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Parametric Design of HDPE Testing Specimens for Boatbuilding Applications

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Abstract. Innovative materials have been used in boat construction in recent years; a thorough investigation of their mechanical and strength properties is required through comprehensive laboratory testing designed to characterize their suitability for maritime applications. An example of these materials is High-Density Polyethylene (HDPE), a thermoplastic polymer that has already found widespread use in other industrial sectors due to its durability, resistance to corrosion, ease of processing, and recyclable. To understand the proper approaches for the execution of mechanical tests, The relevant regulations and standards governing the preparation and testing of material specimens were thoroughly analyzed. In particular, International Organization for Standardization (ISO) and American Society for Testing and Materials International (ASTM) standards illustrate the geometry and dimension of the testing specimen. These standards are also referenced in the regulations of ship classification societies, which are beginning to provide recommendations on the use of this innovative material. However, sometimes the dimensions specified in the regulations must be reviewed and adapted to the raw material's shape and the testing machines available in the laboratories where the experimental testing campaign will be conducted. Based on these concepts, this paper aims to focus on the process of shaping prototypes for the experimental campaign using advanced parametric design software. These tools were compared with traditional two-dimensional drafting software to evaluate their effectiveness in terms of drawing adaptability, and efficiency. These findings underscore the importance of modern design tools in streamlining the experimental process and enhancing the overall reliability of material assessments.

Keywords. HDPE, boatbuilding, specimen geometry, parametric model, Grasshopper

1. Introduction

In recent years, the maritime industry has witnessed a growing interest in the adoption of innovative materials for boat construction [1], driven by the pursuit of enhanced performance, sustainability, and durability [2,3]. Among these materials, High-Density Polyethylene (HDPE), a thermoplastic polymer widely used in various industrial sectors,

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has emerged as a promising candidate due to its notable properties, including high durability, corrosion resistance, ease of processing, and recyclability [4,5]. Despite its increasing adoption, particularly in non-traditional marine applications, a comprehensive understanding of its mechanical behavior under maritime conditions remains limited.

To ensure the suitability of such materials for marine use [6,7], it is essential to conduct rigorous laboratory testing, informed by established standards and regulations. The International Organization for Standardization (ISO) and the American Society for Testing and Materials (ASTM) provide detailed guidelines on the geometry and dimensions of test specimens, which are increasingly being referenced by ship classification societies.

However, applying these standards to innovative materials like HDPE often requires adaptation due to the unique characteristics of the raw material and the specific capabilities of available laboratory equipment [8]. This necessitates a flexible approach to specimen design, accommodating variations in material form and testing apparatus.

In this context, advanced parametric design tools, such as Grasshopper integrated with Rhinoceros 3D, offer significant advantages [9,10]. These tools enable the creation of adaptable and precise digital models of test specimens, facilitating rapid adjustments to meet specific testing requirements. Parametric modeling allows for the efficient generation of both two-dimensional and three-dimensional representations, streamlining the design process [11].

So, this study explores the integration of advanced parametric design tools in the preparation of test specimens for experimental campaigns. By leveraging parametric modeling software, the process of designing and customizing specimen geometries can be significantly streamlined, offering improved adaptability and efficiency. The aim of this work is to assess the advantages of these digital tools in the context of experimental design, with particular attention to their role in facilitating compliance with regulatory standards and enhancing the reliability of mechanical characterization.

2. ISO and ASTM Standards

After a careful analysis of the regulations [12], the authors undertook an in-depth research into the existing standards to correctly identify both the geometries of the specimens and the experimental tests.
In particular, the International Organization for Standardization (ISO) and American Society for Testing and Materials (ASTM) standards were analyzed.

2.1. ISO standard

ISO 527 specifies the general principles for determining the tensile properties of plastics and plastic composites under defined conditions [13]. Within this standard, several types of test specimens are outlined, each designed to accommodate different categories of materials.

The methods described in the standard must be employed to investigate the tensile behavior of these specimens and to determine key mechanical properties such as tensile strength, tensile modulus, and other characteristics of the tensile stress–strain relationship under the specified conditions.

According to the procedure, the test specimen is extended along its principal longitudinal axis at a constant speed until either fracture occurs or a predetermined level of stress (load) or strain (elongation) is reached. During this process, the load applied to the specimen and the corresponding elongation are measured continuously. The methods can be applied to specimens that are either molded directly to the required dimensions or machined, cut, or punched from finished and semi-finished products, such as moldings, laminates, films, and extruded or cast sheets.

To ensure consistency and comparability of results, the standard specifies preferred dimensions for the test specimens. If tests are conducted using specimens of different dimensions or those prepared under varying conditions, the results may not be directly comparable. Additional variables, such as the testing speed and the preconditioning of the specimens, may also influence the outcomes. Therefore, when comparative data are needed, these factors must be carefully controlled and thoroughly documented.

The testing procedure requires that the specimen be extended along its primary longitudinal axis at a constant velocity until it fractures or until the stress or strain reaches a predetermined limit. Throughout this process, both the load sustained by the specimen and its elongation are recorded. The frequency of data acquisition must be sufficiently high to ensure accurate measurements of these parameters. Specifically, the data acquisition rate depends on:

- v: the test speed, in mm/min;
- L_0/L: the ratio between the actual length and the initial reference length;
- r: the minimum resolution, in mm, of the strain signal required to ensure measurement accuracy.

The test should be conducted in the same atmosphere used for conditioning the specimen, unless otherwise agreed upon by the involved parties—for instance, in cases where testing at elevated or reduced temperatures is required. The preferred standard atmosphere is (23 ± 2) °C and (50 ± 10) % relative humidity (RH), except when the material's properties are known to be insensitive to moisture, in which case humidity control is not necessary.

Regarding specimen geometry, the preferred types, whenever possible, are dumb-bell-shaped specimens of types 1A and 1B, as illustrated in Figure 1 and detailed in Table 1. Type 1A is intended for directly injection-molded multipurpose specimens, while type 1B is suitable for machined specimens. Type 1A may also be used for compression-molded specimens. Table 1 provides the specific dimensions corresponding to types 1A and 1B test specimens.

Table 1. Dimensions of type 1A and 1B test specimens [13].

	Specimen type	1A	1B
L_3	Overall length	170	≥ 150
L_1	Length of narrow parallel-sided portion	80 ÷ 2	60 ÷ 0.5
R	Radius	24 ÷ 1	60 ÷ 0.5
L_2	Distance between broad parallel-sided portions	109.3 ÷ 3.2	108 ÷ 1.6
B_2	Width at ends	20 ÷ 0.2	20 ÷ 0.2
B_1	Width at narrow portion	10 ÷ 0.2	10 ÷ 0.2
h	Preferred thickness	4 ÷ 0.2	4 ÷ 0.2
L_0	Gauge length (preferred)	75 ÷ 0.5	50 ÷ 0.5
L_0	Gauge length (acceptable if required for quality control or when specified)	50 ÷ 0.5	-
L	Initial distance between grips	115 ÷ 1	115 ÷ 1

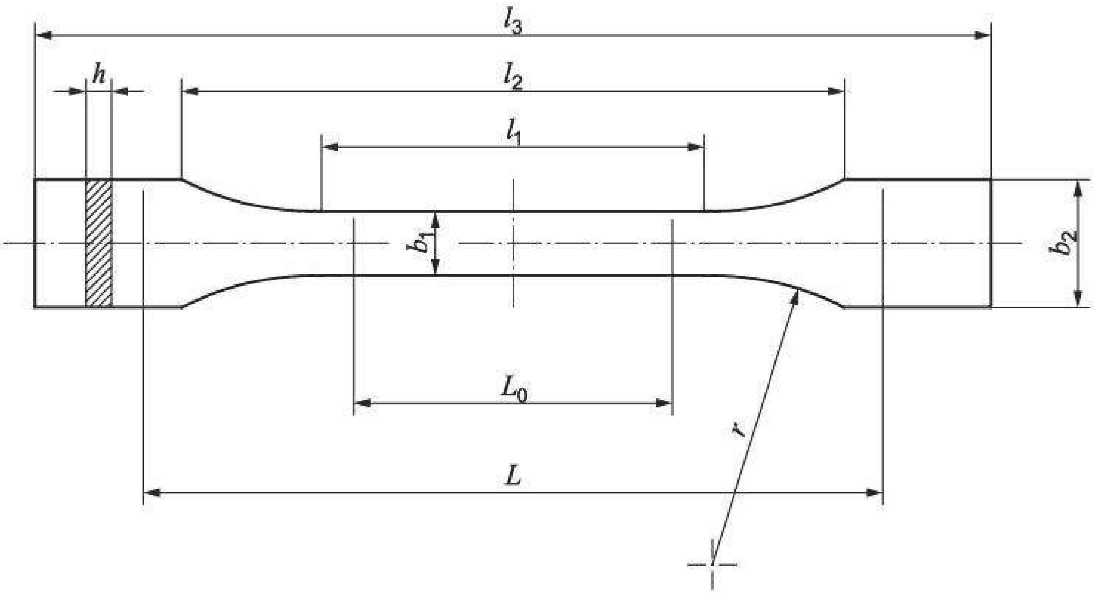

Figure 1. Specimen Type 1A and 1B.

2.2. ASTM Standard

This test method covers the determination of the tensile properties of unreinforced and reinforced plastics in the form of standard dumbbell-shaped test specimens when tested under defined conditions of pretreatment, temperature, humidity, and testing machine speed. This test method is applicable for testing materials of any thickness up to 14 mm (0.55 in.) [14]. However, for testing specimens in the form of thin sheeting, including film less than 1.0 mm (0.04 in.) in thickness, ASTM standard D882 is the preferred test method [15]. Materials with a thickness greater than 14 mm (0.55 in.) shall be reduced by machining. This test method includes the option of determining Poisson's ratio at room temperature.

The test specimen shall conform to the dimensions shown in Figure 2. The Type I specimen is the preferred specimen and shall be used where sufficient material having a thickness of 7 mm (0.28 in.) or less is available. The Type II specimen is recommended when a material does not break in the narrow section with the preferred Type I specimen. The Type V specimen shall be used where only limited material having a thickness of 4 mm (0.16 in.) or less is available for evaluation, or where a large number of specimens are to be exposed in a limited space (thermal and environmental stability tests, etc.). The Type III specimen must be used for all materials with a thickness of greater than 7 mm (0.28 in.) but not more than 14 mm (0.55 in.).

The test specimen shall conform to the dimensions shown in Figure 2. The Type III specimen must be used for all materials with a thickness greater than 7 mm (0.28 in.) but not more than 14 mm (0.55 in.). The test specimen for reinforced composites, including highly orthotropic laminates, shall conform to the dimensions of the Type I specimen shown in Figure 2. Methods of preparing test specimens include injection molding, machining operations, or die cutting, from materials in sheet, plate, slab, or similar form.

Table 2 illustrate the specimen dimensions as a function of the thickness from ASTM Standard.

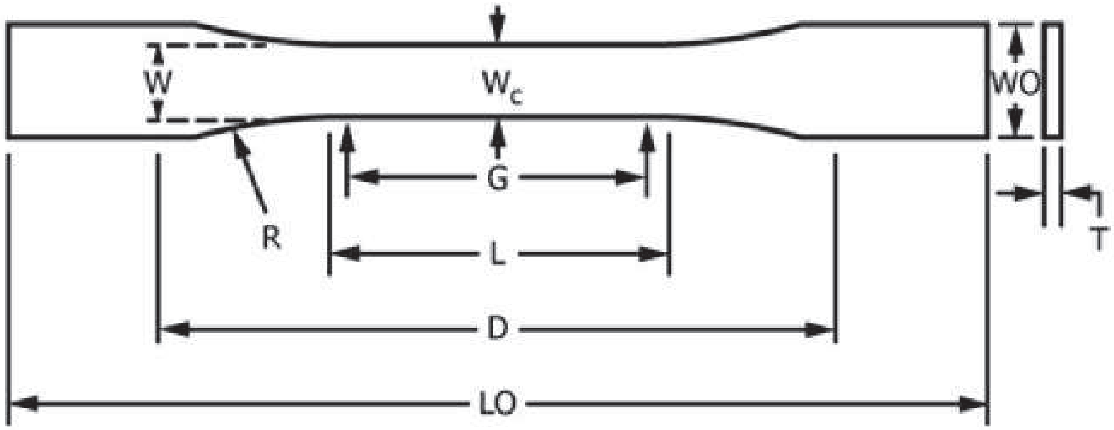

Figure 2 - Specimen Type I, II, III, and V.

Table 2. Specimen dimensions from ASTM Standard [14].

Dimensions	Type I 7 (0.28) or under	Type II 7 (0.28) or under	Type III Over 7 to 14 (0.28 to 0.55)	Type V 4 (0.16) or under	Tolerance
W – Width of narrow section	13 (0.5)	6 (0.25)	19 (0.75)	3.18 (0.125)	± 0.5 (± 0.02)
L – Length of narrow section	57 (2.25)	57 (2.25)	57 (2.25)	9.53 (0.375)	± 0.5 (± 0.02)
W_0 – Width overall, min	19 (0.75)	19 (0.75)	29 (1.13)		+ 6.4 (+ 0.25)
W_0 – Width overall, min				9.53 (0.375)	+ 3.18 (+ 0.125)
L_0 – Length overall, min	165 (6.5)	183 (7.2)	246 (9.7)	63.5 (2.5)	No max
G – Gage length	50 (2)	50 (2)	50 (2)	7.62 (0.3)	± 0.25 (± 0.01)
D – Distance between grips	115 (4.5)	135 (5.3)	115 (4.5)	25.4 (1)	± 0.5 (± 0.2)
R – Radius of fillet	76 (3)	76 (3)	76 (3)	12.7 (0.5)	± 1 (± 0.04)
R_0 – Outer radius					± 1 (± 0.04)

The main dimensions are all in millimeters – mm - and in (inches) in this table.

3. Geometries of specimens

For the purposes of the present study and the related experimental campaign on HDPE, the authors first focused on simplified rectangular-shaped specimens as presented in [12] and deriving from other tensile tests performed in the past on various materials [16].

After a thorough and in-depth review of the regulations and technical standards cited in the previous chapters, it became necessary to reconsider the geometric shapes and dimensions of the specimens, taking into account the specific requirements of the machinery used for the experimental tests. This step was essential to ensure that the tests could be conducted correctly and that the obtained results were reliable and compliant with the applicable regulations.

During this phase of analysis, it emerged that the use of simple rectangular specimens was incompatible with the limitations imposed by the testing equipment. Specifically, the available machinery exhibited significant constraints regarding the length, thickness, and width of the specimens, making it impossible to test samples with thicknesses exceeding 15 mm, lengths greater than 180 mm, and widths exceeding 40 mm. These restrictions necessitated a redefinition of the specimen shapes, leading to the adoption of a dog-bone geometry, which is better suited to the characteristics of the tests to be performed and allows for optimal load application during mechanical testing.

The selection of this new geometry required a rapid update of the technical drawings associated with the various specimens. Due to the necessity of completing this task within a limited timeframe and with a high degree of precision, a workflow based on advanced digital tools was adopted—specifically, the use of Grasshopper. This graphical algorithm editor operates as a plug-in for Rhino® and is seamlessly integrated with its 3D modeling environment. It enables the efficient creation, manipulation, and modification of complex geometric and organic forms across a wide range of scales, from small design objects to large architectural structures. Grasshopper operates through the construction of node-based diagrams that define the mathematical and geometric relationships within a 3D model. This methodology allows the generation of intricate three-dimensional geometries, which can be dynamically updated by modifying the input parameters specified during the initial diagram setup. Such real-time parametric control provides immediate benefits in terms of formal analysis and design flexibility [17, 18].

One of the key advantages of Grasshopper lies in its ability to produce an immediate three-dimensional representation of the desired object, thereby eliminating the need for an intermediate 2D modeling phase followed by 3D conversion [19]. This significantly streamlines the design process and enables rapid updates to the geometry by simply adjusting the input parameters. By defining the main dimensions of the specimens—such as length, width, thickness, and fillet radius—the software can automatically generate basic shapes, which can then be refined and combined to form more complex configurations. An additional strength of this approach is the capability to incorporate mathematical formulas and relationships that correlate the various geometric dimensions. As a result, any modification to a parameter automatically propagates throughout the model, maintaining internal coherence. Furthermore, Grasshopper provides a wide array of built-in functions that facilitate process automation and support the rapid development of a code structure capable of generating the required 3D geometry with both precision and efficiency [20].

Figure 3 shows the code developed for generating the 3D models. In particular, the variable parameters selected include the specimen length—identified as having the greatest influence on machine compatibility—along with the grip width, the width of the specimen's useful area (to ensure a square cross-section), and the thickness. In Figure 4, the authors show the preview of the specimens as they appear within the software before being exported into the required formats for the subsequent production or simulation phase. This methodology has not only accelerated and optimized the design phase but has also ensured greater accuracy in the definition of geometries, reducing the risk of errors and enhancing the overall process of specimen fabrication. In addition to these advantages, this type of software directly provides the two-dimensional drawing files that can be used on computer numerical control (CNC) machines for the production of the desired specimens

Finally, Figure 5 - Figure 8 display the specimens used for experimental campaign. In particular, Figure 5 shows the dog bone specimen for tensile test; Figure 6 depicts the specimen for head-welded tensile testing; Figure 7 illustrates the specimen used for angle-welded tensile testing; and finally, Figure 8 shows the specimen for tensile testing using metal bolts.

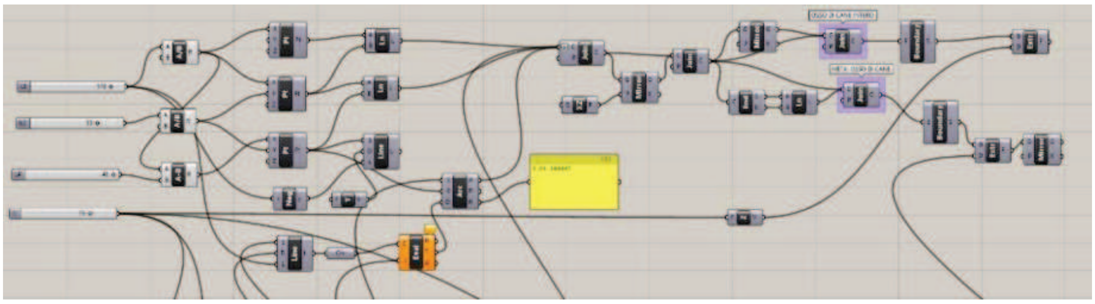

Figure 3 - Example of the code in Grasshopper.

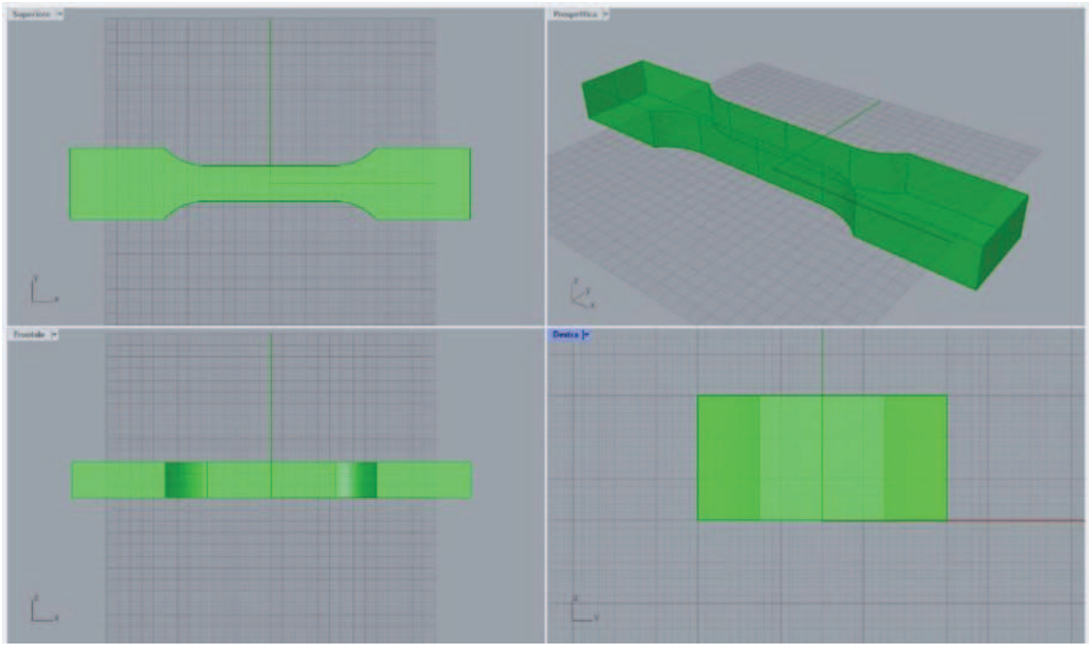

Figure 4 - Example of the geometry of the specimen in Grasshopper.

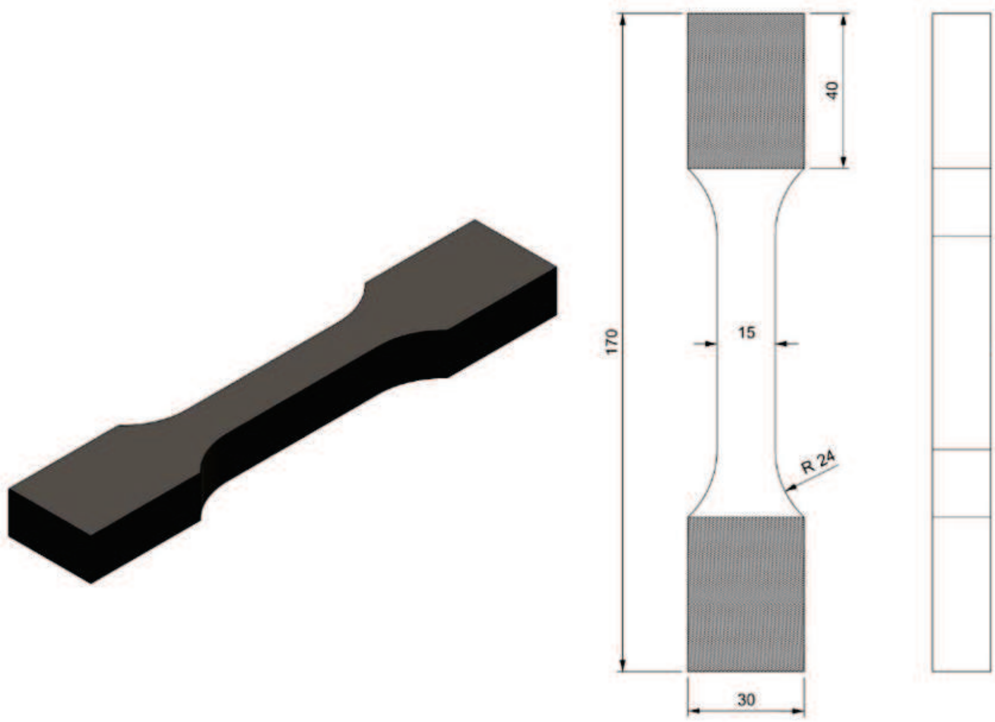

Figure 5 - Tensile test specimen, dog bone.

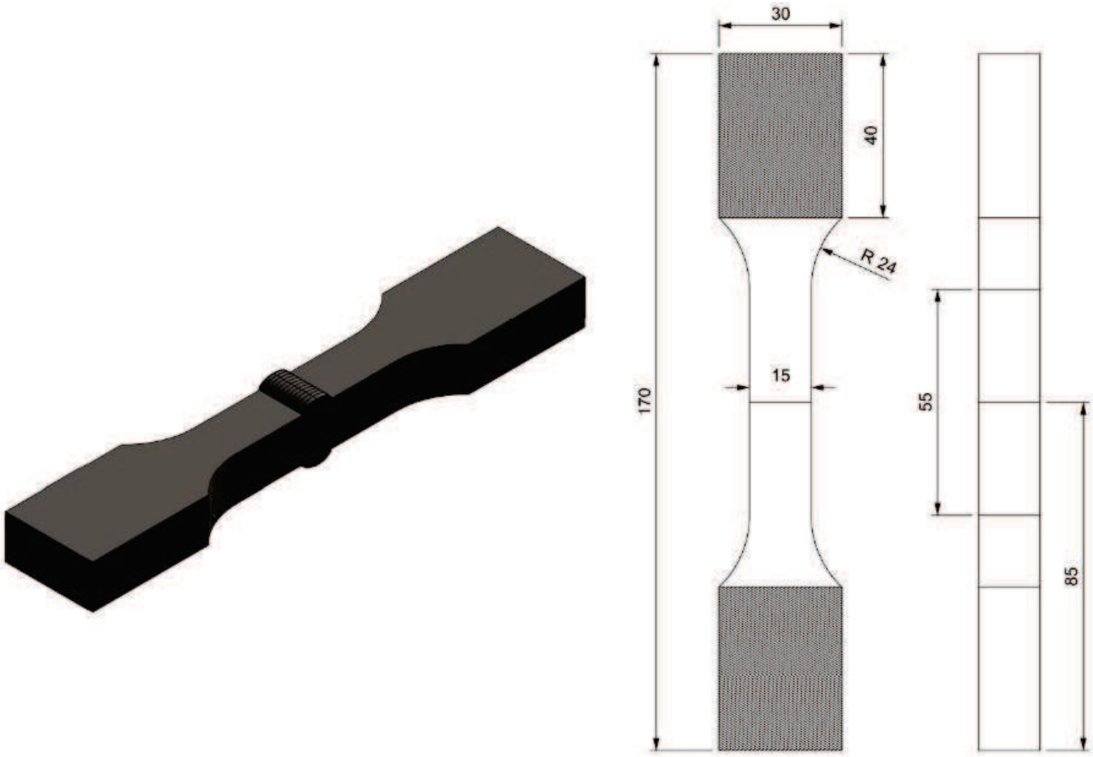

Figure 6 - Tensile test specimen, dog bone, with butt welding.

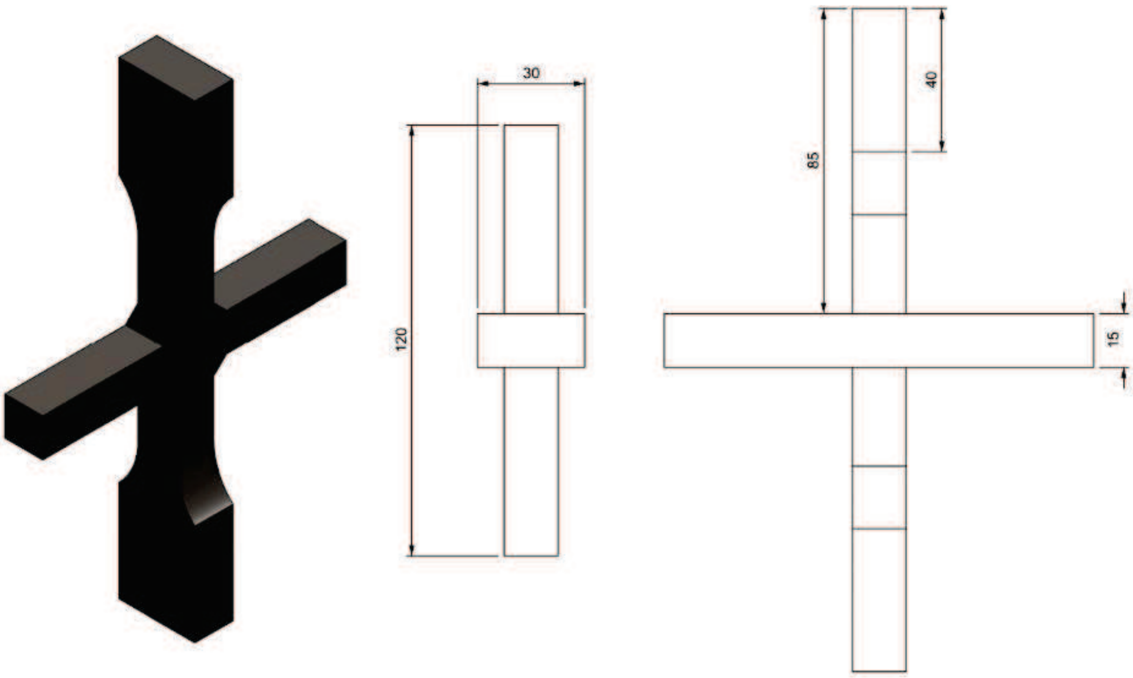

Figure 7 - Tensile test specimen, dog bone, with fillet welding.

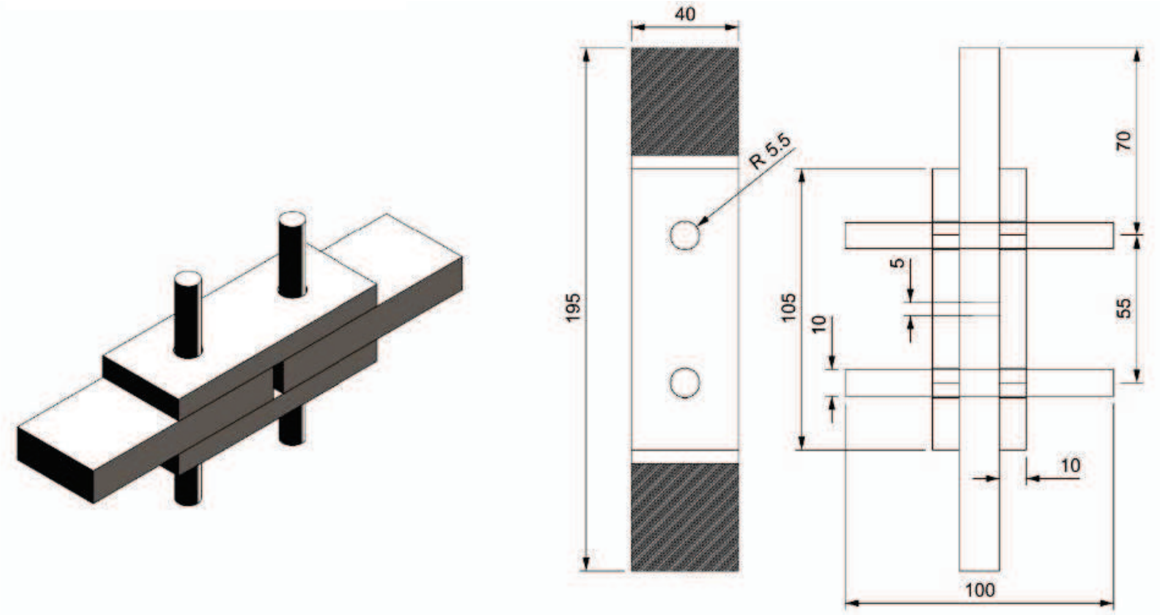

Figure 8 - Tensile test specimen with steel bolts.

4. Conclusion

In the context of the growing interest in alternative materials for marine applications, a fundamental prerequisite for their adoption is the thorough evaluation of their mechanical properties through standardized testing procedures, procedures that, in the case of innovative materials such as HDPE, often require adaptations of the specimens to take into account the unique characteristics of the material and the limitations of the available laboratory equipment.

After conducting research into material characteristics and reviewing regulations and standards, the production of test specimens commenced. Specifically, in order to adhere to ISO and ASTM standards, dog-bone specimens were studied. Using the aforementioned Grasshopper code, both two-dimensional and three-dimensional drawings were extracted in a single step, eliminating the need for multiple drawing software applications. For more complex shapes, simplified forms were initially extracted, subsequently assembled as required, and then detailed 2D and 3D drawings were produced.

In conclusion, this approach demonstrated several advantages, including a reduction in drawing preparation time, decreased fabrication effort, and enhanced accuracy in approximating complex curvatures. However, the most significant benefit of employing parametric software such as Grasshopper lies in its ability to generate fully navigable three-dimensional models in real time, without the need for additional modeling platforms. Importantly, the geometries produced through this workflow are not merely visual representations, but precise digital outputs that can be directly exported for use in computer numerical control (CNC) machining. This direct compatibility with manufacturing processes streamlines the transition from design to fabrication, minimizing potential sources of error, eliminating redundant file conversions, and ensuring that the designed specimens can be produced with high fidelity and reproducibility.

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