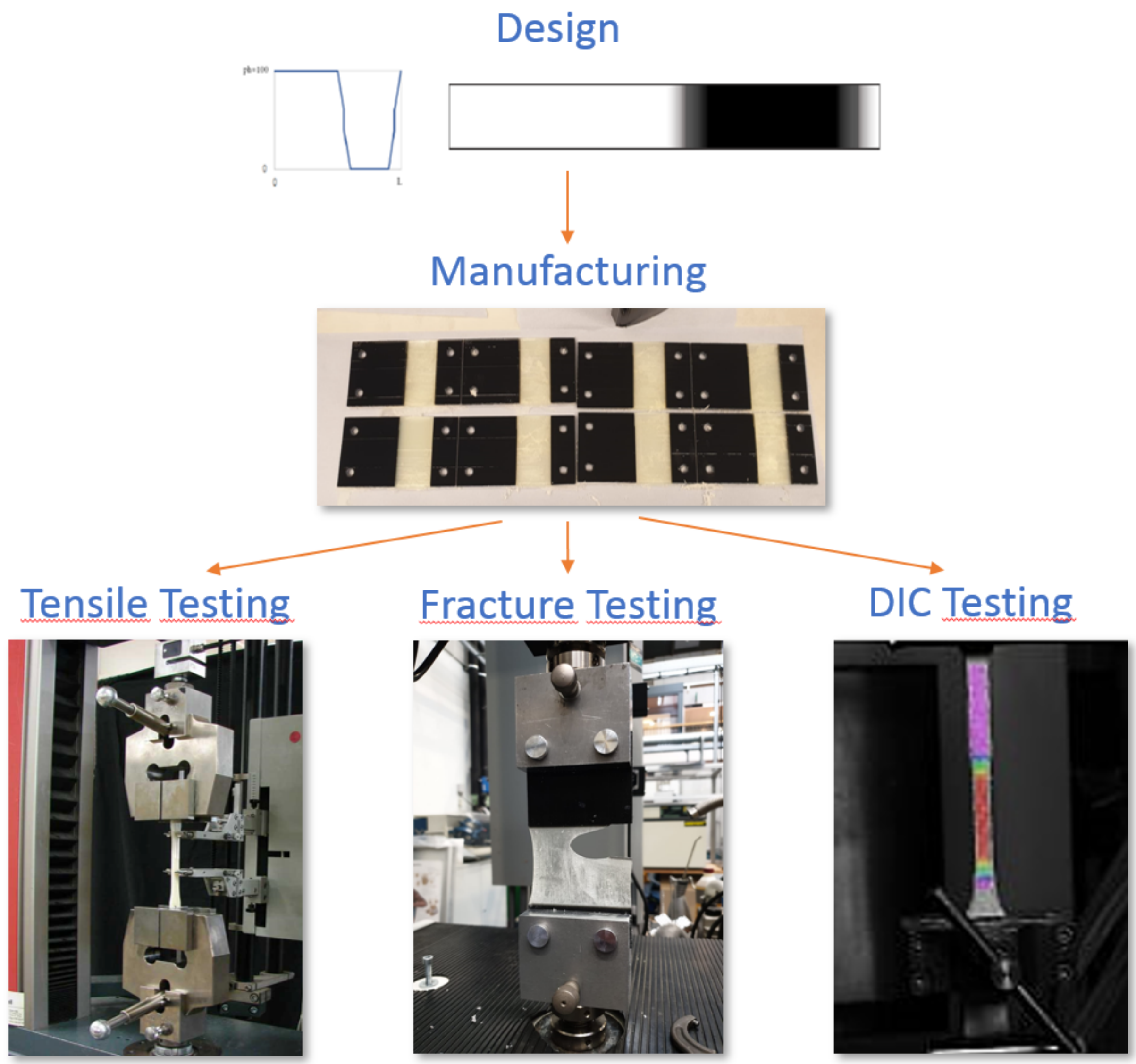

Figure 5: *The experimental setup.*

B Specimens and Gradients

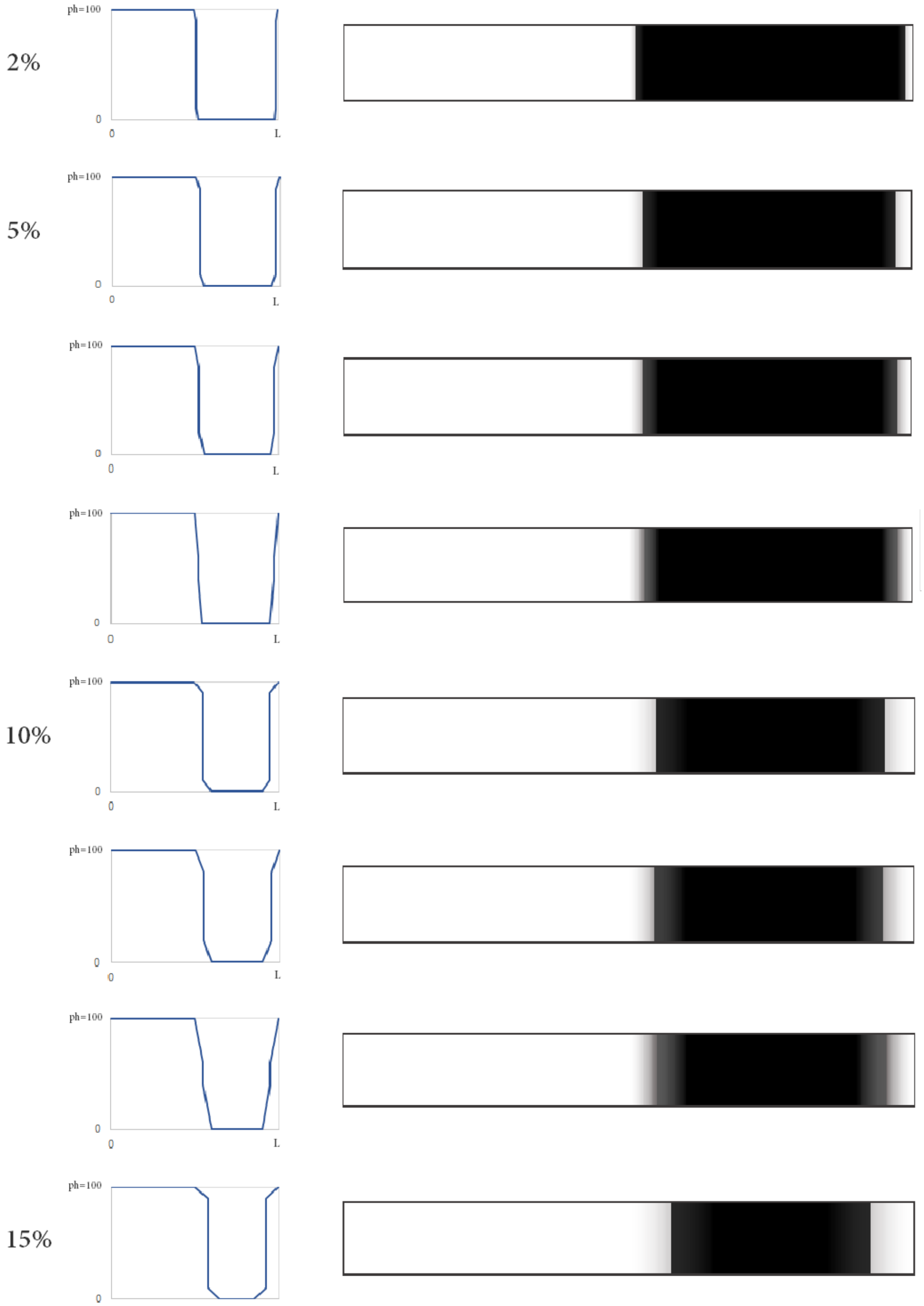

Figure 6: *The different specimens with their corresponding gradients.*

Table 1: Percentage hard material in every different type of specimen

W [%]	$\rho_h - \rho_{h'}$ [%]	Average percentage hard material [%]	DIC
2	80	51.1	Yes
5	80	52.6	Yes
	60	52.6	Yes
	20	52.6	Yes
10	80	55.1	Yes
	60	55.1	No
	20	55.1	No
15	80	57.6	Yes

C Fracture Graphs

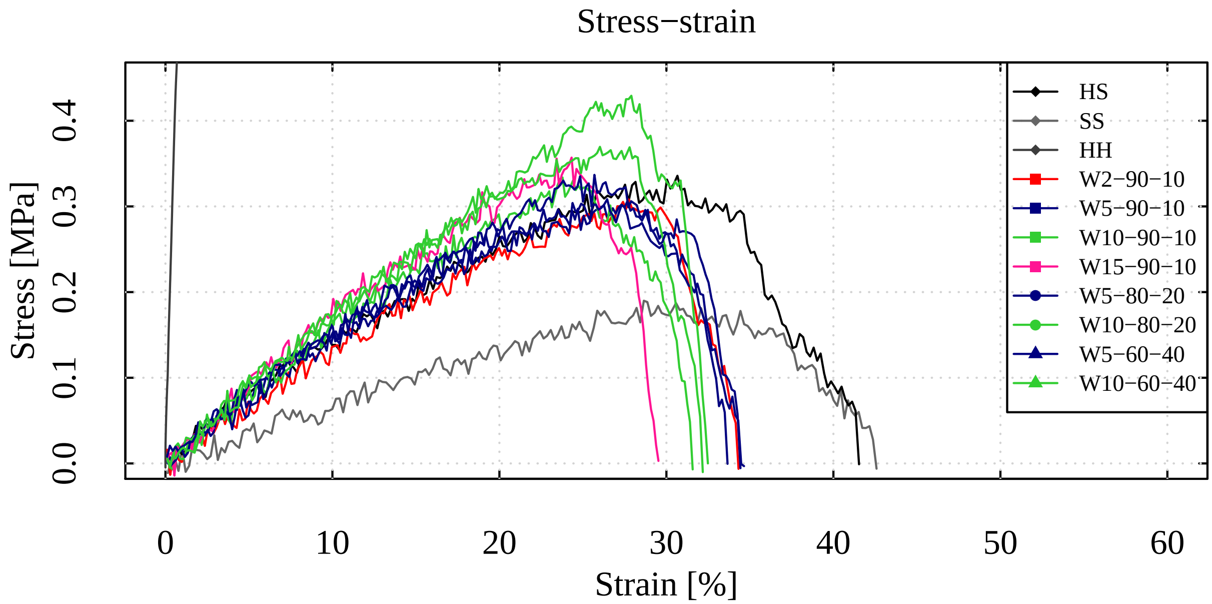

Figure 7: *Stress-strain curve of representative specimens. Denoted by the width, followed by the hardness gradients, all in percentages.*

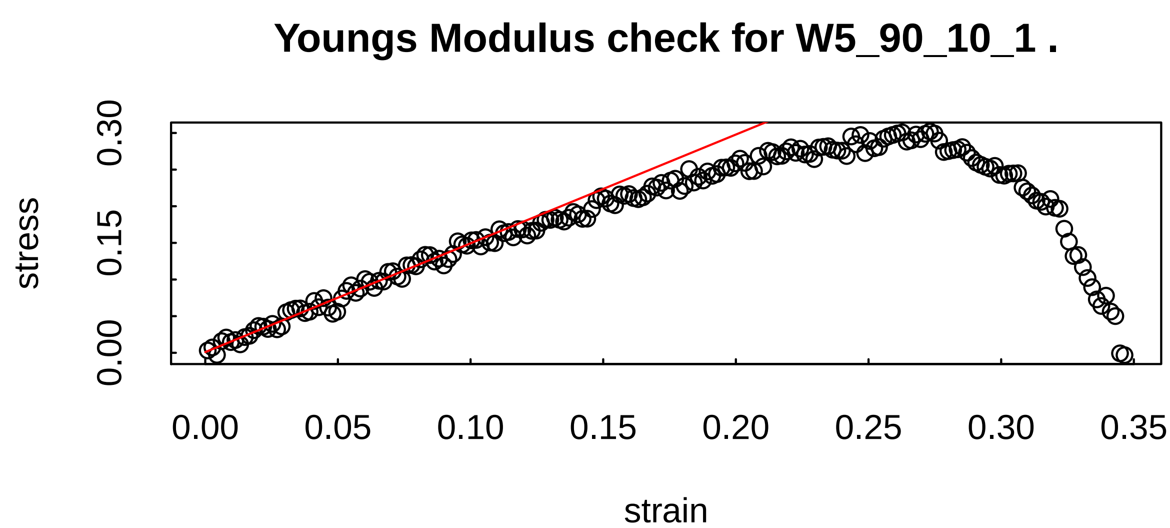

Figure 8: *Example of a Young's modulus check on the stress-strain curve as generated in RStudio.*

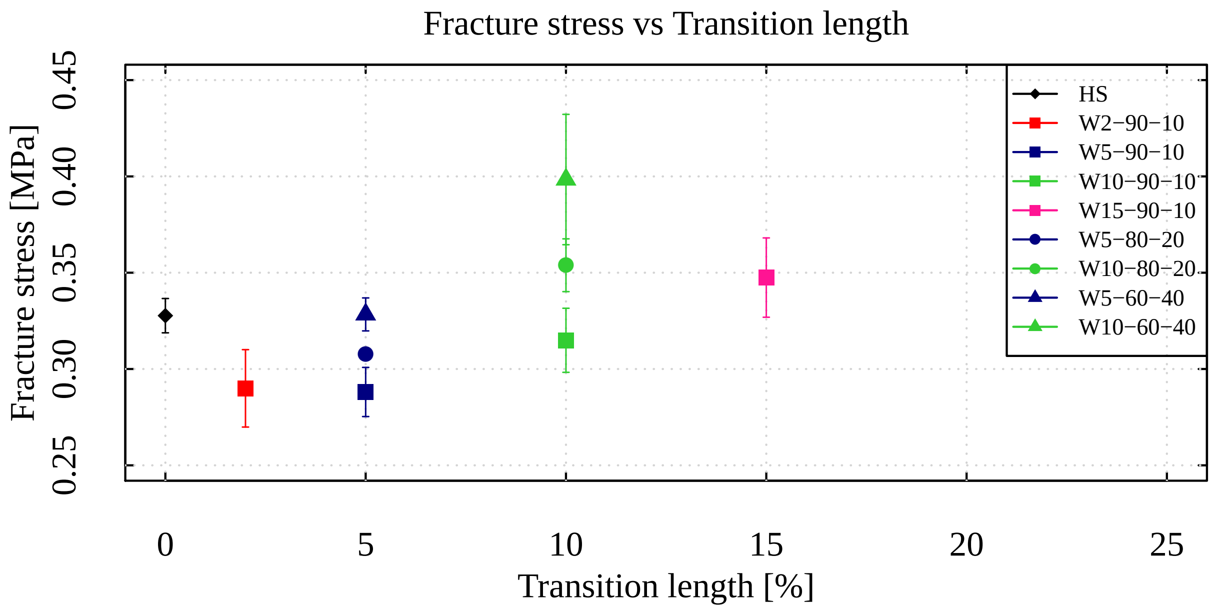

Figure 9: *Fracture stress versus the transition zone lengths*

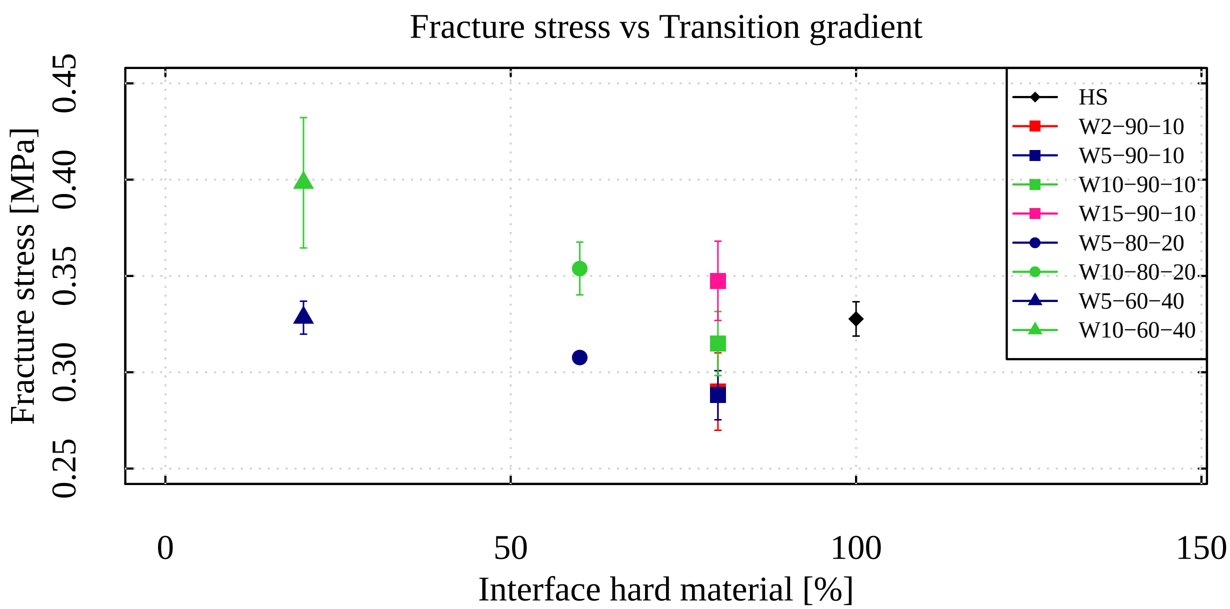

Figure 10: *Fracture stress versus the transition gradient ($\rho_h - \rho_{h'}$)*

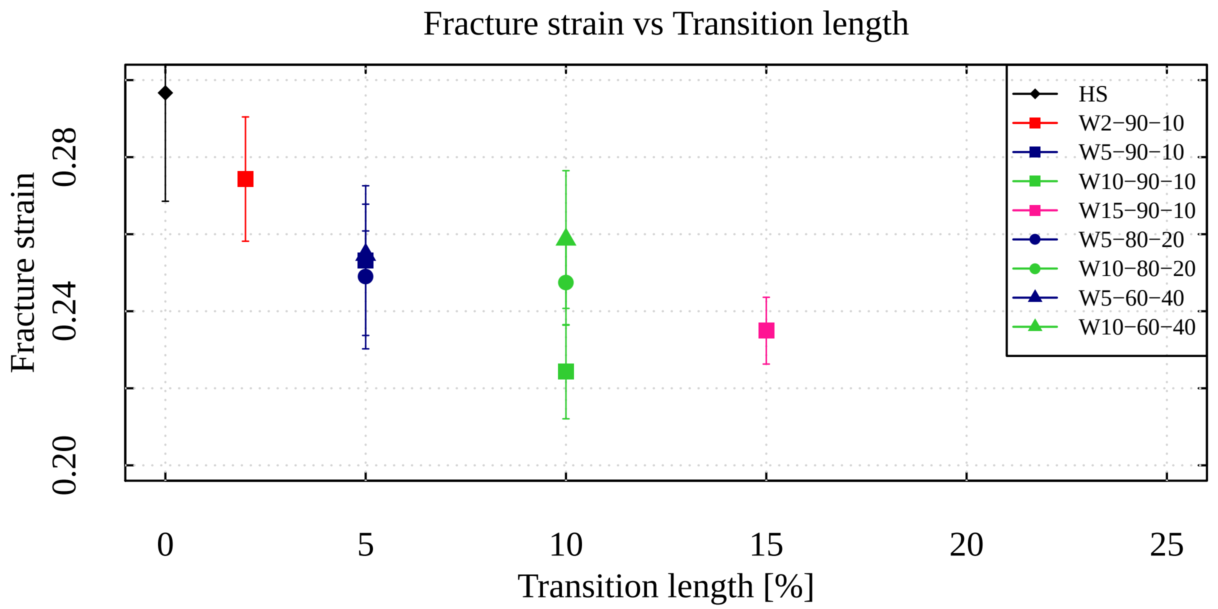

Figure 11: *Fracture strain versus transition zone length*

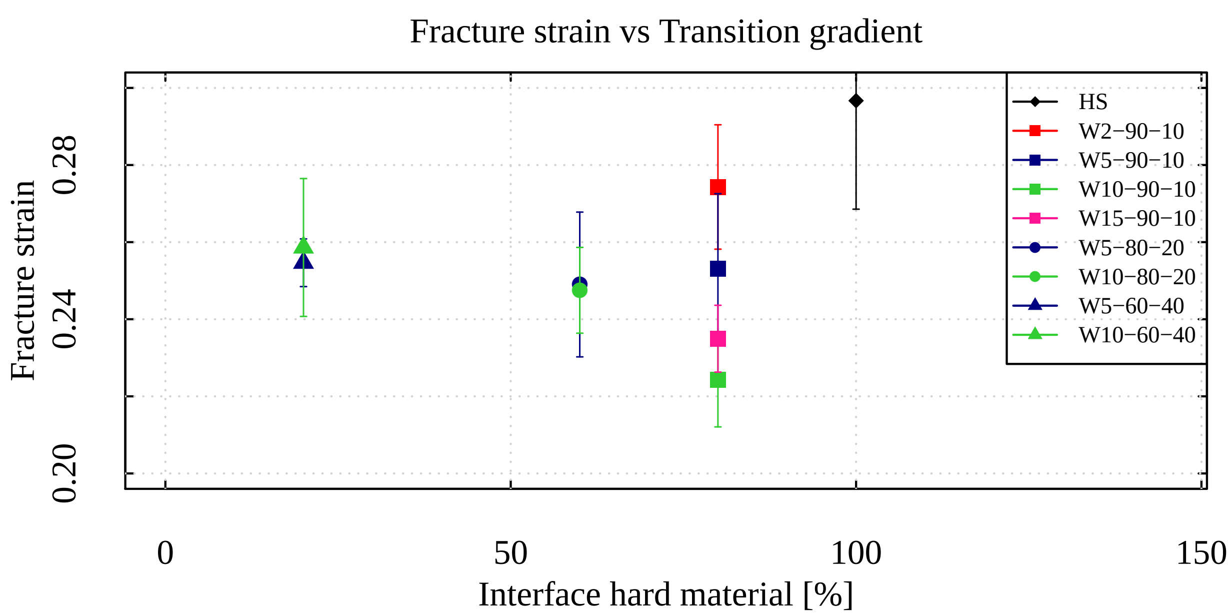

Figure 12: *Fracture strain versus transition gradient*

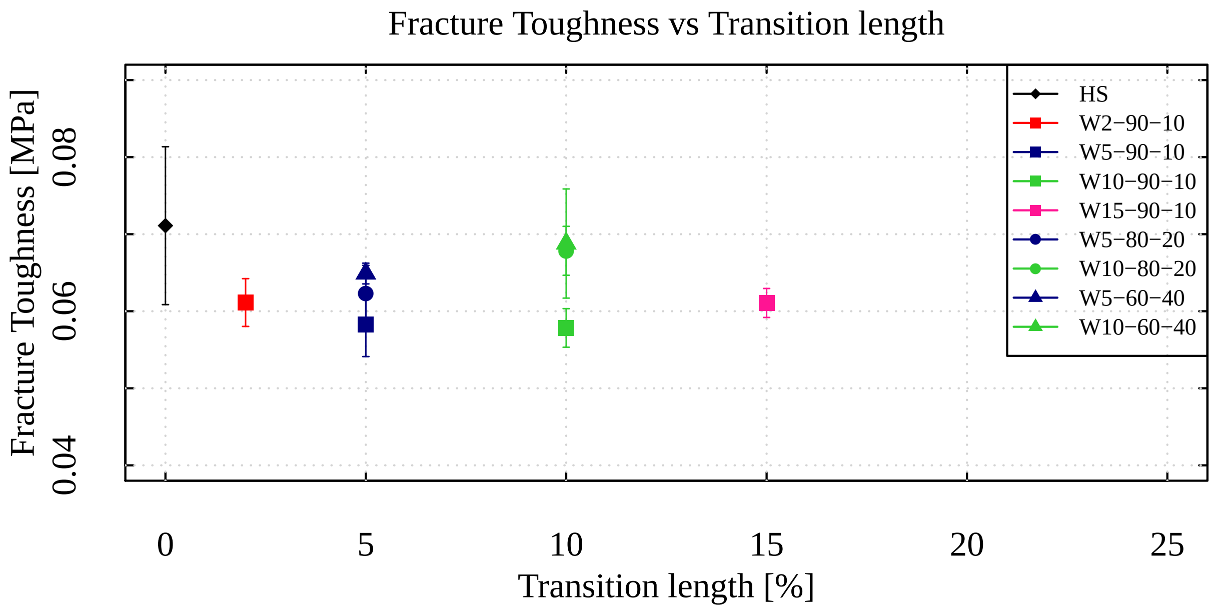

Figure 13: *Fracture Toughness versus transition zone length*

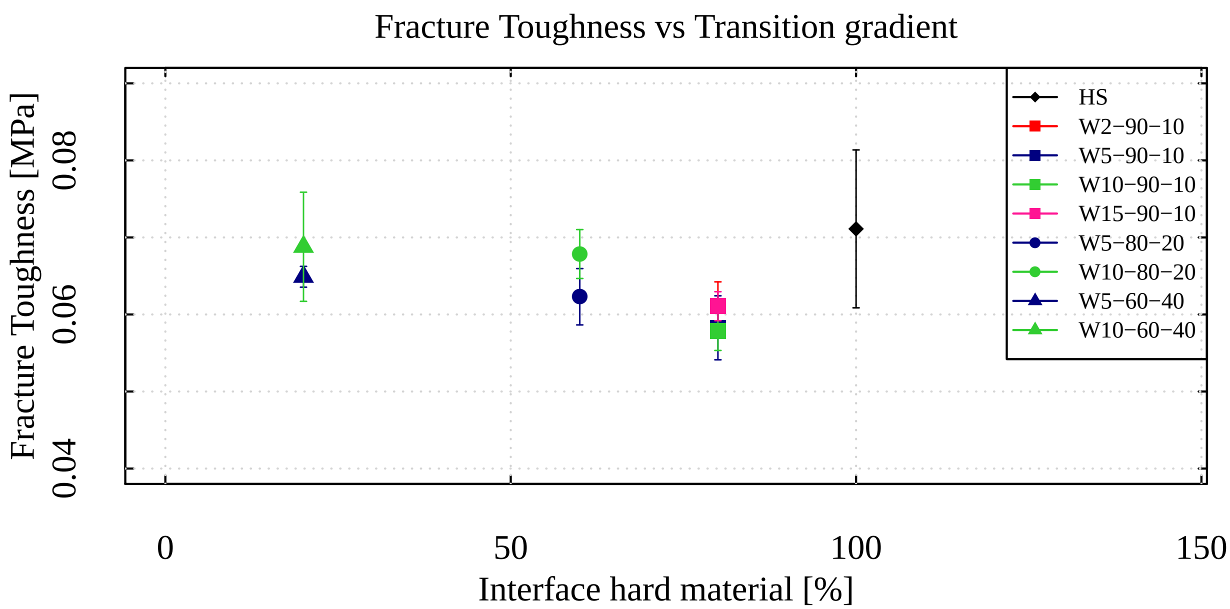

Figure 14: *Fracture Toughness versus transition gradient*

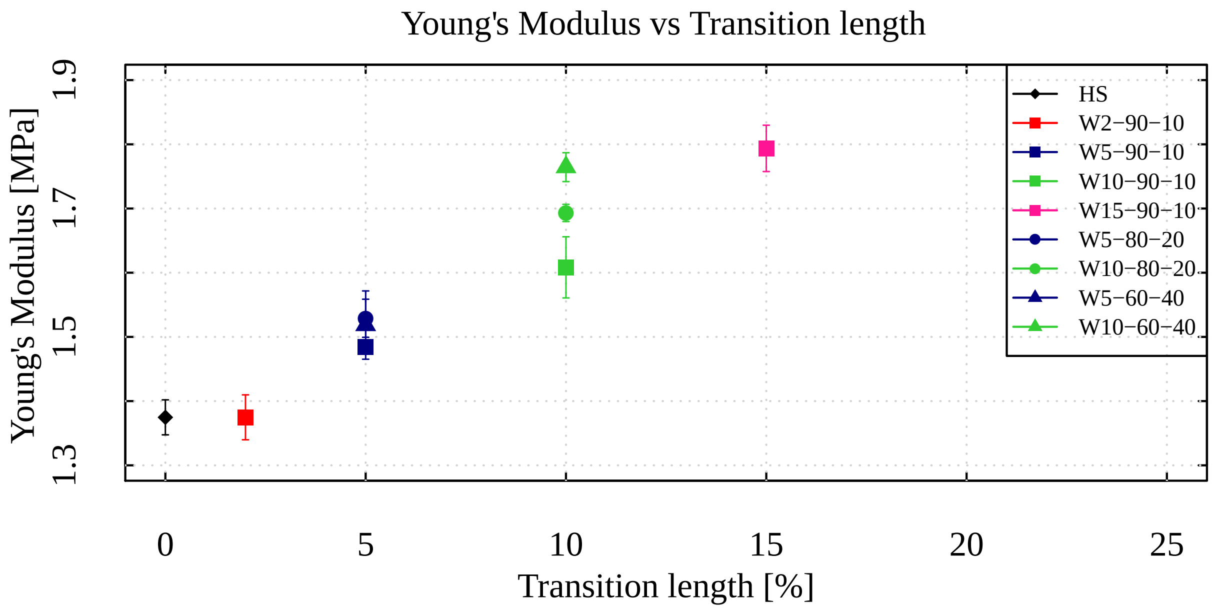

Figure 15: *Young's Modulus versus transition zone length*

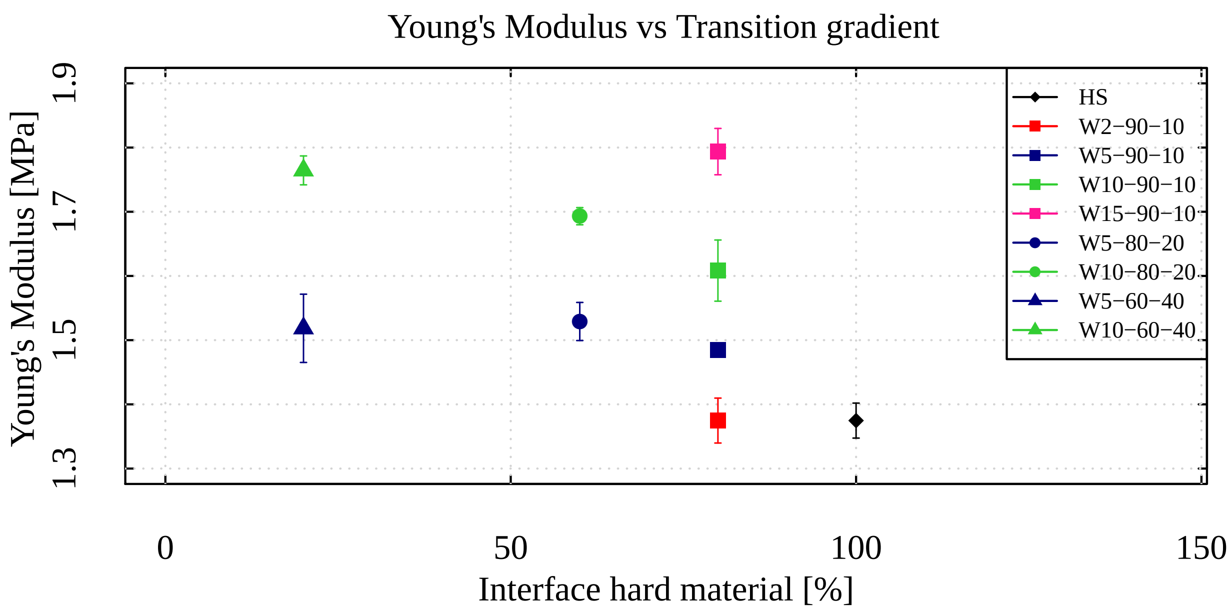

Figure 16: *Young's Modulus versus transition gradient*

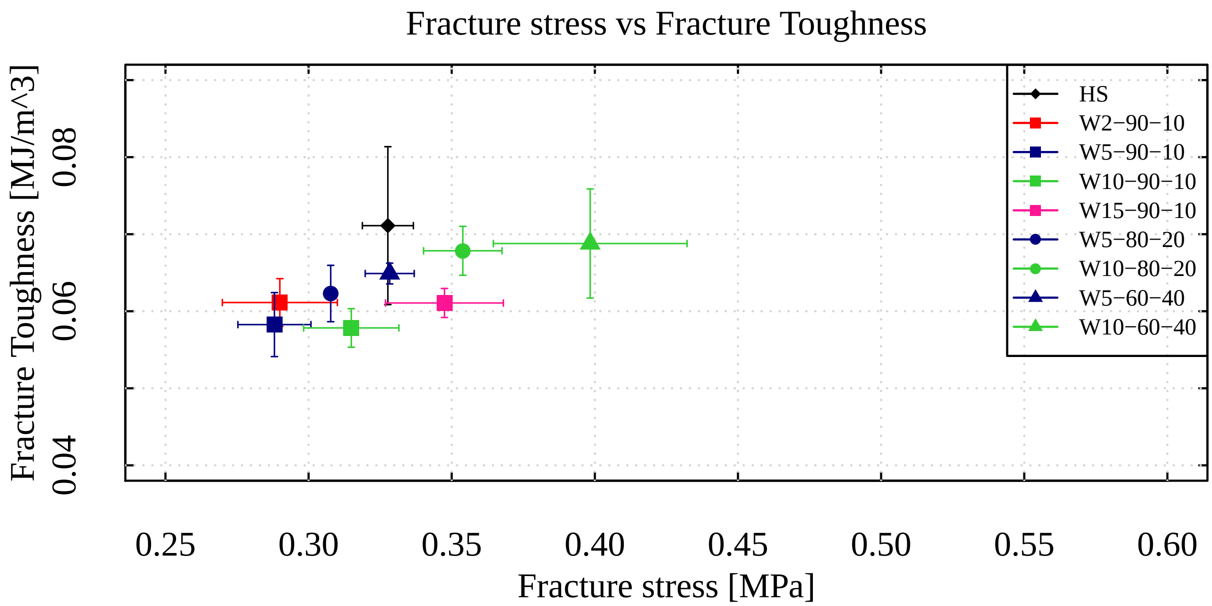

Figure 17: *Fracture stress versus fracture toughness*

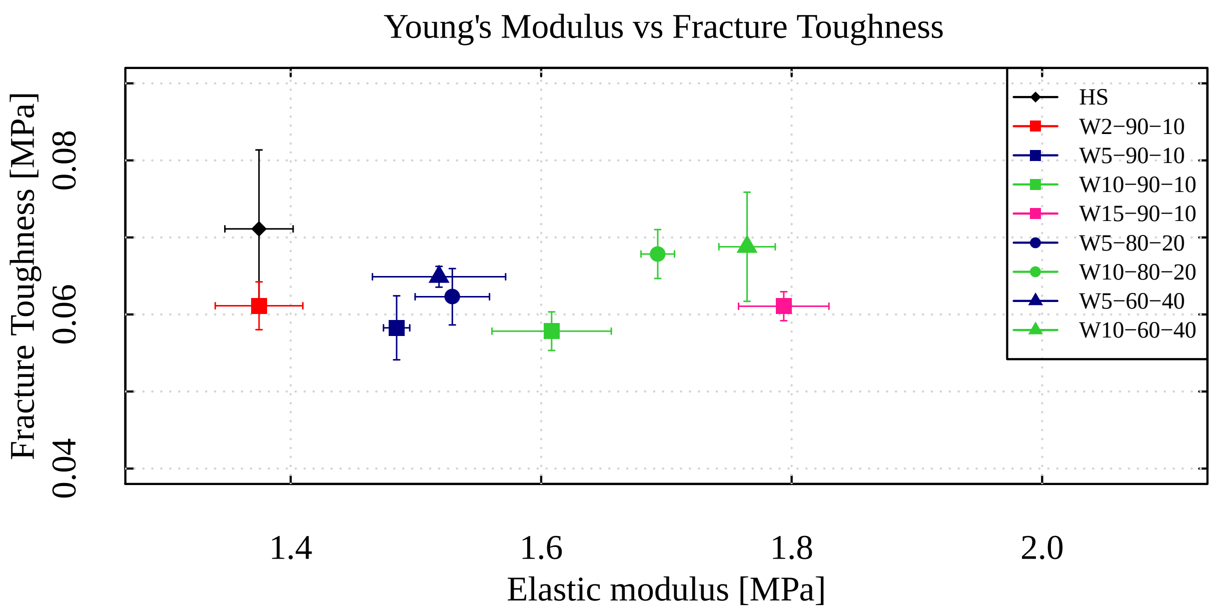

Figure 18: *Young's Modulus versus fracture toughness*

Table 2: Data frame of the fracture test

	specimen name	specimen factors	specimen gradients	Young's modulus	Strain at max stress	Fracture toughness	Max strain	Fracture strength
1	SS.1	W0	0/0	0.7358793	0.28648000	0.04528569	0.42584000	0.1899500
2	SS.2	W0	0/0	0.7032206	0.35553333	0.05481252	0.47509333	0.2023611
3	SS.3	W0	0/0	0.6261499	0.39932000	0.06252564	0.51970667	0.2171222
4	HH.1	W0	100/100	565.8109431	0.03982278	0.19928430	0.03982278	13.8151761
5	HH.2	W0	100/100	539.2181361	0.04786600	0.34052333	0.04786600	16.0640666
6	HH.3	W0	100/100	577.1296537	0.04616336	0.32472809	0.04616336	16.2124200
7	HS.1	W0	100/0	1.4035702	0.30658667	0.08113294	0.41534667	0.3357722
8	HS.2	W0	100/0	1.3494699	0.31853333	0.07154436	0.36870667	0.3291778
9	HS.3	W0	100/0	1.3710933	0.26493333	0.06064715	0.33613333	0.3181444
10	W2.90.10.1	W2	90/10	1.3765865	0.28860000	0.05843447	0.35253333	0.2684056
11	W2.90.10.2	W2	90/10	1.4087718	0.25681333	0.06452064	0.36537333	0.2933167
12	W2.90.10.3	W2	90/10	1.3388931	0.27750667	0.06043149	0.34318667	0.3081667
13	W5.60.40.1	W5	60/40	1.4575357	0.25688000	0.06621323	0.33660000	0.3368167
14	W5.60.40.2	W5	60/40	1.5555881	0.24765333	0.06495018	0.34018667	0.3197000
15	W5.60.40.3	W5	60/40	1.5422220	0.25941333	0.06351802	0.33990667	0.3285167
16	W5.80.20.1	W5	80/20	1.5610258	0.22814667	0.05997602	0.34189333	0.3064833
17	W5.80.20.2	W5	80/20	1.5237917	0.26453333	0.06651469	0.34434667	0.3083556
18	W5.80.20.3	W5	80/20	1.5023608	0.25436000	0.06041263	0.32680000	0.3083556
19	W5.90.10.1	W5	90/10	1.4842718	0.27314667	0.06244853	0.34649333	0.3020278
20	W5.90.10.2	W5	90/10	1.4743032	0.25192000	0.05820754	0.36090667	0.2852056
21	W5.90.10.3	W5	90/10	1.4952417	0.23434667	0.05414182	0.32182667	0.2769944
22	W10.60.40.1	W10	60/40	1.7674410	0.25114667	0.06629849	0.30504000	0.4038500
23	W10.60.40.2	W10	60/40	1.7852453	0.27901333	0.07677915	0.32484000	0.4291444
24	W10.60.40.3	W10	60/40	1.7405540	0.24566667	0.06328150	0.30772000	0.3621389
25	W10.80.20.1	W10	80/20	1.6840206	0.23949333	0.06935332	0.32682667	0.3480222
26	W10.80.20.2	W10	80/20	1.6867702	0.26020000	0.06998466	0.32178667	0.3695389
27	W10.80.20.3	W10	80/20	1.7084660	0.24281333	0.06419688	0.31401333	0.3440778
28	W10.90.10.1	W10	90/10	1.5573405	0.21392000	0.05523083	0.30438667	0.3085111
29	W10.90.10.2	W10	90/10	1.6517065	0.22120000	0.05804083	0.31036000	0.3024444
30	W10.90.10.3	W10	90/10	1.6160097	0.23777333	0.06022566	0.31573333	0.3338056
31	W15.90.10.1	W15	90/10	1.7614437	0.23568000	0.06319736	0.32586667	0.3615778
32	W15.90.10.2	W15	90/10	1.7869618	0.22594667	0.06038736	0.30212000	0.3238389
33	W15.90.10.3	W15	90/10	1.8326585	0.24322667	0.05962809	0.29524000	0.3570000

Table 3: Mean data of the fracture test

	namelabels	mean Young's modulus	mean Strain at max stress	mean Fracture toughness	mean Max strain	mean Fracture strength
1	0/0, W0	0.6884166	0.34711111	0.05420795	0.47354667	0.2031444
2	100/100, W0	560.7195776	0.04461738	0.28817857	0.04461738	15.3638875
3	100/0, W0	1.3747112	0.29668444	0.07110815	0.37339556	0.3276981
4	90/10, W2	1.3747504	0.27430667	0.06112887	0.35369778	0.2899630
5	90/10, W5	1.4846056	0.25313778	0.05826597	0.34307556	0.2880759
6	90/10, W10	1.6083522	0.22429778	0.05783244	0.31016000	0.3149204
7	90/10, W15	1.7936880	0.23495111	0.06107093	0.30774222	0.3474722
8	80/20, W5	1.5290594	0.24901333	0.06230111	0.33768000	0.3077315
9	80/20, W10	1.6930856	0.24750222	0.06784495	0.32087556	0.3538796
10	60/40, W5	1.5184486	0.25464889	0.06489381	0.33889778	0.3283444
11	60/40, W10	1.7644134	0.25860889	0.06878638	0.31253333	0.3983778

Table 4: Standard deviation data of the fracture test

	namelabels	sd Young's modulus	sd Strain at max stress	sd Fracture toughness	sd Max strain	sd Fracture strength
1	0/0, W0	0.05634273	0.056889514	0.008635862	0.046952443	0.013603037
2	100/100, W0	19.46181626	0.004238619	0.077388737	0.004238619	1.343273101
3	100/0, W0	0.02723101	0.028138595	0.010249860	0.039814285	0.008906549
4	90/10, W2	0.03497551	0.016133135	0.003102439	0.011139075	0.020091590
5	90/10, W5	0.01047327	0.019428645	0.004153663	0.019762907	0.012761121
6	90/10, W10	0.04764675	0.012224670	0.002503928	0.005675977	0.016633965
7	90/10, W15	0.03608070	0.008663028	0.001880259	0.016068765	0.020594656
8	80/20, W5	0.02968511	0.018773319	0.003655589	0.009501869	0.001080928
9	80/20, W10	0.01339058	0.011121186	0.003175057	0.006455073	0.013703976
10	60/40, W5	0.05317374	0.006189329	0.001348486	0.001994853	0.008559633
11	60/40, W10	0.02249893	0.017881935	0.007084407	0.010741794	0.033836298

D Tensile Graphs

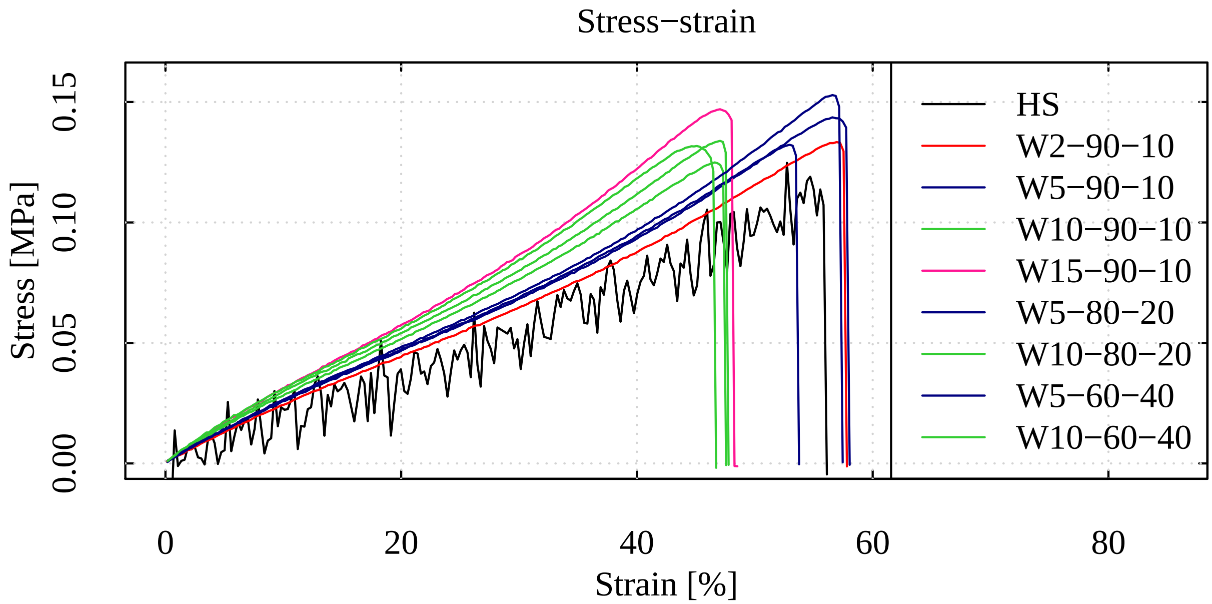

Figure 19: *Stress-strain curve of representative specimens. Denoted by the width, followed by the hardness gradients, all in percentages.*

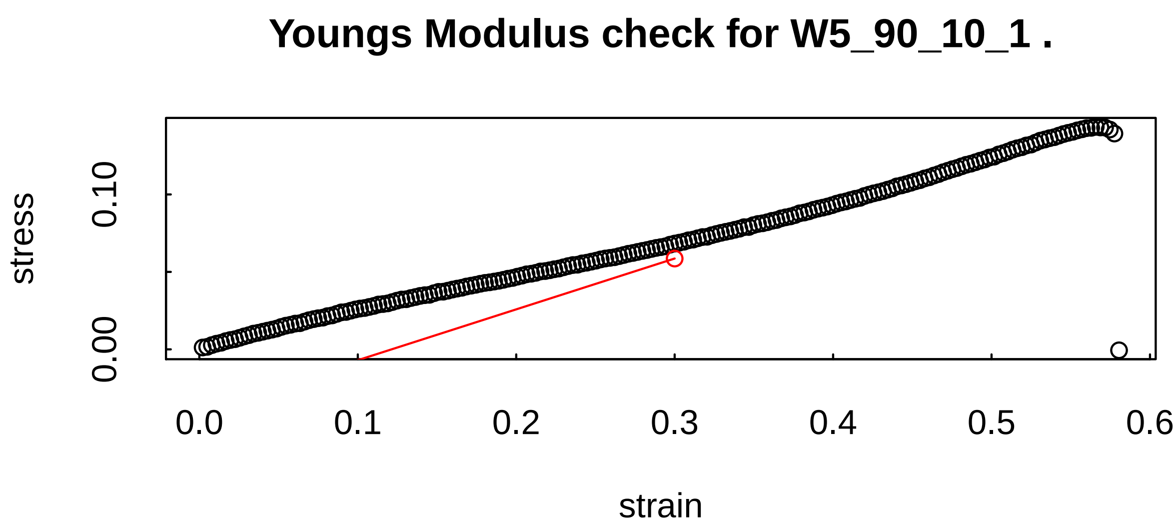

Figure 20: *Example of a Young's modulus check on the stress-strain curve as generated in RStudio.*

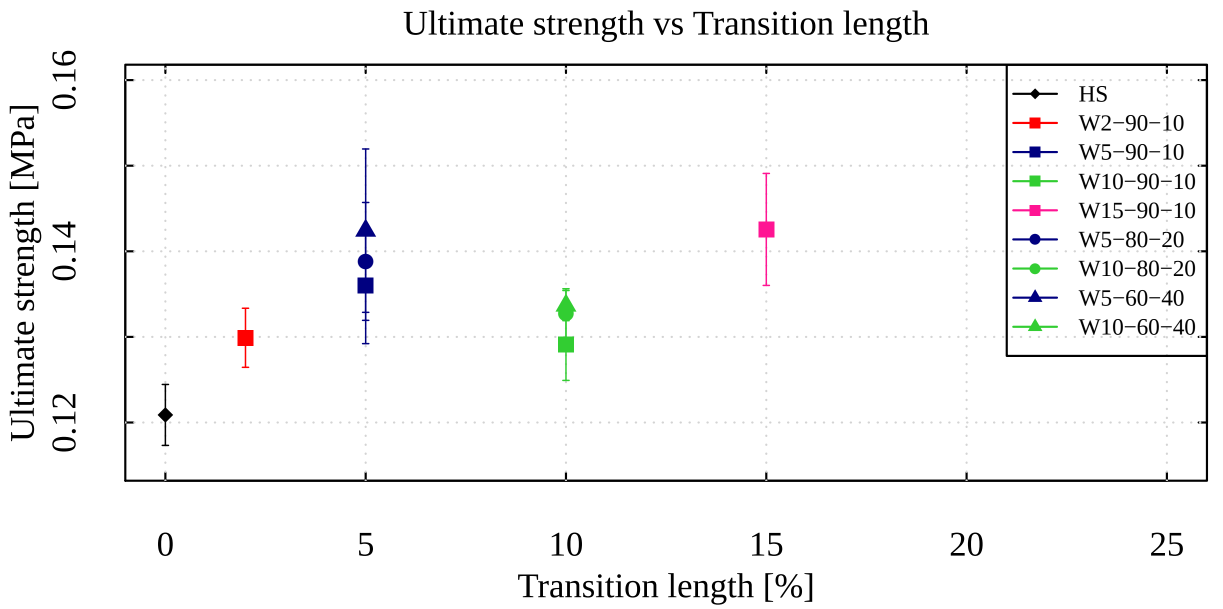

Figure 21: *Ultimate strength versus transition zone length*

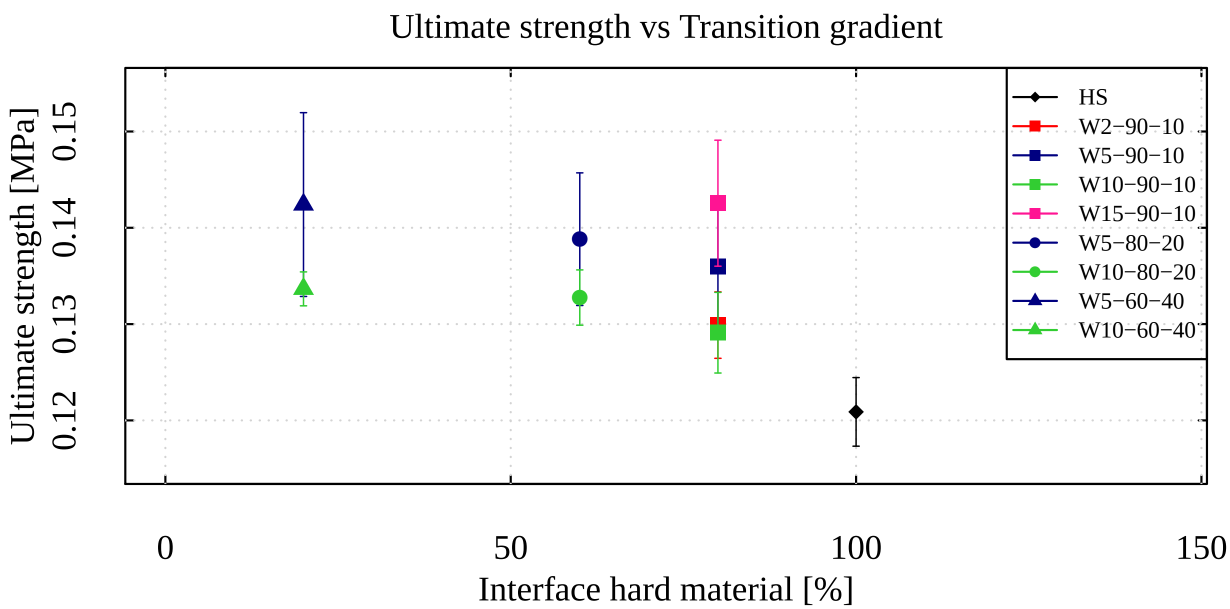

Figure 22: *Ultimate strength versus transition zone gradient*

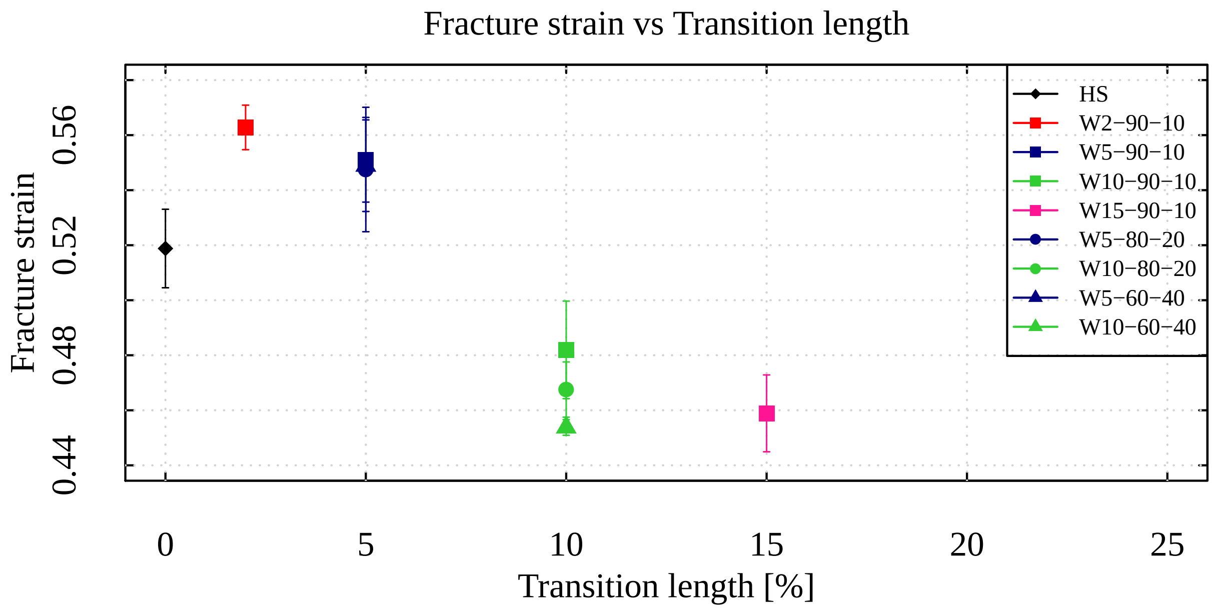

Figure 23: *Fracture strain versus transition zone length*

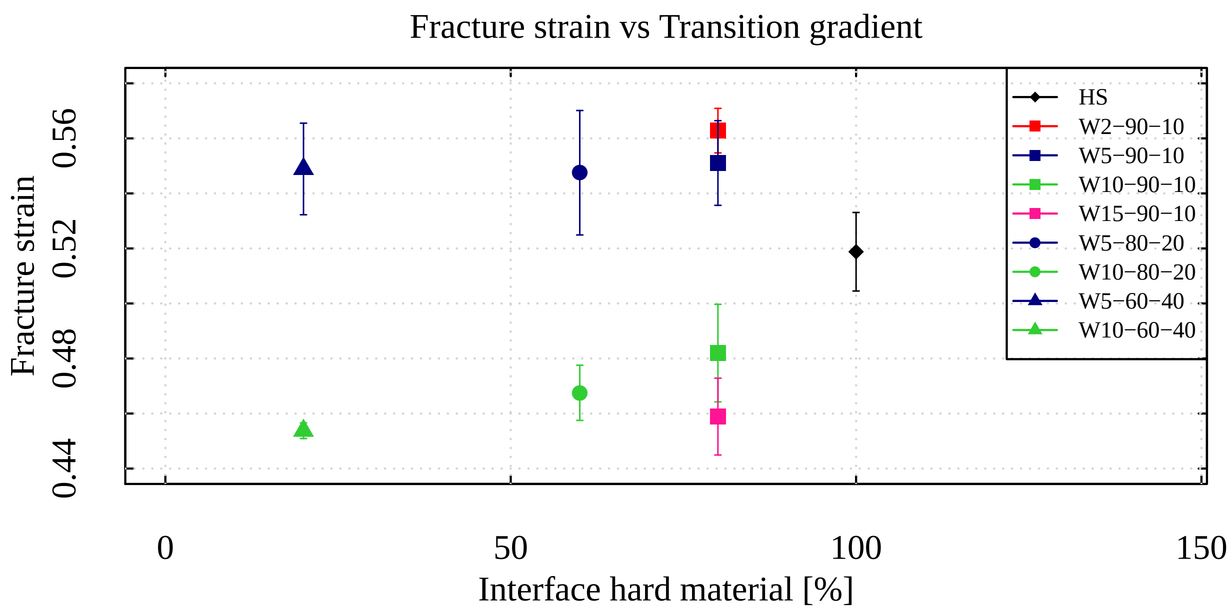

Figure 24: *Fracture strain versus transition zone gradient*

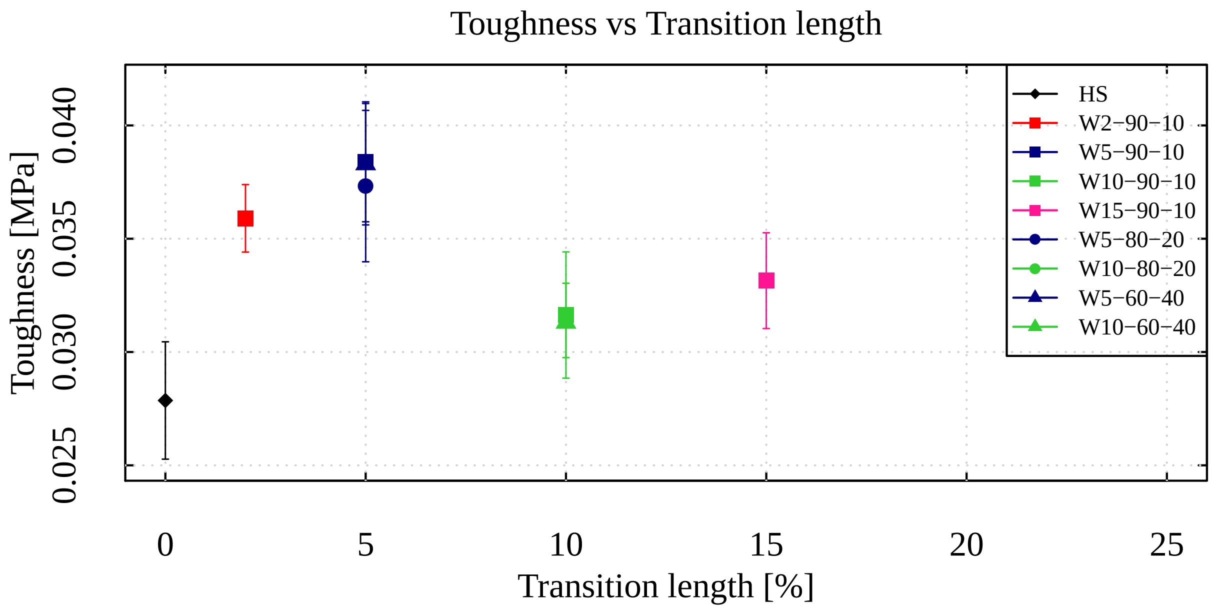

Figure 25: *Toughness versus transition zone length*

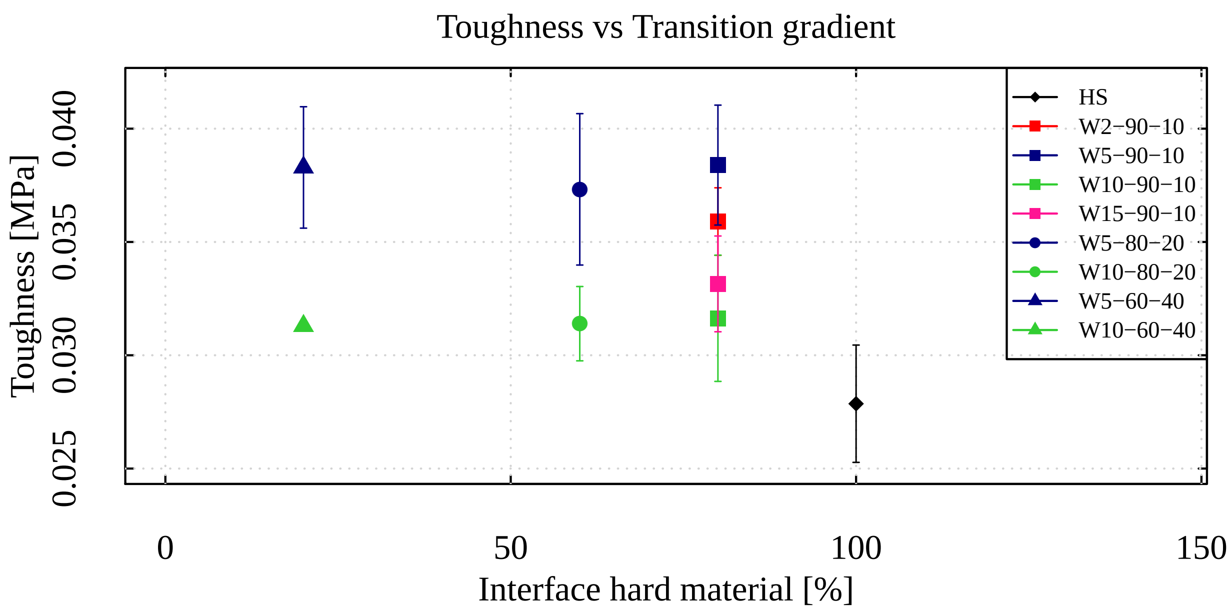

Figure 26: *Toughness versus transition zone gradient*

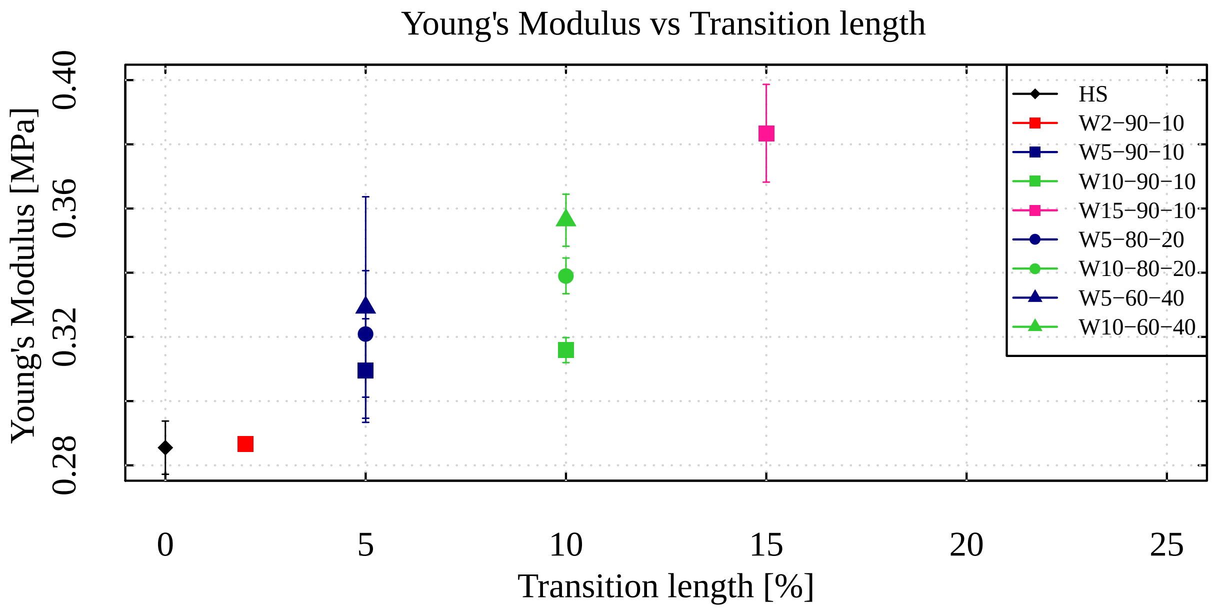

Figure 27: *Young's Modulus versus transition zone length*

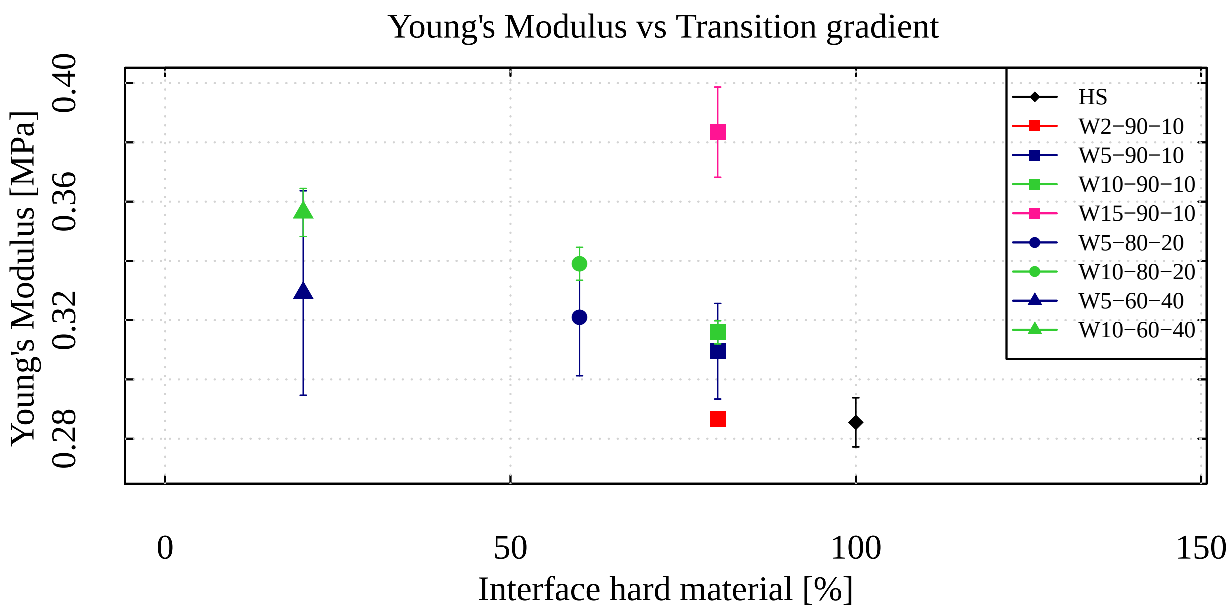

Figure 28: *Young's Modulus versus transition zone gradient*

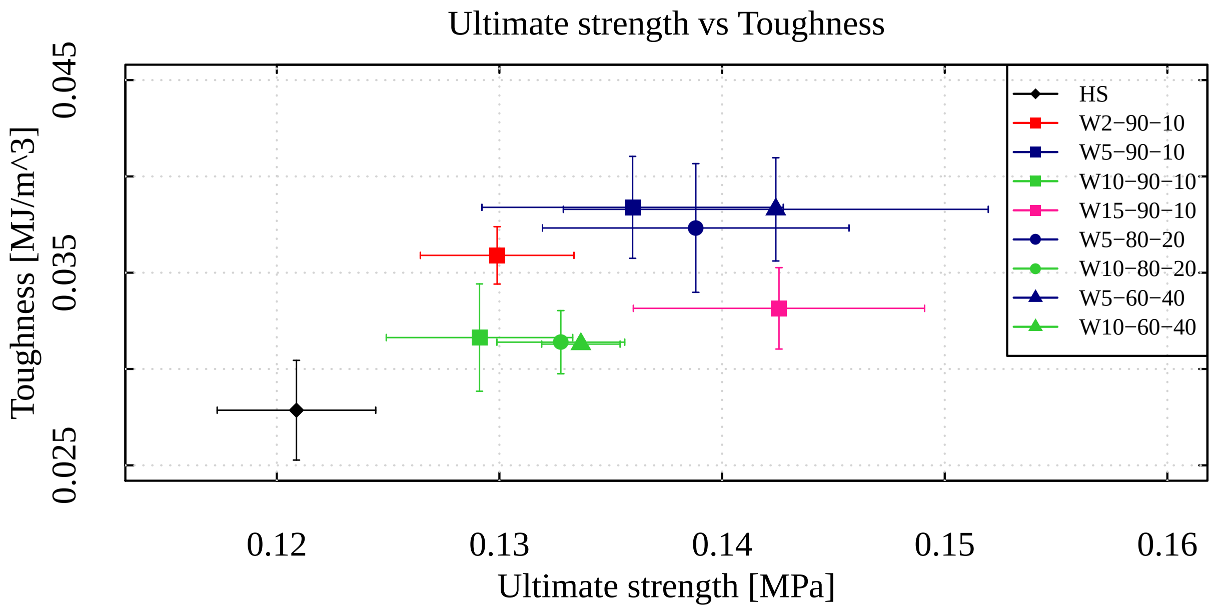

Figure 29: *Ultimate strength versus Toughness*

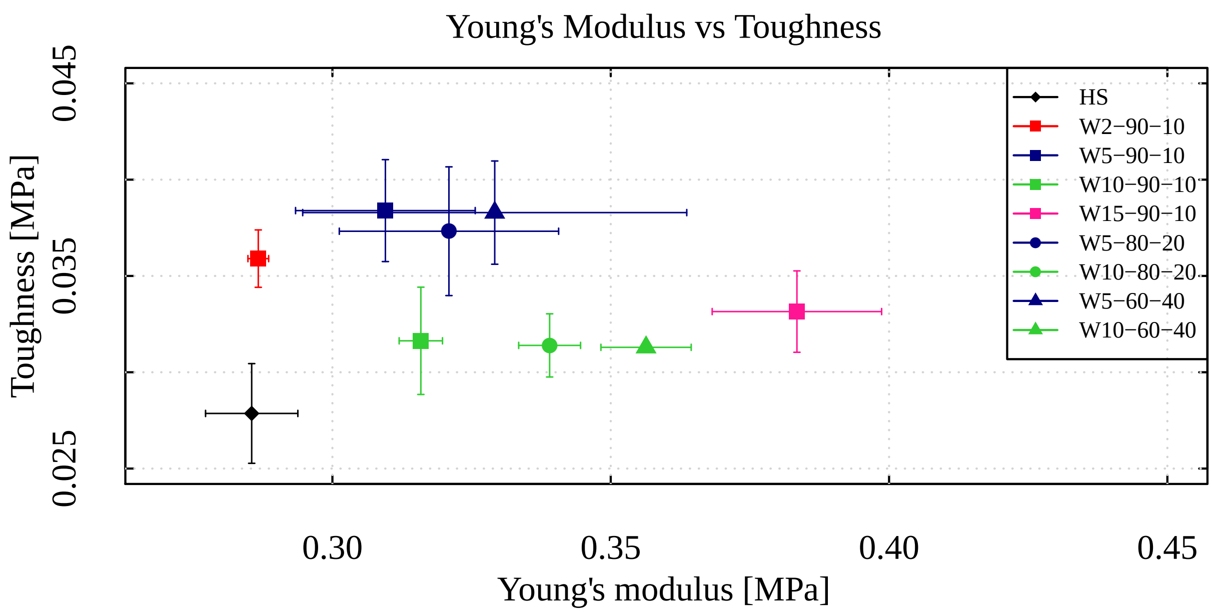

Figure 30: *Young's Modulus versus Toughness*

Table 5: Dataframe of the tensile test

	specimen name	specimen factors	specimen gradients	Young's modulus	Strain at max stress	Toughness	Max train	Ultimate Strength
1	SS.1	W0	0/0	0.1242585	1.05846667	0.05404591	1.0692400	0.1270889
2	SS.2	W0	0/0	0.1395506	1.18577333	0.07656222	1.1917600	0.1394611
3	SS.3	W0	0/0	0.1210711	1.11056000	0.06379537	1.1275733	0.1195778
4	HH.1	W0	100/100	162.0582385	0.09004533	0.93835924	0.1378267	10.0816667
5	HH.2	W0	100/100	140.9305114	0.08978000	1.69962932	0.2738267	8.1433333
6	HH.3	W0	100/100	185.0457807	0.08387867	1.02001938	0.1524800	9.5700000
7	HS.1	W0	100/0	0.2796574	0.52725333	0.02933800	0.5611333	0.1247444
8	HS.2	W0	100/0	0.2949841	0.50232000	0.02487143	0.5233867	0.1177278
9	HS.3	W0	100/0	0.2818479	0.52681333	0.02937286	0.5636667	0.1201833
10	W2.90.10.1	W2	90/10	0.2861826	0.56521333	0.03595793	0.5740133	0.1298722
11	W2.90.10.2	W2	90/10	0.2851194	0.55378667	0.03438284	0.5594133	0.1264611
12	W2.90.10.3	W2	90/10	0.2887397	0.56942667	0.03736009	0.5781333	0.1333611
13	W5.60.40.1	W5	60/40	0.3673477	0.56582667	0.04089546	0.5745467	0.1528778
14	W5.60.40.2	W5	60/40	0.3002579	0.53256000	0.03554246	0.5407867	0.1341944
15	W5.60.40.3	W5	60/40	0.3198655	0.54829333	0.03842894	0.5595467	0.1401667
16	W5.80.20.1	W5	80/20	0.3230558	0.54020000	0.03663818	0.5514133	0.1382444
17	W5.80.20.2	W5	80/20	0.3002579	0.52946667	0.03437647	0.5375733	0.1322389
18	W5.80.20.3	W5	80/20	0.3394927	0.57288000	0.04095261	0.5847067	0.1459722
19	W5.90.10.1	W5	90/10	0.3281508	0.56576000	0.04015384	0.5804800	0.1436389
20	W5.90.10.2	W5	90/10	0.3002579	0.55233333	0.03967485	0.6142133	0.1335000
21	W5.90.10.3	W5	90/10	0.3001397	0.53506667	0.03534986	0.5488667	0.1308056
22	W10.60.40.1	W10	60/40	0.3617123	0.45638667	0.03147567	0.4706000	0.1351500
23	W10.60.40.2	W10	60/40	0.3470128	0.45073333	0.03131425	0.4671867	0.1317167
24	W10.60.40.3	W10	60/40	0.3603104	0.45413333	0.03109112	0.4682533	0.1341111
25	W10.80.20.1	W10	80/20	0.3419179	0.47573333	0.03305016	0.4931867	0.1349167
26	W10.80.20.2	W10	80/20	0.3425340	0.47052000	0.03136018	0.4777600	0.1338556
27	W10.80.20.3	W10	80/20	0.3326099	0.45634667	0.02977098	0.4657467	0.1295000
28	W10.90.10.1	W10	90/10	0.3200318	0.47885333	0.03063408	0.4861733	0.1291000
29	W10.90.10.2	W10	90/10	0.3153123	0.50104000	0.03477961	0.5166667	0.1332944
30	W10.90.10.3	W10	90/10	0.3123124	0.46598667	0.02948329	0.4756533	0.1249222
31	W15.90.10.1	W15	90/10	0.3936909	0.46272000	0.03390412	0.4771600	0.1456278
32	W15.90.10.2	W15	90/10	0.3659568	0.44340000	0.03076335	0.4548533	0.1350444
33	W15.90.10.3	W15	90/10	0.3906905	0.47053333	0.03478203	0.4852133	0.1469944

Table 6: Mean data of the tensile test

	namelabels	mean Young's modulus	mean Strain at max stress	mean Toughness	mean Max strain	mean Ultimate strength
1	0/0, W0	0.1282934	1.11826667	0.06480117	1.1295244	0.1287093
2	100/100, W0	162.6781769	0.08790133	1.21933598	0.1880444	9.2650000
3	100/0, W0	0.2854965	0.51879556	0.02786076	0.5493956	0.1208852
4	90/10, W2	0.2866806	0.56280889	0.03590029	0.5705200	0.1298981
5	90/10, W5	0.3095161	0.55105333	0.03839285	0.5811867	0.1359815
6	90/10, W10	0.3158855	0.48196000	0.03163232	0.4928311	0.1291056
7	90/10, W15	0.3834461	0.45888444	0.03314984	0.4724089	0.1425556
8	80/20, W5	0.3209355	0.54751556	0.03732242	0.5578978	0.1388185
9	80/20, W10	0.3390206	0.46753333	0.03139377	0.4788978	0.1327574
10	60/40, W5	0.3291571	0.54889333	0.03828895	0.5582933	0.1424130
11	60/40, W10	0.3563452	0.45375111	0.03129368	0.4686800	0.1336593

Table 7: Standard deviation data of the tensile test

	namelabels	sd Young's modulus	sd Strain at max stress	sd Toughness	sd Max strain	sd Ultimate strength
1	0/0, W0	0.009878457	0.064002276	0.0112918027	0.061283299	0.010040216
2	100/100, W0	22.064167547	0.003486257	0.4179454107	0.074649999	1.004516191
3	100/0, W0	0.008289201	0.014269946	0.0025889000	0.022559946	0.003560597
4	90/10, W2	0.001860793	0.008092491	0.0014894625	0.009836775	0.003450073
5	90/10, W5	0.016138195	0.015386649	0.0026461638	0.032679064	0.006766973
6	90/10, W10	0.003891503	0.017731965	0.0027856993	0.021301828	0.004186114
7	90/10, W15	0.015220220	0.013967393	0.0021128572	0.015727752	0.006540607
8	80/20, W5	0.019703134	0.022612328	0.0033410382	0.024226510	0.006884641
9	80/20, W10	0.005560384	0.010032489	0.0016398483	0.013755337	0.002870456
10	60/40, W5	0.034496538	0.016641448	0.0026792447	0.016914861	0.009542071
11	60/40, W10	0.008112385	0.002845982	0.0001930997	0.001746209	0.001760702

E DIC Images

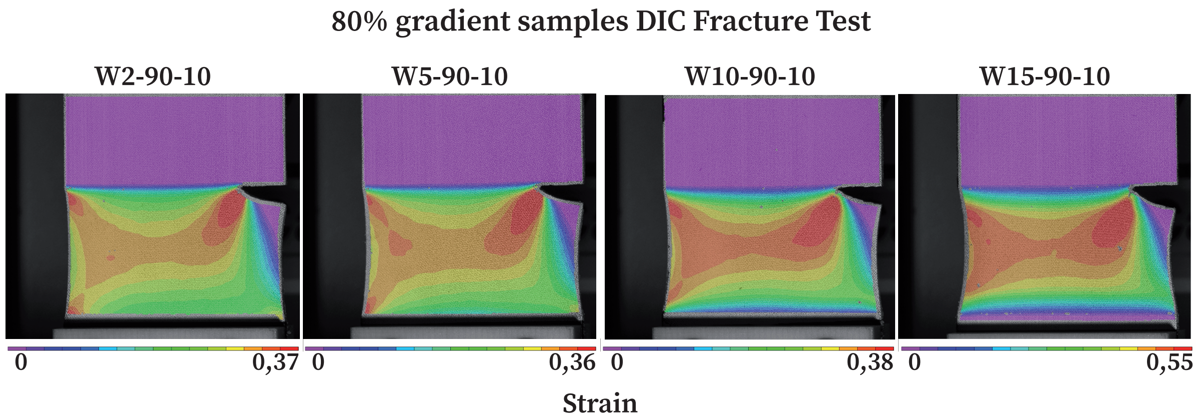

Figure 31: *80 % gradient specimens DIC Fracture Test*

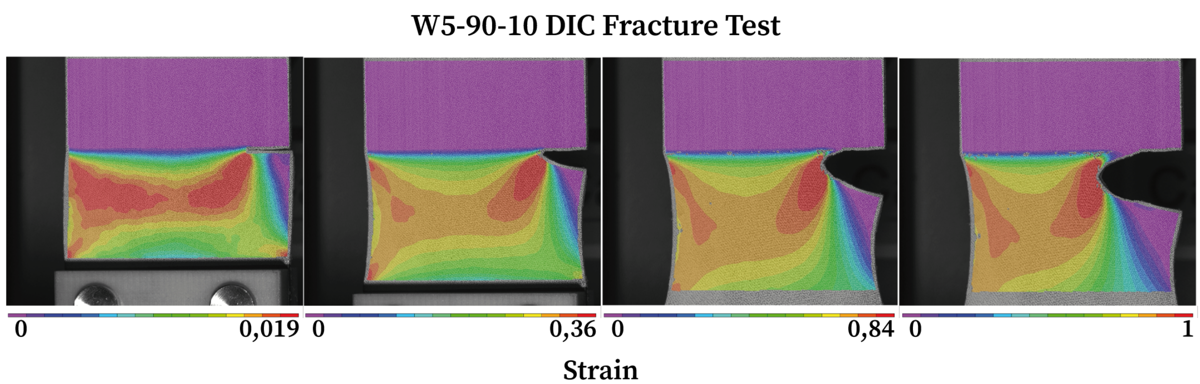

Figure 32: *W5-90-10 DIC Fracture Test*

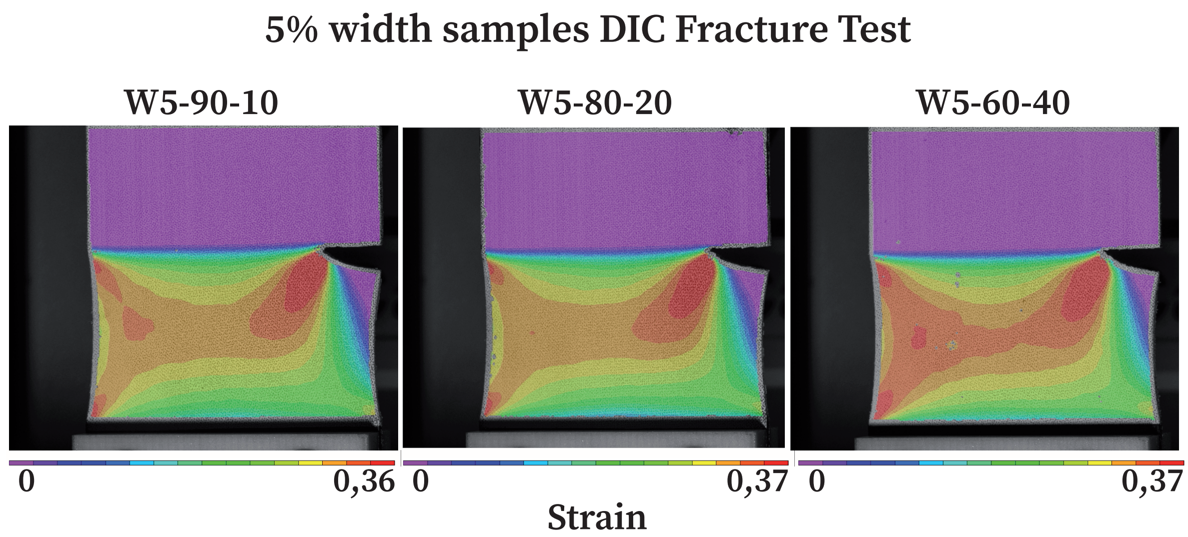

Figure 33: *5% width samples DIC Fracture Test*

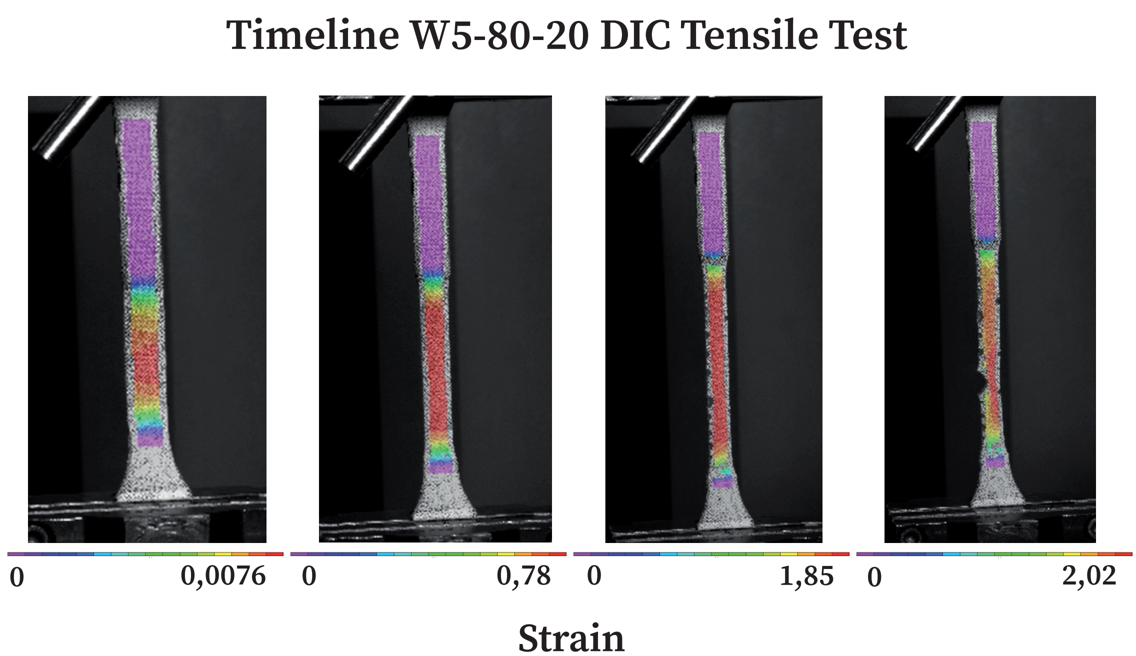

Figure 34: *Timeline of the DIC Tensile Test*

F R-Code

This code has been used to process the data retrieved from the tensile tests. Except for graph titles and axis range, the code for the fracture tests is exactly the same.

```r
#################################################################
# read data
#library(extrafont) # load fonts (Helvetica)
#################################################################
# Fracture Tests
rm(list=ls())
t=3        #dikte sample
W=75       #totale breedte
10 <- 75   #taken from the center of the holes for the screws
cracklength <- 15
area <- t * (W- cracklength)
setwd("C:/Users/Rob/Desktop/BEP_BioMech/Eindcode/")
######################################
### Horizontal Gradient
######################################

# Soft-Soft
SS.1<-read.table(file = "S0_d100_1.txt",header=TRUE, sep="\t")
SS.1[,length(SS.1)+1]<-data.frame(stress= (SS.1$Load..N.)/area)
SS.1[,length(SS.1)+1]<-data.frame(strain = SS.1$Deflection.from.Preload..mm./10)

SS.2<-read.table(file = "S0_d100_2.txt",header=TRUE, sep="\t")
SS.2[,length(SS.2)+1]<-data.frame(stress= (SS.2$Load..N.)/area)
SS.2[,length(SS.2)+1]<-data.frame(strain = SS.2$Deflection.from.Preload..mm./10)

SS.3<-read.table(file = "S0_d100_3.txt",header=TRUE, sep="\t")
SS.3[,length(SS.3)+1]<-data.frame(stress= (SS.3$Load..N.)/area)
SS.3[,length(SS.3)+1]<-data.frame(strain = SS.3$Deflection.from.Preload..mm./10)

# Hard-Hard
HH.1<-read.table(file = "S0_d0_1.txt",header=TRUE, sep="\t")
HH.1[,length(HH.1)+1]<-data.frame(stress= (HH.1$Load..N.)/area)
HH.1[,length(HH.1)+1]<-data.frame(strain = HH.1$Deflection.from.Preload..mm./10)

HH.2<-read.table(file = "S0_d0_2.txt",header=TRUE, sep="\t")
HH.2[,length(HH.2)+1]<-data.frame(stress= (HH.2$Load..N.)/area)
HH.2[,length(HH.2)+1]<-data.frame(strain = HH.2$Deflection.from.Preload..mm./10)

HH.3<-read.table(file = "S0_d0_3.txt",header=TRUE, sep="\t")
HH.3[,length(HH.3)+1]<-data.frame(stress= (HH.3$Load..N.)/area)
HH.3[,length(HH.3)+1]<-data.frame(strain = HH.3$Deflection.from.Preload..mm./10)


# 0-meting
HS.1<-read.table(file = "Linear_Hard_soft_H_1.txt",header=TRUE, sep="\t")
HS.1[,length(HS.1)+1]<-data.frame(stress= (HS.1$Load..N.)/area)
HS.1[,length(HS.1)+1]<-data.frame(strain = HS.1$Deflection.from.Preload..mm./10)

HS.2<-read.table(file = "Linear_Hard_soft_H_2.txt",header=TRUE, sep="\t")
HS.2[,length(HS.2)+1]<-data.frame(stress= (HS.2$Load..N.)/area)
HS.2[,length(HS.2)+1]<-data.frame(strain = HS.2$Deflection.from.Preload..mm./10)

HS.3<-read.table(file = "Linear_Hard_soft_H_3.txt",header=TRUE, sep="\t")
HS.3[,length(HS.3)+1]<-data.frame(stress= (HS.3$Load..N.)/area)
HS.3[,length(HS.3)+1]<-data.frame(strain = HS.3$Deflection.from.Preload..mm./10)

#

W2.90.10.1<-read.table(file = "W2_90_10_1.txt",header=TRUE, sep="\t")
W2.90.10.1[,length(W2.90.10.1)+1]<-data.frame(stress= (W2.90.10.1$Load..N.)/area)
W2.90.10.1[,length(W2.90.10.1)+1]<-data.frame(strain = W2.90.10.1$Deflection.from.Preload..mm./10)

W2.90.10.2<-read.table(file = "W2_90_10_2.txt",header=TRUE, sep="\t")
W2.90.10.2[,length(W2.90.10.2)+1]<-data.frame(stress= (W2.90.10.2$Load..N.)/area)
W2.90.10.2[,length(W2.90.10.2)+1]<-data.frame(strain = W2.90.10.2$Deflection.from.Preload..mm./10)

W2.90.10.3<-read.table(file = "W2_90_10_3.txt",header=TRUE, sep="\t")
W2.90.10.3[,length(W2.90.10.3)+1]<-data.frame(stress= (W2.90.10.3$Load..N.)/area)
W2.90.10.3[,length(W2.90.10.3)+1]<-data.frame(strain = W2.90.10.3$Deflection.from.Preload..mm./10)

#

W5.60.40.1<-read.table(file = "W5_60_40_1.txt",header=TRUE, sep="\t")
W5.60.40.1[,length(W5.60.40.1)+1]<-data.frame(stress= (W5.60.40.1$Load..N.)/area)
W5.60.40.1[,length(W5.60.40.1)+1]<-data.frame(strain = W5.60.40.1$Deflection.from.Preload..mm./10)

W5.60.40.2<-read.table(file = "W5_60_40_2.txt",header=TRUE, sep="\t")
W5.60.40.2[,length(W5.60.40.2)+1]<-data.frame(stress= (W5.60.40.2$Load..N.)/area)
W5.60.40.2[,length(W5.60.40.2)+1]<-data.frame(strain = W5.60.40.2$Deflection.from.Preload..mm./10)

W5.60.40.3<-read.table(file = "W5_60_40_3.txt",header=TRUE, sep="\t")
W5.60.40.3[,length(W5.60.40.3)+1]<-data.frame(stress= (W5.60.40.3$Load..N.)/area)
W5.60.40.3[,length(W5.60.40.3)+1]<-data.frame(strain = W5.60.40.3$Deflection.from.Preload..mm./10)

W5.80.20.1<-read.table(file = "W5_80_20_1.txt",header=TRUE, sep="\t")
W5.80.20.1[,length(W5.80.20.1)+1]<-data.frame(stress= (W5.80.20.1$Load..N.)/area)
W5.80.20.1[,length(W5.80.20.1)+1]<-data.frame(strain = W5.80.20.1$Deflection.from.Preload..mm./10)

W5.80.20.2<-read.table(file = "W5_80_20_2.txt",header=TRUE, sep="\t")
W5.80.20.2[,length(W5.80.20.2)+1]<-data.frame(stress= (W5.80.20.2$Load..N.)/area)
W5.80.20.2[,length(W5.80.20.2)+1]<-data.frame(strain = W5.80.20.2$Deflection.from.Preload..mm./10)

W5.80.20.3<-read.table(file = "W5_80_20_3.txt",header=TRUE, sep="\t")
W5.80.20.3[,length(W5.80.20.3)+1]<-data.frame(stress= (W5.80.20.3$Load..N.)/area)
W5.80.20.3[,length(W5.80.20.3)+1]<-data.frame(strain = W5.80.20.3$Deflection.from.Preload..mm./10)

W5.90.10.1<-read.table(file = "W5_90_10_1.txt",header=TRUE, sep="\t")
W5.90.10.1[,length(W5.90.10.1)+1]<-data.frame(stress= (W5.90.10.1$Load..N.)/area)
W5.90.10.1[,length(W5.90.10.1)+1]<-data.frame(strain = W5.90.10.1$Deflection.from.Preload..mm./10)

W5.90.10.2<-read.table(file = "W5_90_10_2.txt",header=TRUE, sep="\t")
```

```
W5.90.10.2[,length(W5.90.10.2)+1]<-data.frame(stress= (W5.90.10.2$Load..N.)/area)
W5.90.10.2[,length(W5.90.10.2)+1]<-data.frame(strain = W5.90.10.2$Deflection.from.Preload..mm./10)

W5.90.10.3<-read.table(file = "W5_90_10_3.txt",header=TRUE,sep="\t")
W5.90.10.3[,length(W5.90.10.3)+1]<-data.frame(stress= (W5.90.10.3$Load..N.)/area)
W5.90.10.3[,length(W5.90.10.3)+1]<-data.frame(strain = W5.90.10.3$Deflection.from.Preload..mm./10)

#

W10.60.40.1<-read.table(file = "W10_60_40_1.txt",header=TRUE,sep="\t")
W10.60.40.1[,length(W10.60.40.1)+1]<-data.frame(stress= (W10.60.40.1$Load..N.)/area)
W10.60.40.1[,length(W10.60.40.1)+1]<-data.frame(strain = W10.60.40.1$Deflection.from.Preload..mm./10)

W10.60.40.2<-read.table(file = "W10_60_40_2.txt",header=TRUE,sep="\t")
W10.60.40.2[,length(W10.60.40.2)+1]<-data.frame(stress= (W10.60.40.2$Load..N.)/area)
W10.60.40.2[,length(W10.60.40.2)+1]<-data.frame(strain = W10.60.40.2$Deflection.from.Preload..mm./10)

W10.60.40.3<-read.table(file = "W10_60_40_3.txt",header=TRUE,sep="\t")
W10.60.40.3[,length(W10.60.40.3)+1]<-data.frame(stress= (W10.60.40.3$Load..N.)/area)
W10.60.40.3[,length(W10.60.40.3)+1]<-data.frame(strain = W10.60.40.3$Deflection.from.Preload..mm./10)

W10.80.20.1<-read.table(file = "W10_80_20_1.txt",header=TRUE,sep="\t")
W10.80.20.1[,length(W10.80.20.1)+1]<-data.frame(stress= (W10.80.20.1$Load..N.)/area)
W10.80.20.1[,length(W10.80.20.1)+1]<-data.frame(strain = W10.80.20.1$Deflection.from.Preload..mm./10)

W10.80.20.2<-read.table(file = "W10_80_20_2.txt",header=TRUE,sep="\t")
W10.80.20.2[,length(W10.80.20.2)+1]<-data.frame(stress= (W10.80.20.2$Load..N.)/area)
W10.80.20.2[,length(W10.80.20.2)+1]<-data.frame(strain = W10.80.20.2$Deflection.from.Preload..mm./10)

W10.80.20.3<-read.table(file = "W10_80_20_3.txt",header=TRUE,sep="\t")
W10.80.20.3[,length(W10.80.20.3)+1]<-data.frame(stress= (W10.80.20.3$Load..N.)/area)
W10.80.20.3[,length(W10.80.20.3)+1]<-data.frame(strain = W10.80.20.3$Deflection.from.Preload..mm./10)

W10.90.10.1<-read.table(file = "W10_90_10_1.txt",header=TRUE,sep="\t")
W10.90.10.1[,length(W10.90.10.1)+1]<-data.frame(stress= (W10.90.10.1$Load..N.)/area)
W10.90.10.1[,length(W10.90.10.1)+1]<-data.frame(strain = W10.90.10.1$Deflection.from.Preload..mm./10)

W10.90.10.2<-read.table(file = "W10_90_10_2.txt",header=TRUE,sep="\t")
W10.90.10.2[,length(W10.90.10.2)+1]<-data.frame(stress= (W10.90.10.2$Load..N.)/area)
W10.90.10.2[,length(W10.90.10.2)+1]<-data.frame(strain = W10.90.10.2$Deflection.from.Preload..mm./10)

W10.90.10.3<-read.table(file = "W10_90_10_3.txt",header=TRUE,sep="\t")
W10.90.10.3[,length(W10.90.10.3)+1]<-data.frame(stress= (W10.90.10.3$Load..N.)/area)
W10.90.10.3[,length(W10.90.10.3)+1]<-data.frame(strain = W10.90.10.3$Deflection.from.Preload..mm./10)

#

W15.90.10.1<-read.table(file = "W15_90_10_1.txt",header=TRUE,sep="\t")
W15.90.10.1[,length(W15.90.10.1)+1]<-data.frame(stress= (W15.90.10.1$Load..N.)/area)
W15.90.10.1[,length(W15.90.10.1)+1]<-data.frame(strain = W15.90.10.1$Deflection.from.Preload..mm./10)

W15.90.10.2<-read.table(file = "W15_90_10_2.txt",header=TRUE,sep="\t")
W15.90.10.2[,length(W15.90.10.2)+1]<-data.frame(stress= (W15.90.10.2$Load..N.)/area)
W15.90.10.2[,length(W15.90.10.2)+1]<-data.frame(strain = W15.90.10.2$Deflection.from.Preload..mm./10)

W15.90.10.3<-read.table(file = "W15_90_10_3.txt",header=TRUE,sep="\t")
W15.90.10.3[,length(W15.90.10.3)+1]<-data.frame(stress= (W15.90.10.3$Load..N.)/area)
W15.90.10.3[,length(W15.90.10.3)+1]<-data.frame(strain = W15.90.10.3$Deflection.from.Preload..mm./10)

##plots
plot(W15.90.10.1$strain,W15.90.10.1$stress, type = 'l')
lines(W15.90.10.2$strain,W15.90.10.2$stress,col="red")
lines(W15.90.10.3$strain,W15.90.10.3$stress,col="cyan")

plot(W10.90.10.1$strain,W10.90.10.1$stress, type = 'l')
lines(W10.90.10.2$strain,W10.90.10.2$stress,col="red")
lines(W10.90.10.3$strain,W10.90.10.3$stress,col="cyan")

plot(W10.80.20.1$strain,W10.80.20.1$stress, type = 'l')
lines(W10.80.20.2$strain,W10.80.20.2$stress,col="red")
lines(W10.80.20.3$strain,W10.80.20.3$stress,col="cyan")

plot(W10.60.40.1$strain,W10.60.40.1$stress, type = 'l')
lines(W10.60.40.2$strain,W10.60.40.2$stress,col="red")
lines(W10.60.40.3$strain,W10.60.40.3$stress,col="cyan")

plot(W5.90.10.1$strain,W5.90.10.1$stress, type = 'l')
lines(W5.90.10.2$strain,W5.90.10.2$stress,col="red")
lines(W5.90.10.3$strain,W5.90.10.3$stress,col="cyan")

plot(W5.80.20.1$strain,W5.80.20.1$stress, type = 'l')
lines(W5.80.20.2$strain,W5.80.20.2$stress,col="red")
lines(W5.80.20.3$strain,W5.80.20.3$stress,col="cyan")

plot(W5.60.40.1$strain,W5.60.40.1$stress, type = 'l')
lines(W5.60.40.2$strain,W5.60.40.2$stress,col="red")
lines(W5.60.40.3$strain,W5.60.40.3$stress,col="cyan")

plot(W2.90.10.1$strain,W2.90.10.1$stress, type = 'l')
lines(W2.90.10.2$strain,W2.90.10.2$stress,col="red")
lines(W2.90.10.3$strain,W2.90.10.3$stress,col="cyan")


xlim <- c(0, 0.4)
ylim <- c(0, 0.45)
grid(nx = NULL, ny= NULL, col = "lightgray", lty = "dotted",
     lwd = par("lwd"), equilogs = TRUE)


###########################################
## Functions to calculate the properties ##
###########################################

#### Fracture Toughness

require(pracma)
getFractureToughness<- function (strain,stress){
```

```
  x <- c(strain[2:(length(strain)-1)])                    #-1 omdat er een laatste NA was, bij beide er 1 af
  y <- c(stress[2:(length(stress)-1)])
  FractureToughness <- trapz(x, y) #MJ/m^3
  return(FractureToughness)
}


##########################################
##New function for Youngs modulus (3/11)
#In this function we change the stepsize, it is the window in which the young's modulus is performed
defmovingregression <- function(xdata, ydata, stepsize, inverse=TRUE){

  # if (inverse): not the steepest but the most plane slope is searched
  #xdata = array(xdata)
  #ydata = array(ydata)
  xdata <- xdata[!is.na(xdata)]
  ydata <- ydata[!is.na(ydata)]

  #### Strain at max stress
  maxxdata <- xdata[which.max(ydata)] #The value of the strain at the max stress

  #### Max stress en bijbehorende strain (y)
  xdata <- xdata[xdata<=maxxdata]
  ydata <- ydata[0:which.max(ydata)]


  print (length(ydata))
  print (length(xdata))
  #print(data.S1d25.1$stress<)


  if (inverse == TRUE){
    slope = 0.0
    intercept = 0.0

    for (i in 1:(length(xdata))){
      if (i > length(xdata) - stepsize){
        testslope = sum(dot((xdata[(i - stepsize):i] - mean(xdata[(i - stepsize):i])),
        (ydata[(i - stepsize):i] - mean(ydata[(i - stepsize):i]))))/sum((xdata[(i - stepsize):i]
        - mean(xdata[(i - stepsize):i]))**2)
        testintercept = mean(ydata[(i - stepsize):i]) - testslope*mean(xdata[(i - stepsize):i])
      }
      else if ((i > stepsize) && (i < length(xdata) - stepsize)){
        testslope = sum(dot((xdata[(i - stepsize):(i + stepsize)]
        - mean(xdata[(i - stepsize):(i + stepsize)])), (ydata[(i - stepsize):(i + stepsize)]
        - mean(ydata[(i - stepsize):(i + stepsize)]))))/sum((xdata[(i - stepsize):(i + stepsize)] - mean(xdata[(i - stepsize):(i + stepsize)]))**2)
        testintercept = mean(ydata[(i - stepsize):(i + stepsize)])
        - testslope*mean(xdata[(i - stepsize):(i + stepsize)])
      }

      else if (i < stepsize){
        testslope = sum(dot((xdata[i:(i + stepsize)] - mean(xdata[i:(i + stepsize)])),
        (ydata[i:(i + stepsize)] - mean(ydata[i:(i + stepsize)]))))/sum((xdata[i:(i + stepsize)]
        - mean(xdata[i:(i + stepsize)]))**2)
        testintercept = mean(ydata[i:(i + stepsize)]) - testslope*mean(xdata[i:(i + stepsize)])
      }


      if (testslope >= slope){
        slope = testslope
        intercept = testintercept
      }
    }
  }

  if (inverse==FALSE){
    slope = 100000.0
    intercept = 100000.0

    for (i in 1:(length(xdata))){

      if (i > length(xdata) - stepsize){
        testslope = sum(dot((xdata[(i - stepsize):i] - mean(xdata[(i - stepsize):i])),
        (ydata[(i - stepsize):i] - mean(ydata[(i - stepsize):i]))))/sum((xdata[(i - stepsize):i]
        - mean(xdata[(i - stepsize):i]))**2)
        testintercept = mean(ydata[(i - stepsize):i]) - testslope*mean(xdata[(i - stepsize):i])

      }
      else if ((i > stepsize) && (i < length(xdata) - stepsize)){

        testslope = sum(dot((xdata[(i - stepsize):(i + stepsize)]
        - mean(xdata[(i - stepsize):(i + stepsize)])), (ydata[(i - stepsize):(i + stepsize)]
        - mean(ydata[(i - stepsize):(i + stepsize)]))))/sum((xdata[(i - stepsize):(i + stepsize)]
        - mean(xdata[(i - stepsize):(i + stepsize)]))**2)
        testintercept = mean(ydata[(i - stepsize):(i + stepsize)])
        - testslope*mean(xdata[(i - stepsize):(i + stepsize)])
      }
      else if (i < stepsize){
        testslope = sum(dot((xdata[i:(i + stepsize)] - mean(xdata[i:(i + stepsize)])),
        (ydata[i:(i + stepsize)] - mean(ydata[i:(i + stepsize)]))))/sum((xdata[i:(i + stepsize)]
        - mean(xdata[i:(i + stepsize)]))**2)
        testintercept = mean(ydata[i:(i + stepsize)]) - testslope*mean(xdata[i:(i + stepsize)])
      }

      if (testslope <= slope){
        slope = testslope
        intercept = testintercept
      }
    }
  }
  print (slope)
  return(c(slope, intercept))

}


#Function to check the new young's modulus
```

```
Youngs_plots <- function(sample, strain, stress, res){

  #sample<-"sample"
  pdf(file = paste("stiffnessplots_Fracture/",sample,".pdf",sep=""), width=6,height=3, bg="transparent")
  plot(strain,stress,
       #plot(strain, stress,
       #xlab ="Strain [%]" ,ylab = "Stress [MPa]",
       main =sprintf("Youngs_Modulus_check_for_%s_.",sample) ,cex=1,tck=0.02)

  lines(c(0,0.3),c(res[2],0.3*(res[1])+res[2]),col="red") #this only affects the visualization
  points(0.3,0.3*(res[1])+res[2],col="red")


  dev.off()}

##Ultimate strength
Ultimate.Strength <- function (stress) {
  max_stress <- max(stress, na.rm=TRUE)
  return(max_stress)
}

#The value of the strain at the max stress
Strain.Max.Stress <- function (xdata, ydata) {
maxxdata <- xdata[which.max(ydata)]
xdata <- xdata[xdata<=maxxdata]
ydata <- ydata[0:which.max(ydata)]
return(maxxdata)
}

##maxstrain
Max.Strain <- function (strain) {
  max_strain <- max(strain, na.rm=TRUE)
  return(max_strain)
}

 ###############################################################
  #### Make data file


  Samplenames          <-   c('SS.1' , 'SS.2' , 'SS.3',
                              'HH.1' , 'HH.2' , 'HH.3',
                              'HS.1' , 'HS.2' , 'HS.3',
                              'W2.90.10.1' , 'W2.90.10.2' , 'W2.90.10.3' ,
                              'W5.60.40.1' , 'W5.60.40.2' , 'W5.60.40.3' ,
                              'W5.80.20.1' , 'W5.80.20.2' , 'W5.80.20.3' ,
                              'W5.90.10.1' , 'W5.90.10.2' , 'W5.90.10.3' ,
                              'W10.60.40.1' , 'W10.60.40.2' , 'W10.60.40.3' ,
                              'W10.80.20.1' , 'W10.80.20.2' , 'W10.80.20.3' ,
                              'W10.90.10.1' , 'W10.90.10.2' , 'W10.90.10.3' ,
                              'W15.90.10.1' , 'W15.90.10.2' , 'W15.90.10.3'  )

  Samplefactors        <-   c('W0',  'W0',  'W0',
                              'W0',  'W0',  'W0',
                              'W0',  'W0',  'W0',
                              'W2',  'W2',  'W2',
                              'W5',  'W5',  'W5',
                              'W5',  'W5',  'W5',
                              'W5',  'W5',  'W5',
                              'W10', 'W10', 'W10',
                              'W10', 'W10', 'W10',
                              'W10', 'W10', 'W10',
                              'W15', 'W15', 'W15')

  Samplegradients    <-   c('0/0' , '0/0' , '0/0',
                             '100/100', '100/100', '100/100',
                             '100/0' , '100/0', '100/0',
                            '90/10', '90/10', '90/10',
                             '60/40', '60/40', '60/40',
                             '80/20', '80/20', '80/20',
                             '90/10', '90/10', '90/10',
                             '60/40', '60/40', '60/40',
                             '80/20', '80/20', '80/20',
                             '90/10', '90/10', '90/10',
                             '90/10', '90/10', '90/10')


############################################
#W0

  E_SS_1 <- defmovingregression(SS.1$strain,SS.1$stress,length(SS.1$strain) - length(which(round(SS.1$strain,4) >= 0.1)) ,TRUE)
  Echeck_SS_1 <-Youngs_plots('SS_1',SS.1$strain,SS.1$stress,E_SS_1)

  E_SS_2 <- defmovingregression(SS.2$strain,SS.2$stress,length(SS.2$strain) - length(which(round(SS.2$strain,4) >= 0.1)) ,TRUE)
  Echeck_SS_2 <-Youngs_plots('SS_2',SS.2$strain,SS.2$stress,E_SS_2)

  E_SS_3 <- defmovingregression(SS.3$strain,SS.3$stress,length(SS.3$strain) - length(which(round(SS.3$strain,4) >= 0.1)) ,TRUE)
  Echeck_SS_3 <-Youngs_plots('SS_3',SS.3$strain,SS.3$stress,E_SS_3)


  E_HH_1 <- defmovingregression(HH.1$strain,HH.1$stress,length(HH.1$strain) - length(which(round(HH.1$strain,4) >= 0.005)) ,TRUE)
  Echeck_HH_1 <-Youngs_plots('HH_1',HH.1$strain,HH.1$stress,E_HH_1)

  E_HH_2 <- defmovingregression(HH.2$strain,HH.2$stress,length(HH.2$strain) - length(which(round(HH.2$strain,4) >= 0.005)) ,TRUE)
  Echeck_HH_2 <-Youngs_plots('HH_2',HH.2$strain,HH.2$stress,E_HH_2)

  E_HH_3 <- defmovingregression(HH.3$strain,HH.3$stress,length(HH.3$strain) - length(which(round(HH.3$strain,4) >= 0.005)) ,TRUE)
  Echeck_HH_3 <-Youngs_plots('HH_3',HH.3$strain,HH.3$stress,E_HH_3)



 E_HS_1 <- defmovingregression(HS.1$strain,HS.1$stress,length(HS.1$strain) - length(which(round(HS.1$strain,4) >= 0.1)) ,TRUE)
  Echeck_HS_1 <-Youngs_plots('HS_1',HS.1$strain,HS.1$stress,E_HS_1)

  E_HS_2 <- defmovingregression(HS.2$strain,HS.2$stress,length(HS.2$strain) - length(which(round(HS.2$strain,4) >= 0.1)) ,TRUE)
  Echeck_HS_2 <-Youngs_plots('HS_2',HS.2$strain,HS.2$stress,E_HS_2)
```

```
E_HS_3 <- defmovingregression(HS.3$strain ,HS.3$stress ,length(HS.3$strain) - length(which(round(HS.3$strain ,4) >= 0.1)) ,TRUE)
Echeck_HS_3 <-Youngs_plots('HS_3',HS.3$strain ,HS.3$stress ,E_HS_3)

#W2
E_W2_90_10_1 <- defmovingregression(W2.90.10.1$strain ,W2.90.10.1$stress ,length(W2.90.10.1$strain) - length(which(round(W2.90.10.1$strain ,4) >= 0.1)) ,TRUE)
Echeck_W2_90_10_1 <-Youngs_plots('W2_90_10_1',W2.90.10.1$strain ,W2.90.10.1$stress ,E_W2_90_10_1)

E_W2_90_10_2 <- defmovingregression(W2.90.10.2$strain ,W2.90.10.2$stress ,length(W2.90.10.2$strain) - length(which(round(W2.90.10.2$strain ,4) >= 0.1)) ,TRUE)
Echeck_W2_90_10_2 <-Youngs_plots('W2_90_10_2',W2.90.10.2$strain ,W2.90.10.2$stress ,E_W2_90_10_2)

E_W2_90_10_3 <- defmovingregression(W2.90.10.3$strain ,W2.90.10.3$stress ,length(W2.90.10.3$strain) - length(which(round(W2.90.10.3$strain ,4) >= 0.1)) ,TRUE)
Echeck_W2_90_10_3 <-Youngs_plots('W2_90_10_3',W2.90.10.3$strain ,W2.90.10.3$stress ,E_W2_90_10_3)

#W5

E_W5_90_10_1 <- defmovingregression(W5.90.10.1$strain ,W5.90.10.1$stress ,length(W5.90.10.1$strain) - length(which(round(W5.90.10.1$strain ,4) >= 0.1)) ,TRUE)
Echeck_W5_90_10_1 <-Youngs_plots('W5_90_10_1',W5.90.10.1$strain ,W5.90.10.1$stress ,E_W5_90_10_1)

E_W5_90_10_2 <- defmovingregression(W5.90.10.2$strain ,W5.90.10.2$stress ,length(W5.90.10.2$strain) - length(which(round(W5.90.10.2$strain ,4) >= 0.1)) ,TRUE)
Echeck_W5_90_10_2 <-Youngs_plots('W5_90_10_2',W5.90.10.2$strain ,W5.90.10.2$stress ,E_W5_90_10_2)

E_W5_90_10_3 <- defmovingregression(W5.90.10.3$strain ,W5.90.10.3$stress ,length(W5.90.10.3$strain) - length(which(round(W5.90.10.3$strain ,4) >= 0.1)) ,TRUE)
Echeck_W5_90_10_3 <-Youngs_plots('W5_90_10_3',W5.90.10.3$strain ,W5.90.10.3$stress ,E_W5_90_10_3)


E_W5_80_20_1 <- defmovingregression(W5.80.20.1$strain ,W5.80.20.1$stress ,length(W5.80.20.1$strain) - length(which(round(W5.80.20.1$strain ,4) >= 0.1)) ,TRUE)
Echeck_W5_80_20_1 <-Youngs_plots('W5_80_20_1',W5.80.20.1$strain ,W5.80.20.1$stress ,E_W5_80_20_1)

E_W5_80_20_2 <- defmovingregression(W5.80.20.2$strain ,W5.80.20.2$stress ,length(W5.80.20.2$strain) - length(which(round(W5.80.20.2$strain ,4) >= 0.1)) ,TRUE)
Echeck_W5_80_20_2 <-Youngs_plots('W5_80_20_2',W5.80.20.2$strain ,W5.80.20.2$stress ,E_W5_80_20_2)

E_W5_80_20_3 <- defmovingregression(W5.80.20.3$strain ,W5.80.20.3$stress ,length(W5.80.20.3$strain) - length(which(round(W5.80.20.3$strain ,4) >= 0.1)) ,TRUE)
Echeck_W5_80_20_3 <-Youngs_plots('W5_80_20_3',W5.80.20.3$strain ,W5.80.20.3$stress ,E_W5_80_20_3)


E_W5_60_40_1 <- defmovingregression(W5.60.40.1$strain ,W5.60.40.1$stress ,length(W5.60.40.1$strain) - length(which(round(W5.60.40.1$strain ,4) >= 0.1)) ,TRUE)
Echeck_W5_60_40_1 <-Youngs_plots('W5_60_40_1',W5.60.40.1$strain ,W5.60.40.1$stress ,E_W5_60_40_1)

E_W5_60_40_2 <- defmovingregression(W5.60.40.2$strain ,W5.60.40.2$stress ,length(W5.60.40.2$strain) - length(which(round(W5.60.40.2$strain ,4) >= 0.1)) ,TRUE)
Echeck_W5_60_40_2 <-Youngs_plots('W5_60_40_2',W5.60.40.2$strain ,W5.60.40.2$stress ,E_W5_60_40_2)

E_W5_60_40_3 <- defmovingregression(W5.60.40.3$strain ,W5.60.40.3$stress ,length(W5.60.40.3$strain) - length(which(round(W5.60.40.3$strain ,4) >= 0.1)) ,TRUE)
Echeck_W5_60_40_3 <-Youngs_plots('W5_60_40_3',W5.60.40.3$strain ,W5.60.40.3$stress ,E_W5_60_40_3)

#W10

E_W10_90_10_1 <- defmovingregression(W10.90.10.1$strain ,W10.90.10.1$stress ,length(W10.90.10.1$strain) - length(which(round(W10.90.10.1$strain ,4) >= 0.1)) ,TRUE)
Echeck_W10_90_10_1 <-Youngs_plots('W10_90_10_1',W10.90.10.1$strain ,W10.90.10.1$stress ,E_W10_90_10_1)

E_W10_90_10_2 <- defmovingregression(W10.90.10.2$strain ,W10.90.10.2$stress ,length(W10.90.10.2$strain) - length(which(round(W10.90.10.2$strain ,4) >= 0.1)) ,TRUE)
Echeck_W10_90_10_2 <-Youngs_plots('W10_90_10_2',W10.90.10.2$strain ,W10.90.10.2$stress ,E_W10_90_10_2)

E_W10_90_10_3 <- defmovingregression(W10.90.10.3$strain ,W10.90.10.3$stress ,length(W10.90.10.3$strain) - length(which(round(W10.90.10.3$strain ,4) >= 0.1)) ,TRUE)
Echeck_W10_90_10_3 <-Youngs_plots('W10_90_10_3',W10.90.10.3$strain ,W10.90.10.3$stress ,E_W10_90_10_3)


E_W10_80_20_1 <- defmovingregression(W10.80.20.1$strain ,W10.80.20.1$stress ,length(W10.80.20.1$strain) - length(which(round(W10.80.20.1$strain ,4) >= 0.1)) ,TRUE)
Echeck_W10_80_20_1 <-Youngs_plots('W10_80_20_1',W10.80.20.1$strain ,W10.80.20.1$stress ,E_W10_80_20_1)

E_W10_80_20_2 <- defmovingregression(W10.80.20.2$strain ,W10.80.20.2$stress ,length(W10.80.20.2$strain) - length(which(round(W10.80.20.2$strain ,4) >= 0.1)) ,TRUE)
Echeck_W10_80_20_2 <-Youngs_plots('W10_80_20_2',W10.80.20.2$strain ,W10.80.20.2$stress ,E_W10_80_20_2)

E_W10_80_20_3 <- defmovingregression(W10.80.20.3$strain ,W10.80.20.3$stress ,length(W10.80.20.3$strain) - length(which(round(W10.80.20.3$strain ,4) >= 0.1)) ,TRUE)
Echeck_W10_80_20_3 <-Youngs_plots('W10_80_20_3',W10.80.20.3$strain ,W10.80.20.3$stress ,E_W10_80_20_3)


E_W10_60_40_1 <- defmovingregression(W10.60.40.1$strain ,W10.60.40.1$stress ,length(W10.60.40.1$strain) - length(which(round(W10.60.40.1$strain ,4) >= 0.1)) ,TRUE)
Echeck_W10_60_40_1 <-Youngs_plots('W10_60_40_1',W10.60.40.1$strain ,W10.60.40.1$stress ,E_W10_60_40_1)

E_W10_60_40_2 <- defmovingregression(W10.60.40.2$strain ,W10.60.40.2$stress ,length(W10.60.40.2$strain) - length(which(round(W10.60.40.2$strain ,4) >= 0.1)) ,TRUE)
Echeck_W10_60_40_2 <-Youngs_plots('W10_60_40_2',W10.60.40.2$strain ,W10.60.40.2$stress ,E_W10_60_40_2)

E_W10_60_40_3 <- defmovingregression(W10.60.40.3$strain ,W10.60.40.3$stress ,length(W10.60.40.3$strain) - length(which(round(W10.60.40.3$strain ,4) >= 0.1)) ,TRUE)
Echeck_W10_60_40_3 <-Youngs_plots('W10_60_40_3',W10.60.40.3$strain ,W10.60.40.3$stress ,E_W10_60_40_3)

#W15

E_W15_90_10_1 <- defmovingregression(W15.90.10.1$strain ,W15.90.10.1$stress ,length(W15.90.10.1$strain) - length(which(round(W15.90.10.1$strain ,4) >= 0.1)) ,TRUE)
Echeck_W15_90_10_1 <-Youngs_plots('W15_90_10_1',W15.90.10.1$strain ,W15.90.10.1$stress ,E_W15_90_10_1)

E_W15_90_10_2 <- defmovingregression(W15.90.10.2$strain ,W15.90.10.2$stress ,length(W15.90.10.2$strain) - length(which(round(W15.90.10.2$strain ,4) >= 0.1)) ,TRUE)
Echeck_W15_90_10_2 <-Youngs_plots('W15_90_10_2',W15.90.10.2$strain ,W15.90.10.2$stress ,E_W15_90_10_2)

E_W15_90_10_3 <- defmovingregression(W15.90.10.3$strain ,W15.90.10.3$stress ,length(W15.90.10.3$strain) - length(which(round(W15.90.10.3$strain ,4) >= 0.1)) ,TRUE)
Echeck_W15_90_10_3 <-Youngs_plots('W15_90_10_3',W15.90.10.3$strain ,W15.90.10.3$stress ,E_W15_90_10_3)

#combine

E_all <-c(E_SS_1, E_SS_2, E_SS_3,
          E_HH_1, E_HH_2, E_HH_3,
          E_HS_1, E_HS_2, E_HS_3,
          E_W2_90_10_1, E_W2_90_10_2, E_W2_90_10_3,
          E_W5_60_40_1, E_W5_60_40_2, E_W5_60_40_3,
          E_W5_80_20_1, E_W5_80_20_2, E_W5_80_20_3,
          E_W5_90_10_1, E_W5_90_10_2, E_W5_90_10_3,
          E_W10_60_40_1, E_W10_60_40_2, E_W10_60_40_3,
          E_W10_80_20_1, E_W10_80_20_2, E_W10_80_20_3,
          E_W10_90_10_1, E_W10_90_10_2, E_W10_90_10_3,
          E_W15_90_10_1, E_W15_90_10_2, E_W15_90_10_3)

#E_all gives two terms for each sample, the youngs modulus values are the last and smallest numbers
E_length <- length(E_all)

  YoungsModulus <- c(E_all[seq(E_length ) %% 2 == 1])

  UltimateStrength      <-  c(Ultimate.Strength(SS.1$stress),
                                Ultimate.Strength(SS.2$stress),
```

```
                          Ultimate.Strength(SS.3$stress),
                          Ultimate.Strength(HH.1$stress),
                          Ultimate.Strength(HH.2$stress),
                          Ultimate.Strength(HH.3$stress),
                          Ultimate.Strength(HS.1$stress),
                          Ultimate.Strength(HS.2$stress),
                          Ultimate.Strength(HS.3$stress),
                          Ultimate.Strength(W2.90.10.1$stress),
                          Ultimate.Strength(W2.90.10.2$stress),
                          Ultimate.Strength(W2.90.10.3$stress),
                          Ultimate.Strength(W5.60.40.1$stress),
                          Ultimate.Strength(W5.60.40.2$stress),
                          Ultimate.Strength(W5.60.40.3$stress),
                          Ultimate.Strength(W5.80.20.1$stress),
                          Ultimate.Strength(W5.80.20.2$stress),
                          Ultimate.Strength(W5.80.20.3$stress),
                          Ultimate.Strength(W5.90.10.1$stress),
                          Ultimate.Strength(W5.90.10.2$stress),
                          Ultimate.Strength(W5.90.10.3$stress),
                          Ultimate.Strength(W10.60.40.1$stress),
                          Ultimate.Strength(W10.60.40.2$stress),
                          Ultimate.Strength(W10.60.40.3$stress),
                          Ultimate.Strength(W10.80.20.1$stress),
                          Ultimate.Strength(W10.80.20.2$stress),
                          Ultimate.Strength(W10.80.20.3$stress),
                          Ultimate.Strength(W10.90.10.1$stress),
                          Ultimate.Strength(W10.90.10.2$stress),
                          Ultimate.Strength(W10.90.10.3$stress),
                          Ultimate.Strength(W15.90.10.1$stress),
                          Ultimate.Strength(W15.90.10.2$stress),
                          Ultimate.Strength(W15.90.10.3$stress))

MaxStrain           <-  c(    Max.Strain(SS.1$strain),
                              Max.Strain(SS.2$strain),
                              Max.Strain(SS.3$strain),
                              Max.Strain(HH.1$strain),
                              Max.Strain(HH.2$strain),
                              Max.Strain(HH.3$strain),

                              Max.Strain(HS.1$strain),
                              Max.Strain(HS.2$strain),
                              Max.Strain(HS.3$strain),
                          Max.Strain(W2.90.10.1$strain),
                          Max.Strain(W2.90.10.2$strain),
                          Max.Strain(W2.90.10.3$strain),
                          Max.Strain(W5.60.40.1$strain),
                          Max.Strain(W5.60.40.2$strain),
                          Max.Strain(W5.60.40.3$strain),
                          Max.Strain(W5.80.20.1$strain),
                          Max.Strain(W5.80.20.2$strain),
                          Max.Strain(W5.80.20.3$strain),
                          Max.Strain(W5.90.10.1$strain),
                          Max.Strain(W5.90.10.2$strain),
                          Max.Strain(W5.90.10.3$strain),
                          Max.Strain(W10.60.40.1$strain),
                          Max.Strain(W10.60.40.2$strain),
                          Max.Strain(W10.60.40.3$strain),
                          Max.Strain(W10.80.20.1$strain),
                          Max.Strain(W10.80.20.2$strain),
                          Max.Strain(W10.80.20.3$strain),
                          Max.Strain(W10.90.10.1$strain),
                          Max.Strain(W10.90.10.2$strain),
                          Max.Strain(W10.90.10.3$strain),
                          Max.Strain(W15.90.10.1$strain),
                          Max.Strain(W15.90.10.2$strain),
                          Max.Strain(W15.90.10.3$strain))

FractureToughness   <-  c( getFractureToughness(SS.1$strain,SS.1$stress),
                           getFractureToughness(SS.2$strain,SS.2$stress),
                           getFractureToughness(SS.3$strain,SS.3$stress),
                           getFractureToughness(HH.1$strain,HH.1$stress),
                           getFractureToughness(HH.2$strain,HH.2$stress),
                           getFractureToughness(HH.3$strain,HH.3$stress),

                           getFractureToughness(HS.1$strain,HS.1$stress),
                           getFractureToughness(HS.2$strain,HS.2$stress),
                           getFractureToughness(HS.3$strain,HS.3$stress),
                           getFractureToughness(W2.90.10.1$strain,W2.90.10.1$stress),
                          getFractureToughness(W2.90.10.2$strain,W2.90.10.2$stress),
                          getFractureToughness(W2.90.10.3$strain,W2.90.10.3$stress),
                          getFractureToughness(W5.60.40.1$strain,W5.60.40.1$stress),
                          getFractureToughness(W5.60.40.2$strain,W5.60.40.2$stress),
                          getFractureToughness(W5.60.40.3$strain,W5.60.40.3$stress),
                          getFractureToughness(W5.80.20.1$strain,W5.80.20.1$stress),
                          getFractureToughness(W5.80.20.2$strain,W5.80.20.2$stress),
                          getFractureToughness(W5.80.20.3$strain,W5.80.20.3$stress),
                          getFractureToughness(W5.90.10.1$strain,W5.90.10.1$stress),
                          getFractureToughness(W5.90.10.2$strain,W5.90.10.2$stress),
                          getFractureToughness(W5.90.10.3$strain,W5.90.10.3$stress),
                          getFractureToughness(W10.60.40.1$strain,W10.60.40.1$stress),
                          getFractureToughness(W10.60.40.2$strain,W10.60.40.2$stress),
                          getFractureToughness(W10.60.40.3$strain,W10.60.40.3$stress),
                          getFractureToughness(W10.80.20.1$strain,W10.80.20.1$stress),
                          getFractureToughness(W10.80.20.2$strain,W10.80.20.2$stress),
                          getFractureToughness(W10.80.20.3$strain,W10.80.20.3$stress),
                          getFractureToughness(W10.90.10.1$strain,W10.90.10.1$stress),
                          getFractureToughness(W10.90.10.2$strain,W10.90.10.2$stress),
                          getFractureToughness(W10.90.10.3$strain,W10.90.10.3$stress),
                          getFractureToughness(W15.90.10.1$strain,W15.90.10.1$stress),
                          getFractureToughness(W15.90.10.2$strain,W15.90.10.2$stress),
                          getFractureToughness(W15.90.10.3$strain,W15.90.10.3$stress))



StrainMaxStress     <-     c(Strain.Max.Stress(SS.1$strain,SS.1$stress),
                             Strain.Max.Stress(SS.2$strain,SS.2$stress),
```

```r
                                    Strain.Max.Stress(SS.3$strain,SS.3$stress),
                                    Strain.Max.Stress(HH.1$strain,HH.1$stress),
                                    Strain.Max.Stress(HH.2$strain,HH.2$stress),
                                    Strain.Max.Stress(HH.3$strain,HH.3$stress),

                                    Strain.Max.Stress(HS.1$strain,HS.1$stress),
                                    Strain.Max.Stress(HS.2$strain,HS.2$stress),
                                    Strain.Max.Stress(HS.3$strain,HS.3$stress),
                                    Strain.Max.Stress(W2.90.10.1$strain,W2.90.10.1$stress),
                                    Strain.Max.Stress(W2.90.10.2$strain,W2.90.10.2$stress),
                                    Strain.Max.Stress(W2.90.10.3$strain,W2.90.10.3$stress),
                                    Strain.Max.Stress(W5.60.40.1$strain,W5.60.40.1$stress),
                                    Strain.Max.Stress(W5.60.40.2$strain,W5.60.40.2$stress),
                                    Strain.Max.Stress(W5.60.40.3$strain,W5.60.40.3$stress),
                                    Strain.Max.Stress(W5.80.20.1$strain,W5.80.20.1$stress),
                                    Strain.Max.Stress(W5.80.20.2$strain,W5.80.20.2$stress),
                                    Strain.Max.Stress(W5.80.20.3$strain,W5.80.20.3$stress),
                                    Strain.Max.Stress(W5.90.10.1$strain,W5.90.10.1$stress),
                                    Strain.Max.Stress(W5.90.10.2$strain,W5.90.10.2$stress),
                                    Strain.Max.Stress(W5.90.10.3$strain,W5.90.10.3$stress),
                                    Strain.Max.Stress(W10.60.40.1$strain,W10.60.40.1$stress),
                                    Strain.Max.Stress(W10.60.40.2$strain,W10.60.40.2$stress),
                                    Strain.Max.Stress(W10.60.40.3$strain,W10.60.40.3$stress),
                                    Strain.Max.Stress(W10.80.20.1$strain,W10.80.20.1$stress),
                                    Strain.Max.Stress(W10.80.20.2$strain,W10.80.20.2$stress),
                                    Strain.Max.Stress(W10.80.20.3$strain,W10.80.20.3$stress),
                                    Strain.Max.Stress(W10.90.10.1$strain,W10.90.10.1$stress),
                                    Strain.Max.Stress(W10.90.10.2$strain,W10.90.10.2$stress),
                                    Strain.Max.Stress(W10.90.10.3$strain,W10.90.10.3$stress),
                                    Strain.Max.Stress(W15.90.10.1$strain,W15.90.10.1$stress),
                                    Strain.Max.Stress(W15.90.10.2$strain,W15.90.10.2$stress),
                                    Strain.Max.Stress(W15.90.10.3$strain,W15.90.10.3$stress))

## Export data
export.dataframe <- data.frame(Samplename = Samplenames,Samplefactors= Samplefactors,
Samplegradients= Samplegradients, Youngs_modulus= YoungsModulus,
Strain_at_maxstress = StrainMaxStress, Fracture_Toughness = FractureToughness,
MaxStrain = MaxStrain, Ultimate_Strength = UltimateStrength)

####################################################################################################################################
### Mean and Standard deviations

mean_YoungsModulus <- c(  mean(subset(export.dataframe, Samplefactors == 'W0'& Samplegradients == '0/0')$Youngs_modulus) ,
                          mean(subset(export.dataframe, Samplefactors == 'W0'& Samplegradients == '100/100')$Youngs_modulus) ,

                         mean(subset(export.dataframe, Samplefactors == 'W0'& Samplegradients == '100/0')$Youngs_modulus) ,
                         mean(subset(export.dataframe, Samplefactors == 'W2'& Samplegradients == '90/10')$Youngs_modulus) ,
                         mean(subset(export.dataframe, Samplefactors == 'W5' & Samplegradients == '90/10')$Youngs_modulus),
                         mean(subset(export.dataframe, Samplefactors == 'W10' & Samplegradients == '90/10')$Youngs_modulus),
                         mean(subset(export.dataframe, Samplefactors == 'W15'&Samplegradients == '90/10')$Youngs_modulus),
                         mean(subset(export.dataframe, Samplefactors == 'W5' & Samplegradients == '80/20')$Youngs_modulus),
                         mean(subset(export.dataframe, Samplefactors == 'W10'& Samplegradients == '80/20')$Youngs_modulus),
                         mean(subset(export.dataframe, Samplefactors == 'W5'& Samplegradients == '60/40')$Youngs_modulus),
                         mean(subset(export.dataframe, Samplefactors == 'W10'& Samplegradients == '60/40')$Youngs_modulus)  )

mean_Strain_at_maxstress <- c( mean(subset(export.dataframe, Samplefactors == 'W0'& Samplegradients == '0/0')$Strain_at_maxstress) ,
                               mean(subset(export.dataframe, Samplefactors == 'W0'& Samplegradients == '100/100')$Strain_at_maxstress) ,
                               mean(subset(export.dataframe, Samplefactors == 'W0'& Samplegradients == '100/0')$Strain_at_maxstress) ,
                               mean(subset(export.dataframe, Samplefactors == 'W2'& Samplegradients == '90/10')$Strain_at_maxstress) ,
                               mean(subset(export.dataframe, Samplefactors == 'W5' & Samplegradients == '90/10')$Strain_at_maxstress),
                               mean(subset(export.dataframe, Samplefactors == 'W10' & Samplegradients == '90/10')$Strain_at_maxstress),
                               mean(subset(export.dataframe, Samplefactors == 'W15'&Samplegradients == '90/10')$Strain_at_maxstress),
                               mean(subset(export.dataframe, Samplefactors == 'W5' & Samplegradients == '80/20')$Strain_at_maxstress),
                               mean(subset(export.dataframe, Samplefactors == 'W10'& Samplegradients == '80/20')$Strain_at_maxstress),
                               mean(subset(export.dataframe, Samplefactors == 'W5'& Samplegradients == '60/40')$Strain_at_maxstress),
                               mean(subset(export.dataframe, Samplefactors == 'W10'& Samplegradients == '60/40')$Strain_at_maxstress)  )

mean_Fracture_toughness <- c( mean(subset(export.dataframe, Samplefactors == 'W0'& Samplegradients == '0/0')$Fracture_Toughness) ,
                              mean(subset(export.dataframe, Samplefactors == 'W0'& Samplegradients == '100/100')$Fracture_Toughness) ,
                              mean(subset(export.dataframe, Samplefactors == 'W0'& Samplegradients == '100/0')$Fracture_Toughness) ,
                              mean(subset(export.dataframe, Samplefactors == 'W2'& Samplegradients == '90/10')$Fracture_Toughness) ,
                               mean(subset(export.dataframe, Samplefactors == 'W5' & Samplegradients == '90/10')$Fracture_Toughness),
                               mean(subset(export.dataframe, Samplefactors == 'W10' & Samplegradients == '90/10')$Fracture_Toughness),
                               mean(subset(export.dataframe, Samplefactors == 'W15'&Samplegradients == '90/10')$Fracture_Toughness),
                               mean(subset(export.dataframe, Samplefactors == 'W5' & Samplegradients == '80/20')$Fracture_Toughness),
                               mean(subset(export.dataframe, Samplefactors == 'W10'& Samplegradients == '80/20')$Fracture_Toughness),
                               mean(subset(export.dataframe, Samplefactors == 'W5'& Samplegradients == '60/40')$Fracture_Toughness),
                               mean(subset(export.dataframe, Samplefactors == 'W10'& Samplegradients == '60/40')$Fracture_Toughness)  )

mean_MaxStrain <- c( mean(subset(export.dataframe, Samplefactors == 'W0'& Samplegradients == '0/0')$MaxStrain) ,
                     mean(subset(export.dataframe, Samplefactors == 'W0'& Samplegradients == '100/100')$MaxStrain) ,
                     mean(subset(export.dataframe, Samplefactors == 'W0'& Samplegradients == '100/0')$MaxStrain) ,
                     mean(subset(export.dataframe, Samplefactors == 'W2'& Samplegradients == '90/10')$MaxStrain) ,
                     mean(subset(export.dataframe, Samplefactors == 'W5' & Samplegradients == '90/10')$MaxStrain),
                     mean(subset(export.dataframe, Samplefactors == 'W10' & Samplegradients == '90/10')$MaxStrain),
                     mean(subset(export.dataframe, Samplefactors == 'W15'&Samplegradients == '90/10')$MaxStrain),
                     mean(subset(export.dataframe, Samplefactors == 'W5' & Samplegradients == '80/20')$MaxStrain),
                     mean(subset(export.dataframe, Samplefactors == 'W10'& Samplegradients == '80/20')$MaxStrain),
                     mean(subset(export.dataframe, Samplefactors == 'W5'& Samplegradients == '60/40')$MaxStrain),
                     mean(subset(export.dataframe, Samplefactors == 'W10'& Samplegradients == '60/40')$MaxStrain)  )

mean_Ultimate_strength <- c( mean(subset(export.dataframe, Samplefactors == 'W0'& Samplegradients == '0/0')$Ultimate_Strength) ,
                             mean(subset(export.dataframe, Samplefactors == 'W0'& Samplegradients == '100/100')$Ultimate_Strength) ,
                             mean(subset(export.dataframe, Samplefactors == 'W0'& Samplegradients == '100/0')$Ultimate_Strength) ,
                             mean(subset(export.dataframe, Samplefactors == 'W2'& Samplegradients == '90/10')$Ultimate_Strength) ,
                     mean(subset(export.dataframe, Samplefactors == 'W5' & Samplegradients == '90/10')$Ultimate_Strength),
                     mean(subset(export.dataframe, Samplefactors == 'W10' & Samplegradients == '90/10')$Ultimate_Strength),
                     mean(subset(export.dataframe, Samplefactors == 'W15'&Samplegradients == '90/10')$Ultimate_Strength),
                     mean(subset(export.dataframe, Samplefactors == 'W5' & Samplegradients == '80/20')$Ultimate_Strength),
                     mean(subset(export.dataframe, Samplefactors == 'W10'& Samplegradients == '80/20')$Ultimate_Strength),
                     mean(subset(export.dataframe, Samplefactors == 'W5'& Samplegradients == '60/40')$Ultimate_Strength),
                     mean(subset(export.dataframe, Samplefactors == 'W10'& Samplegradients == '60/40')$Ultimate_Strength)  )


#standard deviation

sd_YoungsModulus <- c( sd(subset(export.dataframe, Samplefactors == 'W0'& Samplegradients == '0/0')$Youngs_modulus) ,
```

```
                             sd(subset(export.dataframe, Samplefactors == 'W0'& Samplegradients == '100/100')$Youngs_modulus) ,
                             sd(subset(export.dataframe, Samplefactors == 'W0'& Samplegradients == '100/0')$Youngs_modulus) ,
                             sd(subset(export.dataframe, Samplefactors == 'W2'& Samplegradients == '90/10')$Youngs_modulus) ,
                               sd(subset(export.dataframe, Samplefactors == 'W5' & Samplegradients == '90/10')$Youngs_modulus),
                               sd(subset(export.dataframe, Samplefactors == 'W10' & Samplegradients == '90/10')$Youngs_modulus),
                               sd(subset(export.dataframe, Samplefactors == 'W15'&Samplegradients == '90/10')$Youngs_modulus),
                               sd(subset(export.dataframe, Samplefactors == 'W5' & Samplegradients == '80/20')$Youngs_modulus),
                               sd(subset(export.dataframe, Samplefactors == 'W10'& Samplegradients == '80/20')$Youngs_modulus),
                               sd(subset(export.dataframe, Samplefactors == 'W5'& Samplegradients == '60/40')$Youngs_modulus),
                               sd(subset(export.dataframe, Samplefactors == 'W10'& Samplegradients == '60/40')$Youngs_modulus)  )

sd_Strain_at_maxstress <- c( sd(subset(export.dataframe, Samplefactors == 'W0'& Samplegradients == '0/0')$Strain_at_maxstress) ,
                             sd(subset(export.dataframe, Samplefactors == 'W0'& Samplegradients == '100/100')$Strain_at_maxstress) ,
                             sd(subset(export.dataframe, Samplefactors == 'W0'& Samplegradients == '100/0')$Strain_at_maxstress) ,
                             sd(subset(export.dataframe, Samplefactors == 'W2'& Samplegradients == '90/10')$Strain_at_maxstress) ,
                               sd(subset(export.dataframe, Samplefactors == 'W5' & Samplegradients == '90/10')$Strain_at_maxstress),
                               sd(subset(export.dataframe, Samplefactors == 'W10' & Samplegradients == '90/10')$Strain_at_maxstress),
                               sd(subset(export.dataframe, Samplefactors == 'W15'&Samplegradients == '90/10')$Strain_at_maxstress),
                               sd(subset(export.dataframe, Samplefactors == 'W5' & Samplegradients == '80/20')$Strain_at_maxstress),
                               sd(subset(export.dataframe, Samplefactors == 'W10'& Samplegradients == '80/20')$Strain_at_maxstress),
                               sd(subset(export.dataframe, Samplefactors == 'W5'& Samplegradients == '60/40')$Strain_at_maxstress),
                               sd(subset(export.dataframe, Samplefactors == 'W10'& Samplegradients == '60/40')$Strain_at_maxstress)  )

sd_Fracture_toughness <- c( sd(subset(export.dataframe, Samplefactors == 'W0'& Samplegradients == '0/0')$Fracture_Toughness) ,
                            sd(subset(export.dataframe, Samplefactors == 'W0'& Samplegradients == '100/100')$Fracture_Toughness) ,
                            sd(subset(export.dataframe, Samplefactors == 'W0'& Samplegradients == '100/0')$Fracture_Toughness) ,
                            sd(subset(export.dataframe, Samplefactors == 'W2'& Samplegradients == '90/10')$Fracture_Toughness) ,
                              sd(subset(export.dataframe, Samplefactors == 'W5' & Samplegradients == '90/10')$Fracture_Toughness),
                              sd(subset(export.dataframe, Samplefactors == 'W10' & Samplegradients == '90/10')$Fracture_Toughness),
                              sd(subset(export.dataframe, Samplefactors == 'W15'&Samplegradients == '90/10')$Fracture_Toughness),
                              sd(subset(export.dataframe, Samplefactors == 'W5' & Samplegradients == '80/20')$Fracture_Toughness),
                              sd(subset(export.dataframe, Samplefactors == 'W10'& Samplegradients == '80/20')$Fracture_Toughness),
                              sd(subset(export.dataframe, Samplefactors == 'W5'& Samplegradients == '60/40')$Fracture_Toughness),
                              sd(subset(export.dataframe, Samplefactors == 'W10'& Samplegradients == '60/40')$Fracture_Toughness)  )

sd_MaxStrain <- c( sd(subset(export.dataframe, Samplefactors == 'W0'& Samplegradients == '0/0')$MaxStrain) ,
                   sd(subset(export.dataframe, Samplefactors == 'W0'& Samplegradients == '100/100')$MaxStrain) ,
                   sd(subset(export.dataframe, Samplefactors == 'W0'& Samplegradients == '100/0')$MaxStrain) ,
                   sd(subset(export.dataframe, Samplefactors == 'W2'& Samplegradients == '90/10')$MaxStrain) ,
                     sd(subset(export.dataframe, Samplefactors == 'W5' & Samplegradients == '90/10')$MaxStrain),
                     sd(subset(export.dataframe, Samplefactors == 'W10' & Samplegradients == '90/10')$MaxStrain),
                     sd(subset(export.dataframe, Samplefactors == 'W15'&Samplegradients == '90/10')$MaxStrain),
                     sd(subset(export.dataframe, Samplefactors == 'W5' & Samplegradients == '80/20')$MaxStrain),
                     sd(subset(export.dataframe, Samplefactors == 'W10'& Samplegradients == '80/20')$MaxStrain),
                     sd(subset(export.dataframe, Samplefactors == 'W5'& Samplegradients == '60/40')$MaxStrain),
                     sd(subset(export.dataframe, Samplefactors == 'W10'& Samplegradients == '60/40')$MaxStrain)  )

sd_Ultimate_strength <- c( sd(subset(export.dataframe, Samplefactors == 'W0'& Samplegradients == '0/0')$Ultimate_Strength) ,
                           sd(subset(export.dataframe, Samplefactors == 'W0'& Samplegradients == '100/100')$Ultimate_Strength) ,
                           sd(subset(export.dataframe, Samplefactors == 'W0'& Samplegradients == '100/0')$Ultimate_Strength) ,
                           sd(subset(export.dataframe, Samplefactors == 'W2'& Samplegradients == '90/10')$Ultimate_Strength) ,
                             sd(subset(export.dataframe, Samplefactors == 'W5' & Samplegradients == '90/10')$Ultimate_Strength),
                             sd(subset(export.dataframe, Samplefactors == 'W10' & Samplegradients == '90/10')$Ultimate_Strength),
                             sd(subset(export.dataframe, Samplefactors == 'W15'&Samplegradients == '90/10')$Ultimate_Strength),
                             sd(subset(export.dataframe, Samplefactors == 'W5' & Samplegradients == '80/20')$Ultimate_Strength),
                             sd(subset(export.dataframe, Samplefactors == 'W10'& Samplegradients == '80/20')$Ultimate_Strength),
                             sd(subset(export.dataframe, Samplefactors == 'W5'& Samplegradients == '60/40')$Ultimate_Strength),
                             sd(subset(export.dataframe, Samplefactors == 'W10'& Samplegradients == '60/40')$Ultimate_Strength)  )

## mean and standard deviation data file

namelabels <- c('0/0,_W0', '100/100,_W0', '100/0,_W0',  '90/10,_W2', '90/10,_W5', '90/10,_W10','90/10,_W15' , '80/20,_W5', '80/20,_W10', '60/40,_W5', '60/40,_W10')

data_means_sd <- data.frame(namelabels, mean_YoungsModulus, mean_Strain_at_maxstress,  mean_Fracture_toughness, mean_MaxStrain,  mean_Ultimate_strength,
                            sd_YoungsModulus, sd_Strain_at_maxstress,  sd_Fracture_toughness, sd_MaxStrain,  sd_Ultimate_strength)
#write.csv(data_means_sd, file = "MyData.csv")

##########################################################################################################################################
#graphs

#### Stress-Strain curves,  of every samplekind the one with the highest stress

pdf(file = paste("Rfigures_Fracture/","Strain-stress",".pdf",sep=""), width=6,height=3, bg="transparent")
par(family = "serif", mar=c(3,3,2,1), mgp=c(2,1,0),omi=c(0,0,0, 0), font= 1,font.main=1,cex=1,cex.main=1,cex.lab=1)
plot(NULL, NULL, xlim =c(0,60), ylim=c(0,0.45), xlab ="Strain_[%]" ,ylab = "Stress_[MPa]",
     main = "Stress-strain",cex=1,tck=0.02)
axis(side = 3, tck=0.02, labels = FALSE)
axis(side = 4, tck=0.02, labels = FALSE)
grid(nx = NULL, ny = NULL, col = "lightgray", lty = "dotted")

lines(SS.1$strain*100,SS.1$stress,pch= 22, cex= 1, col="gray40",lwd=1)
lines(HH.1$strain*100,HH.1$stress,pch= 22, cex= 1, col="gray24",lwd=1)
lines(HS.1$strain*100,HS.1$stress,pch= 22, cex= 1, col="black",lwd=1)

lines(W2.90.10.3$strain*100,W2.90.10.3$stress,col="red",lwd=1)
lines(W5.90.10.1$strain*100,W5.90.10.1$stress,col="navy",lwd=1)
lines(W10.90.10.3$strain*100,W10.90.10.3$stress,col="limegreen",lwd=1)
lines(W15.90.10.3$strain*100,W15.90.10.3$stress,col="deeppink",lwd=1)

lines(W5.80.20.2$strain*100,W5.80.20.2$stress,col="navy",lwd=1)
lines(W10.80.20.2$strain*100, W10.80.20.2$stress,col='limegreen',lwd=1)

lines(W5.60.40.1$strain*100, W5.60.40.1$stress,col='navy',lwd=1)
lines(W10.60.40.2$strain*100, W10.60.40.2$stress,col='limegreen',lwd=1)


legend("topright", legend = c("HS", "SS", "HH", "W2-90-10","W5-90-10", "W10-90-10", "W15-90-10", "W5-80-20",
                              "W10-80-20","W5-60-40","W10-60-40"),
       pch = c(18 , 18, 18, 15, 15, 15, 15, 16, 16, 17, 17), cex= 0.7,
       col=c('black', 'gray40', 'gray24', 'red','navy',"limegreen","deeppink","navy","limegreen",
             'navy','limegreen'),lty=c(1))

dev.off()


# Elastic Modulus vs Fracture Toughness
```

```r
pdf(file = paste("plotsforpaper_Fracture/","ElasticModulus_FractureToughness",".pdf",sep=""), width=6,height=3, bg="transparent")
par(family = "serif", mar=c(3,3,2,1),mgp=c(2,1,0),omi=c(0,0,0, 0), font= 1,font.main=1,cex=1,cex.main=1,cex.lab=1)
plot(NULL, NULL, xlim =c(1.3,2.1), ylim=c(0.04,0.09), xlab ="Elastic modulus [MPa]",ylab = "Fracture Toughness [MPa]",
     main = "Young's Modulus vs Fracture Toughness" ,cex=1,tck=0.02)
axis(side = 3, tck=0.02, labels = FALSE)
axis(side = 4, tck=0.02, labels = FALSE)
grid(nx = NULL, ny = NULL, col = "lightgray", lty = "dotted")


 points((subset(data_means_sd, namelabels== '100/0, W0')$mean_YoungsModulus),                #x0
        (subset(data_means_sd, namelabels== '100/0, W0')$mean_Fracture_toughness),
        col= 'black' ,pch=18, cex=1)
arrows(subset(data_means_sd, namelabels== '100/0, W0')$mean_YoungsModulus,
        subset(data_means_sd, namelabels== '100/0, W0')$mean_Fracture_toughness+subset(data_means_sd, namelabels== '100/0, W0')$sd_Fracture_toughness,
        subset(data_means_sd, namelabels== '100/0, W0')$mean_YoungsModulus,
        subset(data_means_sd, namelabels== '100/0, W0')$mean_Fracture_toughness-subset(data_means_sd, namelabels== '100/0, W0')$sd_Fracture_toughness,
        code=3,length=0.015,angle=90,col='black',lwd=0.7)
arrows(subset(data_means_sd, namelabels== '100/0, W0')$mean_YoungsModulus-subset(data_means_sd, namelabels== '100/0, W0')$sd_YoungsModulus,
        subset(data_means_sd, namelabels== '100/0, W0')$mean_Fracture_toughness,
        subset(data_means_sd, namelabels== '100/0, W0')$mean_YoungsModulus+subset(data_means_sd, namelabels== '100/0, W0')$sd_YoungsModulus,
        subset(data_means_sd, namelabels== '100/0, W0')$mean_Fracture_toughness,
        code=3,length=0.015,angle=90,col='black',lwd=0.7)

points((subset(data_means_sd, namelabels== '90/10, W2')$mean_YoungsModulus),                #x0
        (subset(data_means_sd, namelabels== '90/10, W2')$mean_Fracture_toughness),
        col= 'red' ,pch=15, cex=1)
arrows(subset(data_means_sd, namelabels== '90/10, W2')$mean_YoungsModulus,
        subset(data_means_sd, namelabels== '90/10, W2')$mean_Fracture_toughness+subset(data_means_sd, namelabels== '90/10, W2')$sd_Fracture_toughness,
        subset(data_means_sd, namelabels== '90/10, W2')$mean_YoungsModulus,
        subset(data_means_sd, namelabels== '90/10, W2')$mean_Fracture_toughness-subset(data_means_sd, namelabels== '90/10, W2')$sd_Fracture_toughness,
        code=3,length=0.015,angle=90,col='red',lwd=0.7)
arrows(subset(data_means_sd, namelabels== '90/10, W2')$mean_YoungsModulus-subset(data_means_sd, namelabels== '90/10, W2')$sd_YoungsModulus,
        subset(data_means_sd, namelabels== '90/10, W2')$mean_Fracture_toughness,
        subset(data_means_sd, namelabels== '90/10, W2')$mean_YoungsModulus+subset(data_means_sd, namelabels== '90/10, W2')$sd_YoungsModulus,
        subset(data_means_sd, namelabels== '90/10, W2')$mean_Fracture_toughness,
        code=3,length=0.015,angle=90,col='red',lwd=0.7)


points((subset(data_means_sd, namelabels== '90/10, W5')$mean_YoungsModulus),                #x0
        (subset(data_means_sd, namelabels== '90/10, W5')$mean_Fracture_toughness),
        col= 'navy' ,pch=15, cex=1)
arrows(subset(data_means_sd, namelabels== '90/10, W5')$mean_YoungsModulus,
        subset(data_means_sd, namelabels== '90/10, W5')$mean_Fracture_toughness+subset(data_means_sd, namelabels== '90/10, W5')$sd_Fracture_toughness,
        subset(data_means_sd, namelabels== '90/10, W5')$mean_YoungsModulus,
        subset(data_means_sd, namelabels== '90/10, W5')$mean_Fracture_toughness-subset(data_means_sd, namelabels== '90/10, W5')$sd_Fracture_toughness,
        code=3,length=0.015,angle=90,col='navy',lwd=0.7)
arrows(subset(data_means_sd, namelabels== '90/10, W5')$mean_YoungsModulus-subset(data_means_sd, namelabels== '90/10, W5')$sd_YoungsModulus,
        subset(data_means_sd, namelabels== '90/10, W5')$mean_Fracture_toughness,
        subset(data_means_sd, namelabels== '90/10, W5')$mean_YoungsModulus+subset(data_means_sd, namelabels== '90/10, W5')$sd_YoungsModulus,
        subset(data_means_sd, namelabels== '90/10, W5')$mean_Fracture_toughness,
        code=3,length=0.015,angle=90,col='navy',lwd=0.7)

points((subset(data_means_sd, namelabels== '90/10, W10')$mean_YoungsModulus),                #x0
        (subset(data_means_sd, namelabels== '90/10, W10')$mean_Fracture_toughness),
        col= 'limegreen' ,pch=15, cex=1)
arrows(subset(data_means_sd, namelabels== '90/10, W10')$mean_YoungsModulus,
        subset(data_means_sd, namelabels== '90/10, W10')$mean_Fracture_toughness+subset(data_means_sd, namelabels== '90/10, W10')$sd_Fracture_toughness,
        subset(data_means_sd, namelabels== '90/10, W10')$mean_YoungsModulus,
        subset(data_means_sd, namelabels== '90/10, W10')$mean_Fracture_toughness-subset(data_means_sd, namelabels== '90/10, W10')$sd_Fracture_toughness,
        code=3,length=0.015,angle=90,col='limegreen',lwd=0.7)
arrows(subset(data_means_sd, namelabels== '90/10, W10')$mean_YoungsModulus-subset(data_means_sd, namelabels== '90/10, W10')$sd_YoungsModulus,
        subset(data_means_sd, namelabels== '90/10, W10')$mean_Fracture_toughness,
        subset(data_means_sd, namelabels== '90/10, W10')$mean_YoungsModulus+subset(data_means_sd, namelabels== '90/10, W10')$sd_YoungsModulus,
        subset(data_means_sd, namelabels== '90/10, W10')$mean_Fracture_toughness,
        code=3,length=0.015,angle=90,col='limegreen',lwd=0.7)

points((subset(data_means_sd, namelabels== '90/10, W15')$mean_YoungsModulus),                #x0
        (subset(data_means_sd, namelabels== '90/10, W15')$mean_Fracture_toughness),
        col= 'deeppink' ,pch=15, cex=1)
arrows(subset(data_means_sd, namelabels== '90/10, W15')$mean_YoungsModulus,
        subset(data_means_sd, namelabels== '90/10, W15')$mean_Fracture_toughness+subset(data_means_sd, namelabels== '90/10, W15')$sd_Fracture_toughness,
        subset(data_means_sd, namelabels== '90/10, W15')$mean_YoungsModulus,
        subset(data_means_sd, namelabels== '90/10, W15')$mean_Fracture_toughness-subset(data_means_sd, namelabels== '90/10, W15')$sd_Fracture_toughness,
        code=3,length=0.015,angle=90,col='deeppink',lwd=0.7)
arrows(subset(data_means_sd, namelabels== '90/10, W15')$mean_YoungsModulus-subset(data_means_sd, namelabels== '90/10, W15')$sd_YoungsModulus,
        subset(data_means_sd, namelabels== '90/10, W15')$mean_Fracture_toughness,
        subset(data_means_sd, namelabels== '90/10, W15')$mean_YoungsModulus+subset(data_means_sd, namelabels== '90/10, W15')$sd_YoungsModulus,
        subset(data_means_sd, namelabels== '90/10, W15')$mean_Fracture_toughness,
        code=3,length=0.015,angle=90,col='deeppink',lwd=0.7)

points((subset(data_means_sd, namelabels== '80/20, W5')$mean_YoungsModulus),                #x0
        (subset(data_means_sd, namelabels== '80/20, W5')$mean_Fracture_toughness),
        col= 'navy' ,pch=16, cex=1)
arrows(subset(data_means_sd, namelabels== '80/20, W5')$mean_YoungsModulus,
        subset(data_means_sd, namelabels== '80/20, W5')$mean_Fracture_toughness+subset(data_means_sd, namelabels== '80/20, W5')$sd_Fracture_toughness,
        subset(data_means_sd, namelabels== '80/20, W5')$mean_YoungsModulus,
        subset(data_means_sd, namelabels== '80/20, W5')$mean_Fracture_toughness-subset(data_means_sd, namelabels== '80/20, W5')$sd_Fracture_toughness,
        code=3,length=0.015,angle=90,col='navy',lwd=0.7)
arrows(subset(data_means_sd, namelabels== '80/20, W5')$mean_YoungsModulus-subset(data_means_sd, namelabels== '80/20, W5')$sd_YoungsModulus,
        subset(data_means_sd, namelabels== '80/20, W5')$mean_Fracture_toughness,
        subset(data_means_sd, namelabels== '80/20, W5')$mean_YoungsModulus+subset(data_means_sd, namelabels== '80/20, W5')$sd_YoungsModulus,
        subset(data_means_sd, namelabels== '80/20, W5')$mean_Fracture_toughness,
        code=3,length=0.015,angle=90,col='navy',lwd=0.7)

points((subset(data_means_sd, namelabels== '80/20, W10')$mean_YoungsModulus),                #x0
        (subset(data_means_sd, namelabels== '80/20, W10')$mean_Fracture_toughness),
        col= 'limegreen' ,pch=16, cex=1)
arrows(subset(data_means_sd, namelabels== '80/20, W10')$mean_YoungsModulus,
        subset(data_means_sd, namelabels== '80/20, W10')$mean_Fracture_toughness+subset(data_means_sd, namelabels== '80/20, W10')$sd_Fracture_toughness,
        subset(data_means_sd, namelabels== '80/20, W10')$mean_YoungsModulus,
        subset(data_means_sd, namelabels== '80/20, W10')$mean_Fracture_toughness-subset(data_means_sd, namelabels== '80/20, W10')$sd_Fracture_toughness,
        code=3,length=0.015,angle=90,col='limegreen',lwd=0.7)
arrows(subset(data_means_sd, namelabels== '80/20, W10')$mean_YoungsModulus-subset(data_means_sd, namelabels== '80/20, W10')$sd_YoungsModulus,
        subset(data_means_sd, namelabels== '80/20, W10')$mean_Fracture_toughness,
        subset(data_means_sd, namelabels== '80/20, W10')$mean_YoungsModulus+subset(data_means_sd, namelabels== '80/20, W10')$sd_YoungsModulus,
        subset(data_means_sd, namelabels== '80/20, W10')$mean_Fracture_toughness,
```

```
        code=3,length=0.015,angle=90,col='limegreen',lwd=0.7)

points((subset(data_means_sd, namelabels== '60/40, W5')$mean_YoungsModulus),              #x0
        (subset(data_means_sd, namelabels== '60/40, W5')$mean_Fracture_toughness),
        col= 'navy' ,pch=17, cex=1)
arrows(subset(data_means_sd, namelabels== '60/40, W5')$mean_YoungsModulus,
        subset(data_means_sd, namelabels== '60/40, W5')$mean_Fracture_toughness+subset(data_means_sd, namelabels== '60/40, W5')$sd_Fracture_toughness,
        subset(data_means_sd, namelabels== '60/40, W5')$mean_YoungsModulus,
        subset(data_means_sd, namelabels== '60/40, W5')$mean_Fracture_toughness-subset(data_means_sd, namelabels== '60/40, W5')$sd_Fracture_toughness,
        code=3,length=0.015,angle=90,col='navy',lwd=0.7)
arrows(subset(data_means_sd, namelabels== '60/40, W5')$mean_YoungsModulus-subset(data_means_sd, namelabels== '60/40, W5')$sd_YoungsModulus,
        subset(data_means_sd, namelabels== '60/40, W5')$mean_Fracture_toughness,
        subset(data_means_sd, namelabels== '60/40, W5')$mean_YoungsModulus+subset(data_means_sd, namelabels== '60/40, W5')$sd_YoungsModulus,
        subset(data_means_sd, namelabels== '60/40, W5')$mean_Fracture_toughness,
        code=3,length=0.015,angle=90,col='navy',lwd=0.7)

points((subset(data_means_sd, namelabels== '60/40, W10')$mean_YoungsModulus),              #x0
        (subset(data_means_sd, namelabels== '60/40, W10')$mean_Fracture_toughness),
        col= 'limegreen' ,pch=17, cex=1)
arrows(subset(data_means_sd, namelabels== '60/40, W10')$mean_YoungsModulus,
        subset(data_means_sd, namelabels== '60/40, W10')$mean_Fracture_toughness+subset(data_means_sd, namelabels== '60/40, W10')$sd_Fracture_toughness,
        subset(data_means_sd, namelabels== '60/40, W10')$mean_YoungsModulus,
        subset(data_means_sd, namelabels== '60/40, W10')$mean_Fracture_toughness-subset(data_means_sd, namelabels== '60/40, W10')$sd_Fracture_toughness,
        code=3,length=0.015,angle=90,col='limegreen',lwd=0.7)
arrows(subset(data_means_sd, namelabels== '60/40, W10')$mean_YoungsModulus-subset(data_means_sd, namelabels== '60/40, W10')$sd_YoungsModulus,
        subset(data_means_sd, namelabels== '60/40, W10')$mean_Fracture_toughness,
        subset(data_means_sd, namelabels== '60/40, W10')$mean_YoungsModulus+subset(data_means_sd, namelabels== '60/40, W10')$sd_YoungsModulus,
        subset(data_means_sd, namelabels== '60/40, W10')$mean_Fracture_toughness,
        code=3,length=0.015,angle=90,col='limegreen',lwd=0.7)

legend("topright", legend = c("HS", "W2-90-10","W5-90-10", "W10-90-10", "W15-90-10", "W5-80-20",
                                "W10-80-20","W5-60-40","W10-60-40"),
        pch = c(18 , 15, 15, 15, 15, 16, 16, 17, 17), cex= 0.7,
        col=c('black',  'red','navy',"limegreen","deeppink","navy","limegreen",
              'navy','limegreen'),lty=c(1))

dev.off()



# Fracture Toughness vs transition length

pdf(file = paste("plotsforpaper_Fracture/","Fracture_Toughness_vs_transition_length",".pdf",sep=""), width=6,height=3, bg="transparent")
par(family = "serif", mar=c(3,3,2,1),mgp=c(2,1,0),omi=c(0,0,0, 0), font= 1,font.main=1,cex=1,cex.main=1,cex.lab=1)
plot(NULL, NULL, xlim =c(0,25), ylim=c(0.04,0.09), xlab ="Transition length [%]",ylab = "Fracture Toughness [MPa]",
     main = "Fracture Toughness vs Transition length" ,cex=1,tck=0.02)
axis(side = 3, tck=0.02, labels = FALSE)
axis(side = 4, tck=0.02, labels = FALSE)
grid(nx = NULL, ny = NULL, col = "lightgray", lty = "dotted")

points((0),              #x0
        (subset(data_means_sd, namelabels== '100/0, W0')$mean_Fracture_toughness),
        col= 'black' ,pch=18, cex=1)
arrows((0),
        subset(data_means_sd, namelabels== '100/0, W0')$mean_Fracture_toughness+subset(data_means_sd, namelabels== '100/0, W0')$sd_Fracture_toughness,
        (0),
        subset(data_means_sd, namelabels== '100/0, W0')$mean_Fracture_toughness-subset(data_means_sd, namelabels== '100/0, W0')$sd_Fracture_toughness,
        code=3,length=0.015,angle=90,col='black',lwd=0.7)

  points((2),              #x0
        (subset(data_means_sd, namelabels== '90/10, W2')$mean_Fracture_toughness),
        col= 'red' ,pch=15, cex=1)
arrows((2),
        subset(data_means_sd, namelabels== '90/10, W2')$mean_Fracture_toughness+subset(data_means_sd, namelabels== '90/10, W2')$sd_Fracture_toughness,
        (2),
        subset(data_means_sd, namelabels== '90/10, W2')$mean_Fracture_toughness-subset(data_means_sd, namelabels== '90/10, W2')$sd_Fracture_toughness,
        code=3,length=0.015,angle=90,col='red',lwd=0.7)


points((5),              #x0
        (subset(data_means_sd, namelabels== '90/10, W5')$mean_Fracture_toughness),
        col= 'navy' ,pch=15, cex=1)
arrows(5,
        subset(data_means_sd, namelabels== '90/10, W5')$mean_Fracture_toughness+subset(data_means_sd, namelabels== '90/10, W5')$sd_Fracture_toughness,
        5,
        subset(data_means_sd, namelabels== '90/10, W5')$mean_Fracture_toughness-subset(data_means_sd, namelabels== '90/10, W5')$sd_Fracture_toughness,
        code=3,length=0.015,angle=90,col='navy',lwd=0.7)

points((10),              #x0
        (subset(data_means_sd, namelabels== '90/10, W10')$mean_Fracture_toughness),
        col= 'limegreen' ,pch=15, cex=1)
arrows((10),
        subset(data_means_sd, namelabels== '90/10, W10')$mean_Fracture_toughness+subset(data_means_sd, namelabels== '90/10, W10')$sd_Fracture_toughness,
        (10),
        subset(data_means_sd, namelabels== '90/10, W10')$mean_Fracture_toughness-subset(data_means_sd, namelabels== '90/10, W10')$sd_Fracture_toughness,
        code=3,length=0.015,angle=90,col='limegreen',lwd=0.7)


points((15),              #x0
        (subset(data_means_sd, namelabels== '90/10, W15')$mean_Fracture_toughness),
        col= 'deeppink' ,pch=15, cex=1)
arrows(15,
        subset(data_means_sd, namelabels== '90/10, W15')$mean_Fracture_toughness+subset(data_means_sd, namelabels== '90/10, W15')$sd_Fracture_toughness,
        15,
        subset(data_means_sd, namelabels== '90/10, W15')$mean_Fracture_toughness-subset(data_means_sd, namelabels== '90/10, W15')$sd_Fracture_toughness,
        code=3,length=0.015,angle=90,col='deeppink',lwd=0.7)


points((5),              #x0
        (subset(data_means_sd, namelabels== '80/20, W5')$mean_Fracture_toughness),
        col= 'navy' ,pch=16, cex=1)
arrows(5,
        subset(data_means_sd, namelabels== '80/20, W5')$mean_Fracture_toughness+subset(data_means_sd, namelabels== '80/20, W5')$sd_Fracture_toughness,
        5,
        subset(data_means_sd, namelabels== '80/20, W5')$mean_Fracture_toughness-subset(data_means_sd, namelabels== '80/20, W5')$sd_Fracture_toughness,
        code=3,length=0.015,angle=90,col='navy',lwd=0.7)
```

```
points((10),           #x0
        (subset(data_means_sd, namelabels== '80/20,_W10')$mean_Fracture_toughness),
        col= 'limegreen' ,pch=16, cex=1)
arrows(10,
        subset(data_means_sd, namelabels== '80/20,_W10')$mean_Fracture_toughness+subset(data_means_sd, namelabels== '80/20,_W10')$sd_Fracture_toughness,
        10,
        subset(data_means_sd, namelabels== '80/20,_W10')$mean_Fracture_toughness-subset(data_means_sd, namelabels== '80/20,_W10')$sd_Fracture_toughness,
        code=3,length=0.015,angle=90,col='limegreen',lwd=0.7)


points((5),           #x0
        (subset(data_means_sd, namelabels== '60/40,_W5')$mean_Fracture_toughness),
        col= 'navy' ,pch=17, cex=1)
arrows(5,
        subset(data_means_sd, namelabels== '60/40,_W5')$mean_Fracture_toughness+subset(data_means_sd, namelabels== '60/40,_W5')$sd_Fracture_toughness,
        5,
        subset(data_means_sd, namelabels== '60/40,_W5')$mean_Fracture_toughness-subset(data_means_sd, namelabels== '60/40,_W5')$sd_Fracture_toughness,
        code=3,length=0.015,angle=90,col='navy',lwd=0.7)


points((10),           #x0
        (subset(data_means_sd, namelabels== '60/40,_W10')$mean_Fracture_toughness),
        col= 'limegreen' ,pch=17, cex=1)
arrows(10,
        subset(data_means_sd, namelabels== '60/40,_W10')$mean_Fracture_toughness+subset(data_means_sd, namelabels== '60/40,_W10')$sd_Fracture_toughness,
        10,
        subset(data_means_sd, namelabels== '60/40,_W10')$mean_Fracture_toughness-subset(data_means_sd, namelabels== '60/40,_W10')$sd_Fracture_toughness,
        code=3,length=0.015,angle=90,col='limegreen',lwd=0.7)



legend("topright", legend = c("HS", "W2-90-10","W5-90-10", "W10-90-10", "W15-90-10", "W5-80-20",
                                "W10-80-20","W5-60-40","W10-60-40"),
        pch = c(18 , 15, 15, 15, 15, 16, 16, 17, 17), cex= 0.7,
        col=c('black', 'red','navy',"limegreen","deeppink","navy","limegreen",
              'navy','limegreen'),lty=c(1))
dev.off()



# Youngs Modulus vs transition length

pdf(file = paste("plotsforpaper_Fracture/","Youngs_vs_transition_length",".pdf",sep=""), width=6,height=3, bg="transparent")
par(family = "serif", mar=c(3,3,2,1),mgp=c(2,1,0),omi=c(0,0,0, 0), font= 1,font.main=1,cex=1,cex.main=1,cex.lab=1)
plot(NULL, NULL, xlim =c(0,25), ylim=c(1.3,1.9), xlab ="Transition_length_[%]",ylab = "Young's_Modulus_[MPa]",
     main = "Young's_Modulus_vs_Transition_length" ,cex=1,tck=0.02)
axis(side = 3, tck=0.02, labels = FALSE)
axis(side = 4, tck=0.02, labels = FALSE)
grid(nx = NULL, ny = NULL, col = "lightgray", lty = "dotted")

points((0),           #x0
        (subset(data_means_sd, namelabels== '100/0,_W0')$mean_YoungsModulus),
        col= 'black' ,pch=18, cex=1)
arrows((0),
        subset(data_means_sd, namelabels== '100/0,_W0')$mean_YoungsModulus+subset(data_means_sd, namelabels== '100/0,_W0')$sd_YoungsModulus,
        (0),
        subset(data_means_sd, namelabels== '100/0,_W0')$mean_YoungsModulus-subset(data_means_sd, namelabels== '100/0,_W0')$sd_YoungsModulus,
        code=3,length=0.015,angle=90,col='black',lwd=0.7)

 points((2),           #x0
        (subset(data_means_sd, namelabels== '90/10,_W2')$mean_YoungsModulus),
        col= 'red' ,pch=15, cex=1)
arrows((2),
        subset(data_means_sd, namelabels== '90/10,_W2')$mean_YoungsModulus+subset(data_means_sd, namelabels== '90/10,_W2')$sd_YoungsModulus,
        (2),
        subset(data_means_sd, namelabels== '90/10,_W2')$mean_YoungsModulus-subset(data_means_sd, namelabels== '90/10,_W2')$sd_YoungsModulus,
        code=3,length=0.015,angle=90,col='red',lwd=0.7)


points((5),           #x0
        (subset(data_means_sd, namelabels== '90/10,_W5')$mean_YoungsModulus),
        col= 'navy' ,pch=15, cex=1)
arrows(5,
        subset(data_means_sd, namelabels== '90/10,_W5')$mean_YoungsModulus+subset(data_means_sd, namelabels== '90/10,_W5')$sd_YoungsModulus,
        5,
        subset(data_means_sd, namelabels== '90/10,_W5')$mean_YoungsModulus-subset(data_means_sd, namelabels== '90/10,_W5')$sd_YoungsModulus,
        code=3,length=0.015,angle=90,col='navy',lwd=0.7)

points((10),           #x0
        (subset(data_means_sd, namelabels== '90/10,_W10')$mean_YoungsModulus),
        col= 'limegreen' ,pch=15, cex=1)
arrows((10),
        subset(data_means_sd, namelabels== '90/10,_W10')$mean_YoungsModulus+subset(data_means_sd, namelabels== '90/10,_W10')$sd_YoungsModulus,
        (10),
        subset(data_means_sd, namelabels== '90/10,_W10')$mean_YoungsModulus-subset(data_means_sd, namelabels== '90/10,_W10')$sd_YoungsModulus,
        code=3,length=0.015,angle=90,col='limegreen',lwd=0.7)


points((15),           #x0
        (subset(data_means_sd, namelabels== '90/10,_W15')$mean_YoungsModulus),
        col= 'deeppink' ,pch=15, cex=1)
arrows(15,
        subset(data_means_sd, namelabels== '90/10,_W15')$mean_YoungsModulus+subset(data_means_sd, namelabels== '90/10,_W15')$sd_YoungsModulus,
        15,
        subset(data_means_sd, namelabels== '90/10,_W15')$mean_YoungsModulus-subset(data_means_sd, namelabels== '90/10,_W15')$sd_YoungsModulus,
        code=3,length=0.015,angle=90,col='deeppink',lwd=0.7)


points((5),           #x0
        (subset(data_means_sd, namelabels== '80/20,_W5')$mean_YoungsModulus),
        col= 'navy' ,pch=16, cex=1)
arrows(5,
        subset(data_means_sd, namelabels== '80/20,_W5')$mean_YoungsModulus+subset(data_means_sd, namelabels== '80/20,_W5')$sd_YoungsModulus,
        5,
        subset(data_means_sd, namelabels== '80/20,_W5')$mean_YoungsModulus-subset(data_means_sd, namelabels== '80/20,_W5')$sd_YoungsModulus,
        code=3,length=0.015,angle=90,col='navy',lwd=0.7)
```

```r
points((10),          #x0
       (subset(data_means_sd, namelabels== '80/20, W10')$mean_YoungsModulus),
       col= 'limegreen' ,pch=16, cex=1)
arrows(10,
       subset(data_means_sd, namelabels== '80/20, W10')$mean_YoungsModulus+subset(data_means_sd, namelabels== '80/20, W10')$sd_YoungsModulus,
       10,
       subset(data_means_sd, namelabels== '80/20, W10')$mean_YoungsModulus-subset(data_means_sd, namelabels== '80/20, W10')$sd_YoungsModulus,
       code=3,length=0.015,angle=90,col='limegreen',lwd=0.7)


points((5),          #x0
       (subset(data_means_sd, namelabels== '60/40, W5')$mean_YoungsModulus),
       col= 'navy' ,pch=17, cex=1)
arrows(5,
       subset(data_means_sd, namelabels== '60/40, W5')$mean_YoungsModulus+subset(data_means_sd, namelabels== '60/40, W5')$sd_YoungsModulus,
       5,
       subset(data_means_sd, namelabels== '60/40, W5')$mean_YoungsModulus-subset(data_means_sd, namelabels== '60/40, W5')$sd_YoungsModulus,
       code=3,length=0.015,angle=90,col='navy',lwd=0.7)


points((10),          #x0
       (subset(data_means_sd, namelabels== '60/40, W10')$mean_YoungsModulus),
       col= 'limegreen' ,pch=17, cex=1)
arrows(10,
       subset(data_means_sd, namelabels== '60/40, W10')$mean_YoungsModulus+subset(data_means_sd, namelabels== '60/40, W10')$sd_YoungsModulus,
       10,
       subset(data_means_sd, namelabels== '60/40, W10')$mean_YoungsModulus-subset(data_means_sd, namelabels== '60/40, W10')$sd_YoungsModulus,
       code=3,length=0.015,angle=90,col='limegreen',lwd=0.7)

legend("topright", legend = c("HS", "W2-90-10","W5-90-10", "W10-90-10", "W15-90-10", "W5-80-20",
                              "W10-80-20","W5-60-40","W10-60-40"),
       pch = c(18 , 15, 15, 15, 15, 16, 16, 17, 17), cex= 0.7,
       col=c('black', 'red','navy',"limegreen","deeppink","navy","limegreen",
             'navy','limegreen'),lty=c(1))

dev.off()



#fracture strain vs transition length

pdf(file = paste("plotsforpaper_Fracture/","Fracture_strain_vs_transition_length",".pdf",sep=""), width=6,height=3, bg="transparent")
par(family = "serif", mar=c(3,3,2,1),mgp=c(2,1,0),omi=c(0,0,0, 0), font= 1,font.main=1,cex=1,cex.main=1,cex.lab=1)
plot(NULL, NULL, xlim =c(0,25), ylim=c(0.2,0.30), xlab ="Transition length [%]",ylab = "Fracture strain",
    main = "Fracture strain vs Transition length" ,cex=1,tck=0.02)
axis(side = 3, tck=0.02, labels = FALSE)
axis(side = 4, tck=0.02, labels = FALSE)
grid(nx = NULL, ny = NULL, col = "lightgray", lty = "dotted")

points((0),          #x0
       (subset(data_means_sd, namelabels== '100/0, W0')$mean_Strain_at_maxstress),
       col= 'black' ,pch=18, cex=1)
arrows((0),
       subset(data_means_sd, namelabels== '100/0, W0')$mean_Strain_at_maxstress+subset(data_means_sd, namelabels== '100/0, W0')$sd_Strain_at_maxstress,
       (0),
       subset(data_means_sd, namelabels== '100/0, W0')$mean_Strain_at_maxstress-subset(data_means_sd, namelabels== '100/0, W0')$sd_Strain_at_maxstress,
       code=3,length=0.015,angle=90,col='black',lwd=0.7)

points((2),          #x0
       (subset(data_means_sd, namelabels== '90/10, W2')$mean_Strain_at_maxstress),
       col= 'red' ,pch=15, cex=1)
arrows((2),
       subset(data_means_sd, namelabels== '90/10, W2')$mean_Strain_at_maxstress+subset(data_means_sd, namelabels== '90/10, W2')$sd_Strain_at_maxstress,
       (2),
       subset(data_means_sd, namelabels== '90/10, W2')$mean_Strain_at_maxstress-subset(data_means_sd, namelabels== '90/10, W2')$sd_Strain_at_maxstress,
       code=3,length=0.015,angle=90,col='red',lwd=0.7)


points((5),          #x0
       (subset(data_means_sd, namelabels== '90/10, W5')$mean_Strain_at_maxstress),
       col= 'navy' ,pch=15, cex=1)
arrows(5,
       subset(data_means_sd, namelabels== '90/10, W5')$mean_Strain_at_maxstress+subset(data_means_sd, namelabels== '90/10, W5')$sd_Strain_at_maxstress,
       5,
       subset(data_means_sd, namelabels== '90/10, W5')$mean_Strain_at_maxstress-subset(data_means_sd, namelabels== '90/10, W5')$sd_Strain_at_maxstress,
       code=3,length=0.015,angle=90,col='navy',lwd=0.7)

points((10),          #x0
       (subset(data_means_sd, namelabels== '90/10, W10')$mean_Strain_at_maxstress),
       col= 'limegreen' ,pch=15, cex=1)
arrows((10),
       subset(data_means_sd, namelabels== '90/10, W10')$mean_Strain_at_maxstress+subset(data_means_sd, namelabels== '90/10, W10')$sd_Strain_at_maxstress,
       (10),
       subset(data_means_sd, namelabels== '90/10, W10')$mean_Strain_at_maxstress-subset(data_means_sd, namelabels== '90/10, W10')$sd_Strain_at_maxstress,
       code=3,length=0.015,angle=90,col='limegreen',lwd=0.7)


points((15),          #x0
       (subset(data_means_sd, namelabels== '90/10, W15')$mean_Strain_at_maxstress),
       col= 'deeppink' ,pch=15, cex=1)
arrows(15,
       subset(data_means_sd, namelabels== '90/10, W15')$mean_Strain_at_maxstress+subset(data_means_sd, namelabels== '90/10, W15')$sd_Strain_at_maxstress,
       15,
       subset(data_means_sd, namelabels== '90/10, W15')$mean_Strain_at_maxstress-subset(data_means_sd, namelabels== '90/10, W15')$sd_Strain_at_maxstress,
       code=3,length=0.015,angle=90,col='deeppink',lwd=0.7)


points((5),          #x0
       (subset(data_means_sd, namelabels== '80/20, W5')$mean_Strain_at_maxstress),
       col= 'navy' ,pch=16, cex=1)
arrows(5,
       subset(data_means_sd, namelabels== '80/20, W5')$mean_Strain_at_maxstress+subset(data_means_sd, namelabels== '80/20, W5')$sd_Strain_at_maxstress,
       5,
       subset(data_means_sd, namelabels== '80/20, W5')$mean_Strain_at_maxstress-subset(data_means_sd, namelabels== '80/20, W5')$sd_Strain_at_maxstress,
       code=3,length=0.015,angle=90,col='navy',lwd=0.7)
```

```
points((10),                #x0
       (subset(data_means_sd, namelabels== '80/20, W10')$mean_Strain_at_maxstress),
       col= 'limegreen' ,pch=16, cex=1)
arrows(10,
       subset(data_means_sd, namelabels== '80/20, W10')$mean_Strain_at_maxstress+subset(data_means_sd, namelabels== '80/20, W10')$sd_Strain_at_maxstress,
       10,
       subset(data_means_sd, namelabels== '80/20, W10')$mean_Strain_at_maxstress-subset(data_means_sd, namelabels== '80/20, W10')$sd_Strain_at_maxstress,
       code=3,length=0.015,angle=90,col='limegreen',lwd=0.7)


points((5),                #x0
       (subset(data_means_sd, namelabels== '60/40, W5')$mean_Strain_at_maxstress),
       col= 'navy' ,pch=17, cex=1)
arrows(5,
       subset(data_means_sd, namelabels== '60/40, W5')$mean_Strain_at_maxstress+subset(data_means_sd, namelabels== '60/40, W5')$sd_Strain_at_maxstress,
       5,
       subset(data_means_sd, namelabels== '60/40, W5')$mean_Strain_at_maxstress-subset(data_means_sd, namelabels== '60/40, W5')$sd_Strain_at_maxstress,
       code=3,length=0.015,angle=90,col='navy',lwd=0.7)


points((10),                #x0
       (subset(data_means_sd, namelabels== '60/40, W10')$mean_Strain_at_maxstress),
       col= 'limegreen' ,pch=17, cex=1)
arrows(10,
       subset(data_means_sd, namelabels== '60/40, W10')$mean_Strain_at_maxstress+subset(data_means_sd, namelabels== '60/40, W10')$sd_Strain_at_maxstress,
       10,
       subset(data_means_sd, namelabels== '60/40, W10')$mean_Strain_at_maxstress-subset(data_means_sd, namelabels== '60/40, W10')$sd_Strain_at_maxstress,
       code=3,length=0.015,angle=90,col='limegreen',lwd=0.7)



legend("topright", legend = c("HS", "W2-90-10","W5-90-10", "W10-90-10", "W15-90-10", "W5-80-20",
                              "W10-80-20","W5-60-40","W10-60-40"),
       pch = c(18 , 15, 15, 15, 15, 16, 16, 17, 17), cex= 0.7,
       col=c('black',  'red','navy',"limegreen","deeppink","navy","limegreen",
             'navy','limegreen'),lty=c(1))
dev.off()



#fracture stress vs transition length    (staat onder ultimate strength (maar die is eig voor de tensile))

pdf(file = paste("plotsforpaper_Fracture/","Fracture_stress_vs_transition_length",".pdf",sep=""), width=6,height=3, bg="transparent")
par(family = "serif", mar=c(3,3,2,1),mgp=c(2,1,0),omi=c(0,0,0, 0), font= 1,font.main=1,cex=1,cex.main=1,cex.lab=1)
plot(NULL, NULL, xlim =c(0,25), ylim=c(0.25,0.45), xlab ="Transition length [%]",ylab = "Fracture stress [MPa]",
     main = "Fracture stress vs Transition length" ,cex=1,tck=0.02)
axis(side = 3, tck=0.02, labels = FALSE)
axis(side = 4, tck=0.02, labels = FALSE)
grid(nx = NULL, ny = NULL, col = "lightgray", lty = "dotted")

points((0),                #x0
       (subset(data_means_sd, namelabels== '100/0, W0')$mean_Ultimate_strength),
       col= 'black' ,pch=18, cex=1)
arrows((0),
       subset(data_means_sd, namelabels== '100/0, W0')$mean_Ultimate_strength+subset(data_means_sd, namelabels== '100/0, W0')$sd_Ultimate_strength,
       (0),
       subset(data_means_sd, namelabels== '100/0, W0')$mean_Ultimate_strength-subset(data_means_sd, namelabels== '100/0, W0')$sd_Ultimate_strength,
       code=3,length=0.015,angle=90,col='black',lwd=0.7)


 points((2),                #x0
       (subset(data_means_sd, namelabels== '90/10, W2')$mean_Ultimate_strength),
       col= 'red' ,pch=15, cex=1)
arrows((2),
       subset(data_means_sd, namelabels== '90/10, W2')$mean_Ultimate_strength+subset(data_means_sd, namelabels== '90/10, W2')$sd_Ultimate_strength,
       (2),
       subset(data_means_sd, namelabels== '90/10, W2')$mean_Ultimate_strength-subset(data_means_sd, namelabels== '90/10, W2')$sd_Ultimate_strength,
       code=3,length=0.015,angle=90,col='red',lwd=0.7)


points((5),                #x0
       (subset(data_means_sd, namelabels== '90/10, W5')$mean_Ultimate_strength),
       col= 'navy' ,pch=15, cex=1)
arrows(5,
       subset(data_means_sd, namelabels== '90/10, W5')$mean_Ultimate_strength+subset(data_means_sd, namelabels== '90/10, W5')$sd_Ultimate_strength,
       5,
       subset(data_means_sd, namelabels== '90/10, W5')$mean_Ultimate_strength-subset(data_means_sd, namelabels== '90/10, W5')$sd_Ultimate_strength,
       code=3,length=0.015,angle=90,col='navy',lwd=0.7)

points((10),                #x0
       (subset(data_means_sd, namelabels== '90/10, W10')$mean_Ultimate_strength),
       col= 'limegreen' ,pch=15, cex=1)
arrows((10),
       subset(data_means_sd, namelabels== '90/10, W10')$mean_Ultimate_strength+subset(data_means_sd, namelabels== '90/10, W10')$sd_Ultimate_strength,
       (10),
       subset(data_means_sd, namelabels== '90/10, W10')$mean_Ultimate_strength-subset(data_means_sd, namelabels== '90/10, W10')$sd_Ultimate_strength,
       code=3,length=0.015,angle=90,col='limegreen',lwd=0.7)


points((15),                #x0
       (subset(data_means_sd, namelabels== '90/10, W15')$mean_Ultimate_strength),
       col= 'deeppink' ,pch=15, cex=1)
arrows(15,
       subset(data_means_sd, namelabels== '90/10, W15')$mean_Ultimate_strength+subset(data_means_sd, namelabels== '90/10, W15')$sd_Ultimate_strength,
       15,
       subset(data_means_sd, namelabels== '90/10, W15')$mean_Ultimate_strength-subset(data_means_sd, namelabels== '90/10, W15')$sd_Ultimate_strength,
       code=3,length=0.015,angle=90,col='deeppink',lwd=0.7)


points((5),                #x0
       (subset(data_means_sd, namelabels== '80/20, W5')$mean_Ultimate_strength),
       col= 'navy' ,pch=16, cex=1)
arrows(5,
       subset(data_means_sd, namelabels== '80/20, W5')$mean_Ultimate_strength+subset(data_means_sd, namelabels== '80/20, W5')$sd_Ultimate_strength,
       5,
```

```
        subset(data_means_sd, namelabels== '80/20,_W5')$mean_Ultimate_strength-subset(data_means_sd, namelabels== '80/20,_W5')$sd_Ultimate_strength,
        code=3,length=0.015,angle=90,col='navy',lwd=0.7)


points((10),                #x0
        (subset(data_means_sd, namelabels== '80/20,_W10')$mean_Ultimate_strength),
        col= 'limegreen' ,pch=16, cex=1)
arrows(10,
        subset(data_means_sd, namelabels== '80/20,_W10')$mean_Ultimate_strength+subset(data_means_sd, namelabels== '80/20,_W10')$sd_Ultimate_strength,
        10,
        subset(data_means_sd, namelabels== '80/20,_W10')$mean_Ultimate_strength-subset(data_means_sd, namelabels== '80/20,_W10')$sd_Ultimate_strength,
        code=3,length=0.015,angle=90,col='limegreen',lwd=0.7)


points((5),                #x0
        (subset(data_means_sd, namelabels== '60/40,_W5')$mean_Ultimate_strength),
        col= 'navy' ,pch=17, cex=1)
arrows(5,
        subset(data_means_sd, namelabels== '60/40,_W5')$mean_Ultimate_strength+subset(data_means_sd, namelabels== '60/40,_W5')$sd_Ultimate_strength,
        5,
        subset(data_means_sd, namelabels== '60/40,_W5')$mean_Ultimate_strength-subset(data_means_sd, namelabels== '60/40,_W5')$sd_Ultimate_strength,
        code=3,length=0.015,angle=90,col='navy',lwd=0.7)


points((10),                #x0
        (subset(data_means_sd, namelabels== '60/40,_W10')$mean_Ultimate_strength),
        col= 'limegreen' ,pch=17, cex=1)
arrows(10,
        subset(data_means_sd, namelabels== '60/40,_W10')$mean_Ultimate_strength+subset(data_means_sd, namelabels== '60/40,_W10')$sd_Ultimate_strength,
        10,
        subset(data_means_sd, namelabels== '60/40,_W10')$mean_Ultimate_strength-subset(data_means_sd, namelabels== '60/40,_W10')$sd_Ultimate_strength,
        code=3,length=0.015,angle=90,col='limegreen',lwd=0.7)


legend("topright", legend = c("HS", "W2-90-10","W5-90-10", "W10-90-10", "W15-90-10", "W5-80-20",
                              "W10-80-20","W5-60-40","W10-60-40"),
        pch = c(18 , 15, 15, 15, 15, 16, 16, 17, 17), cex= 0.7,
        col=c('black', 'red','navy',"limegreen","deeppink","navy","limegreen",
              'navy','limegreen'),lty=c(1))

dev.off()


#######################################################################################################################################################

# Fracture stress vs Fracture Toughness

pdf(file = paste("plotsforpaper_Fracture/","stress_FractureToughness",".pdf",sep=""), width=6,height=3, bg="transparent")
par(family = "serif", mar=c(3,3,2,1),mgp=c(2,1,0),omi=c(0,0,0, 0), font= 1,font.main=1,cex=1,cex.main=1,cex.lab=1)
plot(NULL, NULL, xlim =c(0.25,0.6), ylim=c(0.04,0.09), xlab ="Fracture_stress_[MPa]",ylab = "Fracture_Toughness_[MJ/m^3]",
     main = "Fracture_stress_vs_Fracture_Toughness" ,cex=1,tck=0.02)
axis(side = 3, tck=0.02, labels = FALSE)
axis(side = 4, tck=0.02, labels = FALSE)
grid(nx = NULL, ny = NULL, col = "lightgray", lty = "dotted")

points((subset(data_means_sd, namelabels== '100/0,_W0')$mean_Ultimate_strength),               #x0
        (subset(data_means_sd, namelabels== '100/0,_W0')$mean_Fracture_toughness),
        col= 'black' ,pch=18, cex=1)
arrows(subset(data_means_sd, namelabels== '100/0,_W0')$mean_Ultimate_strength,
        subset(data_means_sd, namelabels== '100/0,_W0')$mean_Fracture_toughness+subset(data_means_sd, namelabels== '100/0,_W0')$sd_Fracture_toughness,
        subset(data_means_sd, namelabels== '100/0,_W0')$mean_Ultimate_strength,
        subset(data_means_sd, namelabels== '100/0,_W0')$mean_Fracture_toughness-subset(data_means_sd, namelabels== '100/0,_W0')$sd_Fracture_toughness,
        code=3,length=0.015,angle=90,col='black',lwd=0.7)
arrows(subset(data_means_sd, namelabels== '100/0,_W0')$mean_Ultimate_strength-subset(data_means_sd, namelabels== '100/0,_W0')$sd_Ultimate_strength,
        subset(data_means_sd, namelabels== '100/0,_W0')$mean_Fracture_toughness,
        subset(data_means_sd, namelabels== '100/0,_W0')$mean_Ultimate_strength+subset(data_means_sd, namelabels== '100/0,_W0')$sd_Ultimate_strength,
        subset(data_means_sd, namelabels== '100/0,_W0')$mean_Fracture_toughness,
        code=3,length=0.015,angle=90,col='black',lwd=0.7)

points((subset(data_means_sd, namelabels== '90/10,_W2')$mean_Ultimate_strength),               #x0
        (subset(data_means_sd, namelabels== '90/10,_W2')$mean_Fracture_toughness),
        col= 'red' ,pch=15, cex=1)
arrows(subset(data_means_sd, namelabels== '90/10,_W2')$mean_Ultimate_strength,
        subset(data_means_sd, namelabels== '90/10,_W2')$mean_Fracture_toughness+subset(data_means_sd, namelabels== '90/10,_W2')$sd_Fracture_toughness,
        subset(data_means_sd, namelabels== '90/10,_W2')$mean_Ultimate_strength,
        subset(data_means_sd, namelabels== '90/10,_W2')$mean_Fracture_toughness-subset(data_means_sd, namelabels== '90/10,_W2')$sd_Fracture_toughness,
        code=3,length=0.015,angle=90,col='red',lwd=0.7)
arrows(subset(data_means_sd, namelabels== '90/10,_W2')$mean_Ultimate_strength-subset(data_means_sd, namelabels== '90/10,_W2')$sd_Ultimate_strength,
        subset(data_means_sd, namelabels== '90/10,_W2')$mean_Fracture_toughness,
        subset(data_means_sd, namelabels== '90/10,_W2')$mean_Ultimate_strength+subset(data_means_sd, namelabels== '90/10,_W2')$sd_Ultimate_strength,
        subset(data_means_sd, namelabels== '90/10,_W2')$mean_Fracture_toughness,
        code=3,length=0.015,angle=90,col='red',lwd=0.7)


points((subset(data_means_sd, namelabels== '90/10,_W5')$mean_Ultimate_strength),               #x0
        (subset(data_means_sd, namelabels== '90/10,_W5')$mean_Fracture_toughness),
        col= 'navy' ,pch=15, cex=1)
arrows(subset(data_means_sd, namelabels== '90/10,_W5')$mean_Ultimate_strength,
        subset(data_means_sd, namelabels== '90/10,_W5')$mean_Fracture_toughness+subset(data_means_sd, namelabels== '90/10,_W5')$sd_Fracture_toughness,
        subset(data_means_sd, namelabels== '90/10,_W5')$mean_Ultimate_strength,
        subset(data_means_sd, namelabels== '90/10,_W5')$mean_Fracture_toughness-subset(data_means_sd, namelabels== '90/10,_W5')$sd_Fracture_toughness,
        code=3,length=0.015,angle=90,col='navy',lwd=0.7)
arrows(subset(data_means_sd, namelabels== '90/10,_W5')$mean_Ultimate_strength-subset(data_means_sd, namelabels== '90/10,_W5')$sd_Ultimate_strength,
        subset(data_means_sd, namelabels== '90/10,_W5')$mean_Fracture_toughness,
        subset(data_means_sd, namelabels== '90/10,_W5')$mean_Ultimate_strength+subset(data_means_sd, namelabels== '90/10,_W5')$sd_Ultimate_strength,
        subset(data_means_sd, namelabels== '90/10,_W5')$mean_Fracture_toughness,
        code=3,length=0.015,angle=90,col='navy',lwd=0.7)

points((subset(data_means_sd, namelabels== '90/10,_W10')$mean_Ultimate_strength),               #x0
        (subset(data_means_sd, namelabels== '90/10,_W10')$mean_Fracture_toughness),
        col= 'limegreen' ,pch=15, cex=1)
arrows(subset(data_means_sd, namelabels== '90/10,_W10')$mean_Ultimate_strength,
        subset(data_means_sd, namelabels== '90/10,_W10')$mean_Fracture_toughness+subset(data_means_sd, namelabels== '90/10,_W10')$sd_Fracture_toughness,
        subset(data_means_sd, namelabels== '90/10,_W10')$mean_Ultimate_strength,
        subset(data_means_sd, namelabels== '90/10,_W10')$mean_Fracture_toughness-subset(data_means_sd, namelabels== '90/10,_W10')$sd_Fracture_toughness,
        code=3,length=0.015,angle=90,col='limegreen',lwd=0.7)
arrows(subset(data_means_sd, namelabels== '90/10,_W10')$mean_Ultimate_strength-subset(data_means_sd, namelabels== '90/10,_W10')$sd_Ultimate_strength,
```

```r
        subset(data_means_sd, namelabels== '90/10, W10')$mean_Fracture_toughness,
        subset(data_means_sd, namelabels== '90/10, W10')$mean_Ultimate_strength+subset(data_means_sd, namelabels== '90/10, W10')$sd_Ultimate_strength,
        subset(data_means_sd, namelabels== '90/10, W10')$mean_Fracture_toughness,
        code=3,length=0.015,angle=90,col='limegreen',lwd=0.7)

points((subset(data_means_sd, namelabels== '90/10, W15')$mean_Ultimate_strength),          #x0
        (subset(data_means_sd, namelabels== '90/10, W15')$mean_Fracture_toughness),
        col= 'deeppink' ,pch=15, cex=1)
arrows(subset(data_means_sd, namelabels== '90/10, W15')$mean_Ultimate_strength,
        subset(data_means_sd, namelabels== '90/10, W15')$mean_Fracture_toughness+subset(data_means_sd, namelabels== '90/10, W15')$sd_Fracture_toughness,
        subset(data_means_sd, namelabels== '90/10, W15')$mean_Ultimate_strength,
        subset(data_means_sd, namelabels== '90/10, W15')$mean_Fracture_toughness-subset(data_means_sd, namelabels== '90/10, W15')$sd_Fracture_toughness,
        code=3,length=0.015,angle=90,col='deeppink',lwd=0.7)
arrows(subset(data_means_sd, namelabels== '90/10, W15')$mean_Ultimate_strength-subset(data_means_sd, namelabels== '90/10, W15')$sd_Ultimate_strength,
        subset(data_means_sd, namelabels== '90/10, W15')$mean_Fracture_toughness,
        subset(data_means_sd, namelabels== '90/10, W15')$mean_Ultimate_strength+subset(data_means_sd, namelabels== '90/10, W15')$sd_Ultimate_strength,
        subset(data_means_sd, namelabels== '90/10, W15')$mean_Fracture_toughness,
        code=3,length=0.015,angle=90,col='deeppink',lwd=0.7)

points((subset(data_means_sd, namelabels== '80/20, W5')$mean_Ultimate_strength),          #x0
        (subset(data_means_sd, namelabels== '80/20, W5')$mean_Fracture_toughness),
        col= 'navy' ,pch=16, cex=1)
arrows(subset(data_means_sd, namelabels== '80/20, W5')$mean_Ultimate_strength,
        subset(data_means_sd, namelabels== '80/20, W5')$mean_Fracture_toughness+subset(data_means_sd, namelabels== '80/20, W5')$sd_Fracture_toughness,
        subset(data_means_sd, namelabels== '80/20, W5')$mean_Ultimate_strength,
        subset(data_means_sd, namelabels== '80/20, W5')$mean_Fracture_toughness-subset(data_means_sd, namelabels== '80/20, W5')$sd_Fracture_toughness,
        code=3,length=0.015,angle=90,col='navy',lwd=0.7)
arrows(subset(data_means_sd, namelabels== '80/20, W5')$mean_Ultimate_strength-subset(data_means_sd, namelabels== '80/20, W5')$sd_Ultimate_strength,
        subset(data_means_sd, namelabels== '80/20, W5')$mean_Fracture_toughness,
        subset(data_means_sd, namelabels== '80/20, W5')$mean_Ultimate_strength+subset(data_means_sd, namelabels== '80/20, W5')$sd_Ultimate_strength,
        subset(data_means_sd, namelabels== '80/20, W5')$mean_Fracture_toughness,
        code=3,length=0.015,angle=90,col='navy',lwd=0.7)

points((subset(data_means_sd, namelabels== '80/20, W10')$mean_Ultimate_strength),          #x0
        (subset(data_means_sd, namelabels== '80/20, W10')$mean_Fracture_toughness),
        col= 'limegreen' ,pch=16, cex=1)
arrows(subset(data_means_sd, namelabels== '80/20, W10')$mean_Ultimate_strength,
        subset(data_means_sd, namelabels== '80/20, W10')$mean_Fracture_toughness+subset(data_means_sd, namelabels== '80/20, W10')$sd_Fracture_toughness,
        subset(data_means_sd, namelabels== '80/20, W10')$mean_Ultimate_strength,
        subset(data_means_sd, namelabels== '80/20, W10')$mean_Fracture_toughness-subset(data_means_sd, namelabels== '80/20, W10')$sd_Fracture_toughness,
        code=3,length=0.015,angle=90,col='limegreen',lwd=0.7)
arrows(subset(data_means_sd, namelabels== '80/20, W10')$mean_Ultimate_strength-subset(data_means_sd, namelabels== '80/20, W10')$sd_Ultimate_strength,
        subset(data_means_sd, namelabels== '80/20, W10')$mean_Fracture_toughness,
        subset(data_means_sd, namelabels== '80/20, W10')$mean_Ultimate_strength+subset(data_means_sd, namelabels== '80/20, W10')$sd_Ultimate_strength,
        subset(data_means_sd, namelabels== '80/20, W10')$mean_Fracture_toughness,
        code=3,length=0.015,angle=90,col='limegreen',lwd=0.7)

points((subset(data_means_sd, namelabels== '60/40, W5')$mean_Ultimate_strength),          #x0
        (subset(data_means_sd, namelabels== '60/40, W5')$mean_Fracture_toughness),
        col= 'navy' ,pch=17, cex=1)
arrows(subset(data_means_sd, namelabels== '60/40, W5')$mean_Ultimate_strength,
        subset(data_means_sd, namelabels== '60/40, W5')$mean_Fracture_toughness+subset(data_means_sd, namelabels== '60/40, W5')$sd_Fracture_toughness,
        subset(data_means_sd, namelabels== '60/40, W5')$mean_Ultimate_strength,
        subset(data_means_sd, namelabels== '60/40, W5')$mean_Fracture_toughness-subset(data_means_sd, namelabels== '60/40, W5')$sd_Fracture_toughness,
        code=3,length=0.015,angle=90,col='navy',lwd=0.7)
arrows(subset(data_means_sd, namelabels== '60/40, W5')$mean_Ultimate_strength-subset(data_means_sd, namelabels== '60/40, W5')$sd_Ultimate_strength,
        subset(data_means_sd, namelabels== '60/40, W5')$mean_Fracture_toughness,
        subset(data_means_sd, namelabels== '60/40, W5')$mean_Ultimate_strength+subset(data_means_sd, namelabels== '60/40, W5')$sd_Ultimate_strength,
        subset(data_means_sd, namelabels== '60/40, W5')$mean_Fracture_toughness,
        code=3,length=0.015,angle=90,col='navy',lwd=0.7)

points((subset(data_means_sd, namelabels== '60/40, W10')$mean_Ultimate_strength),          #x0
        (subset(data_means_sd, namelabels== '60/40, W10')$mean_Fracture_toughness),
        col= 'limegreen' ,pch=17, cex=1)
arrows(subset(data_means_sd, namelabels== '60/40, W10')$mean_Ultimate_strength,
        subset(data_means_sd, namelabels== '60/40, W10')$mean_Fracture_toughness+subset(data_means_sd, namelabels== '60/40, W10')$sd_Fracture_toughness,
        subset(data_means_sd, namelabels== '60/40, W10')$mean_Ultimate_strength,
        subset(data_means_sd, namelabels== '60/40, W10')$mean_Fracture_toughness-subset(data_means_sd, namelabels== '60/40, W10')$sd_Fracture_toughness,
        code=3,length=0.015,angle=90,col='limegreen',lwd=0.7)
arrows(subset(data_means_sd, namelabels== '60/40, W10')$mean_Ultimate_strength-subset(data_means_sd, namelabels== '60/40, W10')$sd_Ultimate_strength,
        subset(data_means_sd, namelabels== '60/40, W10')$mean_Fracture_toughness,
        subset(data_means_sd, namelabels== '60/40, W10')$mean_Ultimate_strength+subset(data_means_sd, namelabels== '60/40, W10')$sd_Ultimate_strength,
        subset(data_means_sd, namelabels== '60/40, W10')$mean_Fracture_toughness,
        code=3,length=0.015,angle=90,col='limegreen',lwd=0.7)



legend("topright", legend = c("HS", "W2-90-10","W5-90-10", "W10-90-10", "W15-90-10", "W5-80-20",
                              "W10-80-20","W5-60-40","W10-60-40"),
        pch = c(18 , 15, 15, 15, 15, 16, 16, 17, 17), cex= 0.7,
        col=c('black',  'red','navy',"limegreen","deeppink","navy","limegreen",
              'navy','limegreen'),lty=c(1))

dev.off()



# Youngs Modulus vs transition gradient

pdf(file = paste("plotsforpaper_Fracture/","Youngs vs transition gradient",".pdf",sep=""), width=6,height=3, bg="transparent")
par(family = "serif", mar=c(3,3,2,1),mgp=c(2,1,0),omi=c(0,0,0, 0), font= 1,font.main=1,cex=1,cex.main=1,cex.lab=1)
plot(NULL, NULL, xlim =c(0,145), ylim=c(1.3,1.9), xlab ="Interface hard material [%]",ylab = "Young's Modulus [MPa]",
     main = "Young's Modulus vs Transition gradient" ,cex=1,tck=0.02)
axis(side = 3, tck=0.02, labels = FALSE)
axis(side = 4, tck=0.02, labels = FALSE)
grid(nx = NULL, ny = NULL, col = "lightgray", lty = "dotted")

points((100),          #x0
        (subset(data_means_sd, namelabels== '100/0, W0')$mean_YoungsModulus),
        col= 'black' ,pch=18, cex=1)
arrows((100),
        subset(data_means_sd, namelabels== '100/0, W0')$mean_YoungsModulus+subset(data_means_sd, namelabels== '100/0, W0')$sd_YoungsModulus,
        (100),
        subset(data_means_sd, namelabels== '100/0, W0')$mean_YoungsModulus-subset(data_means_sd, namelabels== '100/0, W0')$sd_YoungsModulus,
        code=3,length=0.015,angle=90,col='black',lwd=0.7)

points((80),          #x0
```

```
        (subset(data_means_sd, namelabels== '90/10,_W2')$mean_YoungsModulus),
        col= 'red' ,pch=15, cex=1)
arrows((80),
        subset(data_means_sd, namelabels== '90/10,_W2')$mean_YoungsModulus+subset(data_means_sd, namelabels== '90/10,_W2')$sd_YoungsModulus,
        (80),
        subset(data_means_sd, namelabels== '90/10,_W2')$mean_YoungsModulus-subset(data_means_sd, namelabels== '90/10,_W2')$sd_YoungsModulus,
        code=3,length=0.015,angle=90,col='red',lwd=0.7)


points((80),            #x0
        (subset(data_means_sd, namelabels== '90/10,_W5')$mean_YoungsModulus),
        col= 'navy' ,pch=15, cex=1)
arrows(80,
        subset(data_means_sd, namelabels== '90/10,_W5')$mean_YoungsModulus+subset(data_means_sd, namelabels== '90/10,_W5')$sd_YoungsModulus,
        80,
        subset(data_means_sd, namelabels== '90/10,_W5')$mean_YoungsModulus-subset(data_means_sd, namelabels== '90/10,_W5')$sd_YoungsModulus,
        code=3,length=0.015,angle=90,col='navy',lwd=0.7)

points((80),            #x0
        (subset(data_means_sd, namelabels== '90/10,_W10')$mean_YoungsModulus),
        col= 'limegreen' ,pch=15, cex=1)
arrows((80),
        subset(data_means_sd, namelabels== '90/10,_W10')$mean_YoungsModulus+subset(data_means_sd, namelabels== '90/10,_W10')$sd_YoungsModulus,
        (80),
        subset(data_means_sd, namelabels== '90/10,_W10')$mean_YoungsModulus-subset(data_means_sd, namelabels== '90/10,_W10')$sd_YoungsModulus,
        code=3,length=0.015,angle=90,col='limegreen',lwd=0.7)


points((80),            #x0
        (subset(data_means_sd, namelabels== '90/10,_W15')$mean_YoungsModulus),
        col= 'deeppink' ,pch=15, cex=1)
arrows(80,
        subset(data_means_sd, namelabels== '90/10,_W15')$mean_YoungsModulus+subset(data_means_sd, namelabels== '90/10,_W15')$sd_YoungsModulus,
        80,
        subset(data_means_sd, namelabels== '90/10,_W15')$mean_YoungsModulus-subset(data_means_sd, namelabels== '90/10,_W15')$sd_YoungsModulus,
        code=3,length=0.015,angle=90,col='deeppink',lwd=0.7)


points((60),            #x0
        (subset(data_means_sd, namelabels== '80/20,_W5')$mean_YoungsModulus),
        col= 'navy' ,pch=16, cex=1)
arrows(60,
        subset(data_means_sd, namelabels== '80/20,_W5')$mean_YoungsModulus+subset(data_means_sd, namelabels== '80/20,_W5')$sd_YoungsModulus,
        60,
        subset(data_means_sd, namelabels== '80/20,_W5')$mean_YoungsModulus-subset(data_means_sd, namelabels== '80/20,_W5')$sd_YoungsModulus,
        code=3,length=0.015,angle=90,col='navy',lwd=0.7)


points((60),            #x0
        (subset(data_means_sd, namelabels== '80/20,_W10')$mean_YoungsModulus),
        col= 'limegreen' ,pch=16, cex=1)
arrows(60,
        subset(data_means_sd, namelabels== '80/20,_W10')$mean_YoungsModulus+subset(data_means_sd, namelabels== '80/20,_W10')$sd_YoungsModulus,
        60,
        subset(data_means_sd, namelabels== '80/20,_W10')$mean_YoungsModulus-subset(data_means_sd, namelabels== '80/20,_W10')$sd_YoungsModulus,
        code=3,length=0.015,angle=90,col='limegreen',lwd=0.7)


points((20),            #x0
        (subset(data_means_sd, namelabels== '60/40,_W5')$mean_YoungsModulus),
        col= 'navy' ,pch=17, cex=1)
arrows(20,
        subset(data_means_sd, namelabels== '60/40,_W5')$mean_YoungsModulus+subset(data_means_sd, namelabels== '60/40,_W5')$sd_YoungsModulus,
        20,
        subset(data_means_sd, namelabels== '60/40,_W5')$mean_YoungsModulus-subset(data_means_sd, namelabels== '60/40,_W5')$sd_YoungsModulus,
        code=3,length=0.015,angle=90,col='navy',lwd=0.7)


points((20),            #x0
        (subset(data_means_sd, namelabels== '60/40,_W10')$mean_YoungsModulus),
        col= 'limegreen' ,pch=17, cex=1)
arrows(20,
        subset(data_means_sd, namelabels== '60/40,_W10')$mean_YoungsModulus+subset(data_means_sd, namelabels== '60/40,_W10')$sd_YoungsModulus,
        20,
        subset(data_means_sd, namelabels== '60/40,_W10')$mean_YoungsModulus-subset(data_means_sd, namelabels== '60/40,_W10')$sd_YoungsModulus,
        code=3,length=0.015,angle=90,col='limegreen',lwd=0.7)


legend("topright", legend = c("HS", "W2-90-10","W5-90-10", "W10-90-10", "W15-90-10", "W5-80-20",
                              "W10-80-20","W5-60-40","W10-60-40"),
        pch = c(18 , 15, 15, 15, 15, 16, 16, 17, 17), cex= 0.7,
        col=c('black',  'red','navy',"limegreen","deeppink","navy","limegreen",
              'navy','limegreen'),lty=c(1))
dev.off()



# Fracture Toughness vs transition gradient

pdf(file = paste("plotsforpaper_Fracture/","Fracture_Toughness_vs_transition_gradient",".pdf",sep=""), width=6,height=3, bg="transparent")
par(family = "serif", mar=c(3,3,2,1),mgp=c(2,1,0),omi=c(0,0,0, 0), font= 1,font.main=1,cex=1,cex.main=1,cex.lab=1)
plot(NULL, NULL, xlim =c(0,145), ylim=c(0.04,0.09), xlab ="Interface_hard_material_[%]",ylab = "Fracture_Toughness_[MPa]",
     main = "Fracture_Toughness_vs_Transition_gradient" ,cex=1,tck=0.02)
axis(side = 3, tck=0.02, labels = FALSE)
axis(side = 4, tck=0.02, labels = FALSE)
grid(nx = NULL, ny = NULL, col = "lightgray", lty = "dotted")

points((100),            #x0
        (subset(data_means_sd, namelabels== '100/0,_W0')$mean_Fracture_toughness),
        col= 'black' ,pch=18, cex=1)
arrows((100),
        subset(data_means_sd, namelabels== '100/0,_W0')$mean_Fracture_toughness+subset(data_means_sd, namelabels== '100/0,_W0')$sd_Fracture_toughness,
        (100),
        subset(data_means_sd, namelabels== '100/0,_W0')$mean_Fracture_toughness-subset(data_means_sd, namelabels== '100/0,_W0')$sd_Fracture_toughness,
        code=3,length=0.015,angle=90,col='black',lwd=0.7)
```

```
points((80),            #x0
       (subset(data_means_sd, namelabels== '90/10,_W2')$mean_Fracture_toughness),
       col= 'red' ,pch=15, cex=1)
arrows((80),
       subset(data_means_sd, namelabels== '90/10,_W2')$mean_Fracture_toughness+subset(data_means_sd, namelabels== '90/10,_W2')$sd_Fracture_toughness,
       (80),
       subset(data_means_sd, namelabels== '90/10,_W2')$mean_Fracture_toughness-subset(data_means_sd, namelabels== '90/10,_W2')$sd_Fracture_toughness,
       code=3,length=0.015,angle=90,col='red',lwd=0.7)


points((80),            #x0
       (subset(data_means_sd, namelabels== '90/10,_W5')$mean_Fracture_toughness),
       col= 'navy' ,pch=15, cex=1)
arrows(80,
       subset(data_means_sd, namelabels== '90/10,_W5')$mean_Fracture_toughness+subset(data_means_sd, namelabels== '90/10,_W5')$sd_Fracture_toughness,
       80,
       subset(data_means_sd, namelabels== '90/10,_W5')$mean_Fracture_toughness-subset(data_means_sd, namelabels== '90/10,_W5')$sd_Fracture_toughness,
       code=3,length=0.015,angle=90,col='navy',lwd=0.7)

points((80),            #x0
       (subset(data_means_sd, namelabels== '90/10,_W10')$mean_Fracture_toughness),
       col= 'limegreen' ,pch=15, cex=1)
arrows((80),
       subset(data_means_sd, namelabels== '90/10,_W10')$mean_Fracture_toughness+subset(data_means_sd, namelabels== '90/10,_W10')$sd_Fracture_toughness,
       (80),
       subset(data_means_sd, namelabels== '90/10,_W10')$mean_Fracture_toughness-subset(data_means_sd, namelabels== '90/10,_W10')$sd_Fracture_toughness,
       code=3,length=0.015,angle=90,col='limegreen',lwd=0.7)


points((80),            #x0
       (subset(data_means_sd, namelabels== '90/10,_W15')$mean_Fracture_toughness),
       col= 'deeppink' ,pch=15, cex=1)
arrows(80,
       subset(data_means_sd, namelabels== '90/10,_W15')$mean_Fracture_toughness+subset(data_means_sd, namelabels== '90/10,_W15')$sd_Fracture_toughness,
       80,
       subset(data_means_sd, namelabels== '90/10,_W15')$mean_Fracture_toughness-subset(data_means_sd, namelabels== '90/10,_W15')$sd_Fracture_toughness,
       code=3,length=0.015,angle=90,col='deeppink',lwd=0.7)


points((60),            #x0
       (subset(data_means_sd, namelabels== '80/20,_W5')$mean_Fracture_toughness),
       col= 'navy' ,pch=16, cex=1)
arrows(60,
       subset(data_means_sd, namelabels== '80/20,_W5')$mean_Fracture_toughness+subset(data_means_sd, namelabels== '80/20,_W5')$sd_Fracture_toughness,
       60,
       subset(data_means_sd, namelabels== '80/20,_W5')$mean_Fracture_toughness-subset(data_means_sd, namelabels== '80/20,_W5')$sd_Fracture_toughness,
       code=3,length=0.015,angle=90,col='navy',lwd=0.7)


points((60),            #x0
       (subset(data_means_sd, namelabels== '80/20,_W10')$mean_Fracture_toughness),
       col= 'limegreen' ,pch=16, cex=1)
arrows(60,
       subset(data_means_sd, namelabels== '80/20,_W10')$mean_Fracture_toughness+subset(data_means_sd, namelabels== '80/20,_W10')$sd_Fracture_toughness,
       60,
       subset(data_means_sd, namelabels== '80/20,_W10')$mean_Fracture_toughness-subset(data_means_sd, namelabels== '80/20,_W10')$sd_Fracture_toughness,
       code=3,length=0.015,angle=90,col='limegreen',lwd=0.7)


points((20),            #x0
       (subset(data_means_sd, namelabels== '60/40,_W5')$mean_Fracture_toughness),
       col= 'navy' ,pch=17, cex=1)
arrows(20,
       subset(data_means_sd, namelabels== '60/40,_W5')$mean_Fracture_toughness+subset(data_means_sd, namelabels== '60/40,_W5')$sd_Fracture_toughness,
       20,
       subset(data_means_sd, namelabels== '60/40,_W5')$mean_Fracture_toughness-subset(data_means_sd, namelabels== '60/40,_W5')$sd_Fracture_toughness,
       code=3,length=0.015,angle=90,col='navy',lwd=0.7)


points((20),            #x0
       (subset(data_means_sd, namelabels== '60/40,_W10')$mean_Fracture_toughness),
       col= 'limegreen' ,pch=17, cex=1)
arrows(20,
       subset(data_means_sd, namelabels== '60/40,_W10')$mean_Fracture_toughness+subset(data_means_sd, namelabels== '60/40,_W10')$sd_Fracture_toughness,
       20,
       subset(data_means_sd, namelabels== '60/40,_W10')$mean_Fracture_toughness-subset(data_means_sd, namelabels== '60/40,_W10')$sd_Fracture_toughness,
       code=3,length=0.015,angle=90,col='limegreen',lwd=0.7)


legend("topright", legend = c("HS", "W2-90-10","W5-90-10", "W10-90-10", "W15-90-10", "W5-80-20",
                              "W10-80-20","W5-60-40","W10-60-40"),
       pch = c(18 , 15, 15, 15, 15, 16, 16, 17, 17), cex= 0.7,
       col=c('black',  'red','navy',"limegreen","deeppink","navy","limegreen",
             'navy','limegreen'),lty=c(1))
dev.off()
```

```
#fracture strain vs transition gradient

pdf(file = paste("plotsforpaper_Fracture/","Fracture_strain_vs_transition_gradient",".pdf",sep=""), width=6,height=3, bg="transparent")
par(family = "serif", mar=c(3,3,2,1),mgp=c(2,1,0),omi=c(0,0,0, 0), font= 1,font.main=1,cex=1,cex.main=1,cex.lab=1)
plot(NULL, NULL, xlim =c(0,145), ylim=c(0.2,0.30), xlab ="Interface_hard_material_[%]",ylab = "Fracture_strain",
     main = "Fracture_strain_vs_Transition_gradient" ,cex=1,tck=0.02)
axis(side = 3, tck=0.02, labels = FALSE)
axis(side = 4, tck=0.02, labels = FALSE)
```

```r
grid(nx = NULL, ny = NULL, col = "lightgray", lty = "dotted")

points((100),              #x0
       (subset(data_means_sd, namelabels== '100/0, W0')$mean_Strain_at_maxstress),
       col= 'black' ,pch=18, cex=1)
arrows((100),
       subset(data_means_sd, namelabels== '100/0, W0')$mean_Strain_at_maxstress+subset(data_means_sd, namelabels== '100/0, W0')$sd_Strain_at_maxstress,
       (100),
       subset(data_means_sd, namelabels== '100/0, W0')$mean_Strain_at_maxstress-subset(data_means_sd, namelabels== '100/0, W0')$sd_Strain_at_maxstress,
       code=3,length=0.015,angle=90,col='black',lwd=0.7)

points((80),              #x0
       (subset(data_means_sd, namelabels== '90/10, W2')$mean_Strain_at_maxstress),
       col= 'red' ,pch=15, cex=1)
arrows((80),
       subset(data_means_sd, namelabels== '90/10, W2')$mean_Strain_at_maxstress+subset(data_means_sd, namelabels== '90/10, W2')$sd_Strain_at_maxstress,
       (80),
       subset(data_means_sd, namelabels== '90/10, W2')$mean_Strain_at_maxstress-subset(data_means_sd, namelabels== '90/10, W2')$sd_Strain_at_maxstress,
       code=3,length=0.015,angle=90,col='red',lwd=0.7)


points((80),              #x0
       (subset(data_means_sd, namelabels== '90/10, W5')$mean_Strain_at_maxstress),
       col= 'navy' ,pch=15, cex=1)
arrows(80,
       subset(data_means_sd, namelabels== '90/10, W5')$mean_Strain_at_maxstress+subset(data_means_sd, namelabels== '90/10, W5')$sd_Strain_at_maxstress,
       80,
       subset(data_means_sd, namelabels== '90/10, W5')$mean_Strain_at_maxstress-subset(data_means_sd, namelabels== '90/10, W5')$sd_Strain_at_maxstress,
       code=3,length=0.015,angle=90,col='navy',lwd=0.7)

points((80),              #x0
       (subset(data_means_sd, namelabels== '90/10, W10')$mean_Strain_at_maxstress),
       col= 'limegreen' ,pch=15, cex=1)
arrows((80),
       subset(data_means_sd, namelabels== '90/10, W10')$mean_Strain_at_maxstress+subset(data_means_sd, namelabels== '90/10, W10')$sd_Strain_at_maxstress,
       (80),
       subset(data_means_sd, namelabels== '90/10, W10')$mean_Strain_at_maxstress-subset(data_means_sd, namelabels== '90/10, W10')$sd_Strain_at_maxstress,
       code=3,length=0.015,angle=90,col='limegreen',lwd=0.7)


points((80),              #x0
       (subset(data_means_sd, namelabels== '90/10, W15')$mean_Strain_at_maxstress),
       col= 'deeppink' ,pch=15, cex=1)
arrows(80,
       subset(data_means_sd, namelabels== '90/10, W15')$mean_Strain_at_maxstress+subset(data_means_sd, namelabels== '90/10, W15')$sd_Strain_at_maxstress,
       80,
       subset(data_means_sd, namelabels== '90/10, W15')$mean_Strain_at_maxstress-subset(data_means_sd, namelabels== '90/10, W15')$sd_Strain_at_maxstress,
       code=3,length=0.015,angle=90,col='deeppink',lwd=0.7)


points((60),              #x0
       (subset(data_means_sd, namelabels== '80/20, W5')$mean_Strain_at_maxstress),
       col= 'navy' ,pch=16, cex=1)
arrows(60,
       subset(data_means_sd, namelabels== '80/20, W5')$mean_Strain_at_maxstress+subset(data_means_sd, namelabels== '80/20, W5')$sd_Strain_at_maxstress,
       60,
       subset(data_means_sd, namelabels== '80/20, W5')$mean_Strain_at_maxstress-subset(data_means_sd, namelabels== '80/20, W5')$sd_Strain_at_maxstress,
       code=3,length=0.015,angle=90,col='navy',lwd=0.7)


points((60),              #x0
       (subset(data_means_sd, namelabels== '80/20, W10')$mean_Strain_at_maxstress),
       col= 'limegreen' ,pch=16, cex=1)
arrows(60,
       subset(data_means_sd, namelabels== '80/20, W10')$mean_Strain_at_maxstress+subset(data_means_sd, namelabels== '80/20, W10')$sd_Strain_at_maxstress,
       60,
       subset(data_means_sd, namelabels== '80/20, W10')$mean_Strain_at_maxstress-subset(data_means_sd, namelabels== '80/20, W10')$sd_Strain_at_maxstress,
       code=3,length=0.015,angle=90,col='limegreen',lwd=0.7)


points((20),              #x0
       (subset(data_means_sd, namelabels== '60/40, W5')$mean_Strain_at_maxstress),
       col= 'navy' ,pch=17, cex=1)
arrows(20,
       subset(data_means_sd, namelabels== '60/40, W5')$mean_Strain_at_maxstress+subset(data_means_sd, namelabels== '60/40, W5')$sd_Strain_at_maxstress,
       20,
       subset(data_means_sd, namelabels== '60/40, W5')$mean_Strain_at_maxstress-subset(data_means_sd, namelabels== '60/40, W5')$sd_Strain_at_maxstress,
       code=3,length=0.015,angle=90,col='navy',lwd=0.7)


points((20),              #x0
       (subset(data_means_sd, namelabels== '60/40, W10')$mean_Strain_at_maxstress),
       col= 'limegreen' ,pch=17, cex=1)
arrows(20,
       subset(data_means_sd, namelabels== '60/40, W10')$mean_Strain_at_maxstress+subset(data_means_sd, namelabels== '60/40, W10')$sd_Strain_at_maxstress,
       20,
       subset(data_means_sd, namelabels== '60/40, W10')$mean_Strain_at_maxstress-subset(data_means_sd, namelabels== '60/40, W10')$sd_Strain_at_maxstress,
       code=3,length=0.015,angle=90,col='limegreen',lwd=0.7)


legend("topright", legend = c("HS", "W2-90-10","W5-90-10", "W10-90-10", "W15-90-10", "W5-80-20",
                              "W10-80-20","W5-60-40","W10-60-40"),
       pch = c(18 , 15, 15, 15, 15, 16, 16, 17, 17), cex= 0.7,
       col=c('black', 'red','navy',"limegreen","deeppink","navy","limegreen",
             'navy','limegreen'),lty=c(1))
dev.off()


#fracture stress vs transition gradient    (staat onder ultimate strength (maar die is eig voor de tensile))

pdf(file = paste("plotsforpaper_Fracture/","Fracture_stress_vs_transition_gradient",".pdf",sep=""), width=6,height=3, bg="transparent")
par(family = "serif", mar=c(3,3,2,1),mgp=c(2,1,0),omi=c(0,0,0, 0), font= 1,font.main=1,cex=1,cex.main=1,cex.lab=1)
plot(NULL, NULL, xlim =c(0,145), ylim=c(0.25,0.45), xlab ="Interface hard material [%]",ylab = "Fracture stress [MPa]",
     main = "Fracture stress vs Transition gradient" ,cex=1,tck=0.02)
axis(side = 3, tck=0.02, labels = FALSE)
axis(side = 4, tck=0.02, labels = FALSE)
```

```
grid(nx = NULL, ny = NULL, col = "lightgray", lty = "dotted")

points((100),                #x0
       (subset(data_means_sd, namelabels== '100/0,_W0')$mean_Ultimate_strength),
       col= 'black' ,pch=18, cex=1)
arrows((100),
       subset(data_means_sd, namelabels== '100/0,_W0')$mean_Ultimate_strength+subset(data_means_sd, namelabels== '100/0,_W0')$sd_Ultimate_strength,
       (100),
       subset(data_means_sd, namelabels== '100/0,_W0')$mean_Ultimate_strength-subset(data_means_sd, namelabels== '100/0,_W0')$sd_Ultimate_strength,
       code=3,length=0.015,angle=90,col='black',lwd=0.7)


points((80),                #x0
       (subset(data_means_sd, namelabels== '90/10,_W2')$mean_Ultimate_strength),
       col= 'red' ,pch=15, cex=1)
arrows((80),
       subset(data_means_sd, namelabels== '90/10,_W2')$mean_Ultimate_strength+subset(data_means_sd, namelabels== '90/10,_W2')$sd_Ultimate_strength,
       (80),
       subset(data_means_sd, namelabels== '90/10,_W2')$mean_Ultimate_strength-subset(data_means_sd, namelabels== '90/10,_W2')$sd_Ultimate_strength,
       code=3,length=0.015,angle=90,col='red',lwd=0.7)


points((80),                #x0
       (subset(data_means_sd, namelabels== '90/10,_W5')$mean_Ultimate_strength),
       col= 'navy' ,pch=15, cex=1)
arrows(80,
       subset(data_means_sd, namelabels== '90/10,_W5')$mean_Ultimate_strength+subset(data_means_sd, namelabels== '90/10,_W5')$sd_Ultimate_strength,
       80,
       subset(data_means_sd, namelabels== '90/10,_W5')$mean_Ultimate_strength-subset(data_means_sd, namelabels== '90/10,_W5')$sd_Ultimate_strength,
       code=3,length=0.015,angle=90,col='navy',lwd=0.7)

points((80),                #x0
       (subset(data_means_sd, namelabels== '90/10,_W10')$mean_Ultimate_strength),
       col= 'limegreen' ,pch=15, cex=1)
arrows((80),
       subset(data_means_sd, namelabels== '90/10,_W10')$mean_Ultimate_strength+subset(data_means_sd, namelabels== '90/10,_W10')$sd_Ultimate_strength,
       (80),
       subset(data_means_sd, namelabels== '90/10,_W10')$mean_Ultimate_strength-subset(data_means_sd, namelabels== '90/10,_W10')$sd_Ultimate_strength,
       code=3,length=0.015,angle=90,col='limegreen',lwd=0.7)


points((80),                #x0
       (subset(data_means_sd, namelabels== '90/10,_W15')$mean_Ultimate_strength),
       col= 'deeppink' ,pch=15, cex=1)
arrows(80,
       subset(data_means_sd, namelabels== '90/10,_W15')$mean_Ultimate_strength+subset(data_means_sd, namelabels== '90/10,_W15')$sd_Ultimate_strength,
       80,
       subset(data_means_sd, namelabels== '90/10,_W15')$mean_Ultimate_strength-subset(data_means_sd, namelabels== '90/10,_W15')$sd_Ultimate_strength,
       code=3,length=0.015,angle=90,col='deeppink',lwd=0.7)


points((60),                #x0
       (subset(data_means_sd, namelabels== '80/20,_W5')$mean_Ultimate_strength),
       col= 'navy' ,pch=16, cex=1)
arrows(60,
       subset(data_means_sd, namelabels== '80/20,_W5')$mean_Ultimate_strength+subset(data_means_sd, namelabels== '80/20,_W5')$sd_Ultimate_strength,
       60,
       subset(data_means_sd, namelabels== '80/20,_W5')$mean_Ultimate_strength-subset(data_means_sd, namelabels== '80/20,_W5')$sd_Ultimate_strength,
       code=3,length=0.015,angle=90,col='navy',lwd=0.7)


points((60),                #x0
       (subset(data_means_sd, namelabels== '80/20,_W10')$mean_Ultimate_strength),
       col= 'limegreen' ,pch=16, cex=1)
arrows(60,
       subset(data_means_sd, namelabels== '80/20,_W10')$mean_Ultimate_strength+subset(data_means_sd, namelabels== '80/20,_W10')$sd_Ultimate_strength,
       60,
       subset(data_means_sd, namelabels== '80/20,_W10')$mean_Ultimate_strength-subset(data_means_sd, namelabels== '80/20,_W10')$sd_Ultimate_strength,
       code=3,length=0.015,angle=90,col='limegreen',lwd=0.7)


points((20),                #x0
       (subset(data_means_sd, namelabels== '60/40,_W5')$mean_Ultimate_strength),
       col= 'navy' ,pch=17, cex=1)
arrows(20,
       subset(data_means_sd, namelabels== '60/40,_W5')$mean_Ultimate_strength+subset(data_means_sd, namelabels== '60/40,_W5')$sd_Ultimate_strength,
       20,
       subset(data_means_sd, namelabels== '60/40,_W5')$mean_Ultimate_strength-subset(data_means_sd, namelabels== '60/40,_W5')$sd_Ultimate_strength,
       code=3,length=0.015,angle=90,col='navy',lwd=0.7)


points((20),                #x0
       (subset(data_means_sd, namelabels== '60/40,_W10')$mean_Ultimate_strength),
       col= 'limegreen' ,pch=17, cex=1)
arrows(20,
       subset(data_means_sd, namelabels== '60/40,_W10')$mean_Ultimate_strength+subset(data_means_sd, namelabels== '60/40,_W10')$sd_Ultimate_strength,
       20,
       subset(data_means_sd, namelabels== '60/40,_W10')$mean_Ultimate_strength-subset(data_means_sd, namelabels== '60/40,_W10')$sd_Ultimate_strength,
       code=3,length=0.015,angle=90,col='limegreen',lwd=0.7)


legend("topright", legend = c("HS", "W2-90-10","W5-90-10", "W10-90-10", "W15-90-10", "W5-80-20",
                              "W10-80-20","W5-60-40","W10-60-40"),
       pch = c(18 , 15, 15, 15, 15, 16, 16, 17, 17), cex= 0.7,
       col=c('black',  'red','navy',"limegreen","deeppink","navy","limegreen",
             'navy','limegreen'),lty=c(1))

dev.off()
##########################################################################################################################################
```

G Matlab Code

G.1 The main Matlab code

```
%%
close all;
clear all;
clc;


%MaskPattern=imread('MaskPattern.bmp'); %%Imread of the crack of the fracture sample
%[height,~] = size(imread('MaskPattern.bmp'));

% Mask = imread('MaskNew2.bmp');
Mask(64:181,1059:2031)=255; %%Dimension of the tensile specimen

%%Needed for the fracture specimen
% Mask=[];
%  for i=1:242
%      for j=1:4064
%          if Mask(i,j)==1
%              Mask(i,j)=255;
%          end
%      end
%  end

%% Width% - 2step linear interface

 width =38; %%width is L0, the amount of pixels in the length scale (Tensile = 1904 pixels, fracture)
 width_step=round(width/2); %%Half the length of the wifth

 percentage_step1=60; %%rho_h
 percentage_step2=40; %%rho_h'

 height_dogbone= 118; %% heigth of the specimen
 width_dogbone= 1904; %% width of the specimen

% interface = zeros(892,89);
step1 = zeros(height_dogbone,width_step);
step2 = step1;
figure;

%%Creating variables:
percent_hard1=[];
fraction_hard1=[];
sum_hard=[];

 for j=-1:3 %for 3 mm thick (103 layer for the fracture and 130 for the tensile)

step1(:,:) = linear_vert(118,width_step,100,60); %% ( hoogte, breedte step 1, % vanaf, %heen)
step2(:,:) = linear_vert(118,width_step,40,0);

interface = cat(2,step1,step2); %%interface consist of 2 steps, step 1 and step 2
interface1=[];

Mask(64:181, 1994:2031) = interface; %% Dimension on the interface in the middle of the specimen
% Mask(:, 2156:end)  = 0; %% Dimension of the soft material in a fracture
% specimen
interface1 = 255-interface; %% creating a corresponding interface from the soft material to clamps
Mask(64:181, 2925:2962) = interface1; %%Dimension of the second interface
Mask1 = Mask(64:181, 1059:2962); %%Dimension of the specimen between the clamps

imwrite((Mask1),'2step_interface.png');

values = zeros(2,width_dogbone); volume_frac=zeros(2,width_dogbone); percent_hard=[];
for g = 1:width_dogbone
[values(:,g),volume_frac(:,g),percent_hard(:,g)] = vol_frac (double(Mask1(:,g)));
end

percent_hard1(j+2,:)=percent_hard;

fraction_hard1(j+2,:)=mean(percent_hard);

sum_hard(j+2)=sum(percent_hard);

hold on;
plot(percent_hard,'-');
ylim([0, 100]);
title('Percentage of hard material');
ylabel('Percentage');
xlabel('Pixel width');
legend('HARD material');


applymask1(double(Mask1),15,j);
  destinationFolder = 'D:\my documents\WB jaar 4 - 2018\BEP\hele codeaangepast\5per';
  if ~exist(destinationFolder, 'dir')
  mkdir(destinationFolder);
  end
  baseFileName = sprintf('percent15_%d.png', j); % e.g. "1.png"
  fullFileName = fullfile(destinationFolder, baseFileName);
  imwrite(Mask1, fullFileName);

 end
  writeConfigurationFile('percent15',133)


M=mean(percent_hard1);
M_fraction_hard1=mean(fraction_hard1); %fraction of Mask1

figure
plot(M,'-');
ylim([0, 100]);
title('Percentage of hard material');
ylabel('Percentage');
xlabel('Pixel width');
```

```
legend('HARD material');

figure
plot(fraction_hard1,'-');
ylim([0, 100]);
title('Percentage of hard material');
ylabel('Percentage');
xlabel('Pixel width');
legend('HARD material');

%
```

G.2 The Linear distribution code

```
function [interface] = linear_vert(height,width,max,min)
% height - height of the region that you want to linearise
% width - width of the region that you want to linearize
% max,min - highest percentage,lowest percent(eg. 2 step - 100,90 and 10,0)
 %height=118;width=143;max=90;min=10;
Hard =zeros(1,width);
percentage=[];
     percentage=linspace(max,min,width);
     for i=1:width
         Hard(:,i)= (percentage(1,i));
     end
interface = (zeros(height,width));

interface_percent=Hard;
[pp ll] = size(interface_percent);
for k=1:width
interface(:,k) = randomize(118,1,(interface_percent(1,k)/100));
end

% for g = 1:143
% [values(:,g),volume_frac(:,g),percent_hard(:,g)] = vol_frac (double(interface(:,g)));
% end
end
```

G.3 The complying file code

```
function [] = applymask1( mat,no,j )
%UNTITLED5 Summary of this function goes here
%   Detailed explanation goes here
% mat=zeros(height,width); %use it as an auxiliary matrix
%  mat=double(Mask1);
%MaskTensile=double(imread('maskNew1.png'));
MaskTensile=double((imread('maskNew2.bmp')));%%%%%%%%%%%%%%%%5
MaskTensile(64:181,1059:2962)=0;
%MaskTensile(536:1480,121:356)=0;
[heightMask,widthMask]=size(MaskTensile);
auxMask=(zeros(heightMask, widthMask));
auxMaskB=(zeros(heightMask, widthMask));
%auxMaskB(2048,4096)=255;

%material A is hard material
% baseFileName = sprintf('HSH_sharptensile');
baseFileName = sprintf('percent%d', no);
makeOutputDir(baseFileName);
%Pattern_printed=double(imread(baseFileName));
 auxMask(64:181,1059:2962)=mat;
 B=1-mat; %only for pure hard
% B=255-mat;
auxMaskB(64:181,1059:2962)=B;

PatA=(auxMask+MaskTensile);%don't forget to create a pattern
PatB=(auxMaskB); %no se puede hacer
imwrite(PatB, 'sample.bmp');

PatC=(zeros(heightMask,widthMask));
%PatC(2048,4096)=1;

writeBitmaps1 ((PatA),(PatB),(PatC),baseFileName,j)
end
```