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Pin-bearing mechanical behaviour of composites fabricated via fused filament fabrication as a function of reinforcing, pin diameter and W/D ratio

Luca Giorleo [a,*], Ilaria Papa [b], Alessia Teresa Silvestri [b], Antonino Squillace [b]

[a] University of Brescia, Department of Mechanical and Industrial Engineering, Brescia, Italy
[b] University of Naples Federico II, Department of Chemical, Materials and Industrial Production Engineering, Naples, Italy

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ABSTRACT

Additive manufacturing is an advanced technology able to produce parts with different grades of complexity, including its shape, microstructure, functionality and material. Regarding material complexity nowadays, it is possible to produce polymer parts with customized reinforced fibre filling such as carbon, Kevlar or glass. However, their mechanical behaviour is still under investigation and no data are available on the bearing strength for additively manufactured composites. The aim of this work is to provide a contribution on this topic to ensure safe joint design with the current and innovative technologies. In this article the authors present the experimental characterization of polymer filled with Kevlar to pin bearing test. Samples have been designed as a function of filling and geometry parameters. Results have been analysed with statistical methods. Finding highlight similar and different behaviour regarding samples produced with conventional process. The most interesting result is that the authors demonstrate how the pin diameter is significant for the results, particularly for the stiffness keeping constant the bearing strength.

1. Introduction

Bolted joints are crucial in structures since they are not permanent and requiring an easy maintenance operation. Moreover, they do not change the microstructures of the connecting plates as happens in welding and are easy to assemble [1]. Over the years, the necessity to lighten the structures without compromising the mechanical properties, mainly in aerospace and automotive fields, led to studying bolted joints made of composite materials. This way, a structural integrity can be maintained and less energy expenditure in freight transport can be guaranteed [2,3]. There are two different types of composites joining: mechanical and adhesive. Between them, the mechanical one requires a hole, not influenced by the service temperature and humidity and does not need surface treatment contrary to the adhesive connection [4,5]. However, a possible catastrophic failure since a stress concentration can occur. Four main failures in bolted connections: bearing, shear out, net tension and cleavage. Bearing failure is a progressive damage mechanism only characterized by a hole deformation due to the compressive stress transmitted by the pin. Net tension and shear out are catastrophic failures with high tension and shear stress values, respectively. The last is a hybrid rupture between shear out and net tension [6–8]. Bearing is the most recommended bolted failure because it is not catastrophic, unlike the others [9,10]. To enhance the knowledge on this topic different studies are available focusing the attention on the effect of geometry dimension bearing mechanical behaviour. About sample geometry, high attention was focused on the analysis of the distance between the ratio W/D between samples width (W) and pin diameter (D) and the ratio E/D between the distance of the hole from the boundary (E) and pin diameter (D) [11–17]. In particular: Othman et al. [11] studied the bearing strength of chopped fiberglass reinforced epoxy resin specimen made by vacuum bagging, performing a double lap pin bearing test varying the geometric parameters E and W. It was found that low values of E/D ($\leq$2) led to shear out failure, while low values of W/D ($\leq$2) led to net tension failure. Increasing these two ratios bearing failure occurred, leading to a deformation of the hole before the crack. However, higher bearing strengths occurred when the specimens were not too narrow with a W/D $\geq$ 3. Fiore et al. [12] performed a pin bearing test on a flax fiber reinforced epoxy resin made by vacuum bagging. The idea was to optimize the use of polymer composites reinforced with flax fibers for structural applications. For this reason, a failure map was

* Corresponding author at: Via Branze, 38, 25123 Brescia, Italy.
E-mail address: luca.giorleo@unibs.it (L. Giorleo).

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created as a function of the hole diameter and its ratios with the free edge distance and the width of the specimen. It was discovered that the E/D and W/D had to be higher than 3.0 and 3.75 to obtain bearing failure. Keeping constant E/D and decreasing W/D obtained Net tension failure. On the other hand, keeping constant W/D and decreasing E/D obtained Shear Out failure. Valenza et al. [13] realized a pin-bearing test on a glass fibre-reinforced polyester isophthalic resin; a failure map was created in this case. It was found that E/D and W/D should be higher than 2 and 3.5to obtain bearing failure, respectively. Donghyun Yoon [2] studied a carbon fibre-reinforced epoxy resin made by vacuum bagging. This work conducted a double lap pin bearing test to evaluate the failure modes, varying E/D from 1 to 5 and keeping constant W/D equal to 8. It was discovered that E/D has to be ≥3 to lead to bearing. If this ratio were lower, there would be shear out. In [14], the effects of geometry on the bearing response of fiber metal laminate joints (FML) are numerically investigated. In this work, to study the three main failures of bolted joints, they chose W/D and E/D equal to 6 for bearing, W/D = 6 and E/D = 1.3 for shear-out and finally W/D = 2 and E/D = 6 for net tension. Tajeuna TA [15] exanimated the geometric effects on the mechanical behaviour of Pultruded Fiber Reinforced Polymer (PFRP) on a single bolted connection. It is important to notice that in this work, the diameter considered is not of the hole one, but it was of the bolted. It was found that with E/D = 2 and W/D constant to 5, the failure mode is shear out without bearing. Increasing the first ratio, it was observed that the failure mode was still shear out but with the presence of bearing. With the increase of E/D ratio there was also an increase in the failure load until this ratio reached 5, after this value the failure load started to decrease. However, the bearing failure started to occur with E/D equal to 3. It also investigated the W/D with E/D constant of 5. In these configurations with W/D equal to 3, a net tension failure mode was obtained and by increasing this ratio, the failure mode changed from net tension to cleavage to bearing or shear out. In addition, the ultimate bearing failure load increased up to the point where W/D is equal to 5; after, it started to decrease. In Buket Okutan et al. [16], the effects of geometric parameters on the failure strength for pin-loaded multidirectional fiber glass-reinforced epoxy laminate realized by hand lay-up technique. This work created two different layups: one with the fiber deposed at [0/90/0] and the other [90/0/90]. The E/D ratio varied from 1 to 5 and W/D ratio from 2 to 5. It was noticed that in every configuration before the ultimate failure that was or shear out or net tension had a bearing failure. However, there were differences between the two configurations. The [0/90/0] laminate had a bearing failure when E/D was greater than 3, for lower values of this ratio a shear out failure was observed. The [90/0/90] laminate had different values a bearing failure was recorded for E/D equal to 4 and W/D was 2 or 3, and when E/D was equal to 2 and W/D was 3 or 4. Before reaching these critical values, a net tension failure was observed, except when E/D was 1, and a shear out failure occurred. In addition, with [0/90/0] disposition, it was possible to observe a sudden increase of the ultimate bearing strength for values of E/D that go from 1 to 3. Higher values of this ratio did not influence the bearing strength greatly. On the other hand, [90/0/90] showed a steady increase in the ultimate bearing strength for the rising E/D ratio. In addition, for this configuration, the W/D ratio seemed to influence the bearing strength when E/D = 1. In [0/90/0] laminates, with small values of E/D the bearing strength seemed to be independent of W/D. When E/D reached high values and W/D was greater than 4, bearing strength remained pretty much the same. Meng [17] investigated the effects of geometric parameters on the failure behaviour of mechanically fastened chopped carbon fiber tape-reinforced thermoplastics realized by wet dispersion manufacturing. Here, a pin-loaded test and a bolt-loaded test were conducted with a E/D ratio ranging from 1 to 5 and W/D from 2 to 5. During pin-loaded test, three main failures were observed, while in bolted one, four were. In pin loaded test bearing failure occurred when W/D was ≥2 and W/D ≥3, for lower values were recorded catastrophic failures. In the bolt-loaded test, failure was observed for E/D ≥ 3 and W/D ≥ 4; for lower ratios values, there were catastrophic failures. As it is clear, the researchers tried to evaluate the behaviour of composite reversible joints.

Over the years, it has assisted the rising of Additive Manufacturing (AM) techniques and the possibility of producing composite materials reinforced with continuous fibers that improve the mechanical properties of the printed parts [18–20]. The most performing technique for realizing these materials is Fused Filament Fabrication (FFF) [21,22]. The most characteristic advantages of AM technique are freedom design and a high level of material customization that can be applied to every single layer that composes the printed part, making it lawful to investigate the geometric effect on bolted joints realized with this method [23,24]. Furthermore, a fascinating advantage of this technology is the possibility to project and realize a composite component featured by a complex fiber orientation, which can be applied to geometric interrupts such as holes [25]. Indeed, the curvature of the fiber in composite structures is difficult to create with conventional methods.

Nevertheless, to the authors' knowledge, a few studies have been conducted on enhancing the bearing behaviour of FFF composite elements [26–29]. Furthermore, many studies were carried out on failure modes taking place in joints, but no data are available on this topic for additively manufactured composites. Therefore, the authors intend to fill this knowledge gap to widen the public database to ensure safe joint design with the current and innovative technologies.

In a previous study [27], the authors analysed the pin bearing of a 3D printing composite material with Kevlar reinforcement to determine the effects of fibre orientation, layer design, and fibre distribution along with the specimen thickness. Furthermore, the findings do not indicate any significant influence of the fibre layer position inside the specimen, i.e. this parameter does not limit the freedom when designing a fibre-reinforced part.

Starting from this paper, in this work, the authors have studied the effect of the geometric parameters on failure mode during a pin bearing test for continuous fibre-reinforced composite (CFRC) printed with FFF method, mainly focusing on the W/D ratios. Through a double lap pin bearing test will be tested CFRCs with Kevlar as reinforcement. Four samples' types were designed, setting two levels of filling (with or without fibre reinforcing), two levels of diameters D (6 and 7.2 mm) and six levels of W/D ratio (6, 5.5, 5, 4.5, 4, 3.5). Furthermore, the pin-bearing strength and stiffness were analysed using statistical methods as analysis of variance the technological limit was confirmed for onyx sample that presents always bearing failure. On the contrary, for Kevlar samples with W/D = 3.5, net tension failure occurred coherently with the literature, even if the authors found that W/D ratio is not significant for maximum stress. Pin diameter results significantly in the stiffness keeping constant the bearing strength. This phenomenon is highly interesting because it opens the way to design bolt features as a function of desired mechanical behaviour.

2. Materials and methods

The present chapter described the materials and methods followed by the authors as a function of the three main research steps: samples design, production and testing.

2.1. Samples design

Fig. 1a. shows the standard geometry of a pin bearing sample; the parameters that characterized it geometry are sample width (W), length (L), thickness (T), hole diameter (D) and distance of the hole centre from boundary (E). Table 1 shows the standard values coherent with the ASTM D5961/D5961M-13[30].

Table 1 is reported the ratio W/D and E/D too, because, as discussed in the introduction, these values affect the sample's mechanical behaviour. In this research twenty-four samples were designed, setting two levels of filling (with or without fibre reinforcing), two of diameters D (6 and 7.2 mm) and 6 levels of W/D ratio (6, 5.5, 5, 4.5, 4, 3.5). Length

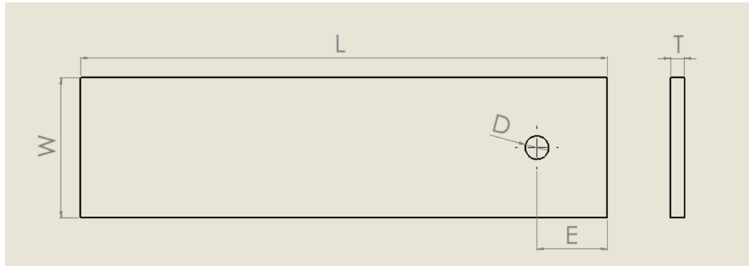


Fig. 1a. Main dimensions (mm) of specimens based on ASTM D5961/D5961M – 10.

Table 1
Geometry designed for the experimental tests.

L [mm]	W [mm]	D [mm]	E [mm]	t [mm]	W/D	E/D
135	36	6	18	3.6	6	3

L, thickness T and E/D ratio have been set equal to the standard values reported in Table 1; E was varied as a function of D to keep the E/D constant. The values chosen for D were the standard one (6 mm) and a value 20% higher (7.2 mm). W/D ratios were set starting from the standard (6) and decreasing its value until 3.5 due to the production limits of the printing machine. Indeed, by using W/D values lower than 3.5, the production process was not able to realize parts with uniform fibre distribution. For clarity of discussion, in Fig. 1b. fibre distribution is reported for geometry with D equal to 6 mm and W/D equal to 3, and it is possible to note discontinuities and the absence of fibre in some zones near the hole.

For each experimental set, two diameters were tested. Three replicas for each experimental set have been designed, obtaining 72 samples (2 level of filling, 2 of pin diameter, 6 W/D ratios and 3 replicas). Table 2 lists all the geometry design.

2.2. Samples production

The specimens were printed with a Mark Two (Markforged, Watertown, MA, USA), which uses fused filament fabrication technology to fabricate parts and is equipped with two nozzles to deposit independently matrix or fibre. For the matrix, we used Onyx, a nylon matrix reinforced with micro carbon fibres [22]. Furthermore, Kevlar was used as the reinforcement. Table 3 lists the main properties of the matrix and fibre.

During the sample printing, the matrix extrusion temperature was set equal to 275 °C while the fibre temperature was 255 °C; no heating procedure was set for the bed plate. The printing machine indicates these parameters as optimal parameters for the printability of the selected material. Based on the sample thickness set in Table 1, the specimens were fabricated as a combination of 36 layers with a layer thickness of 0.1 mm. As reported in the previous subchapter, samples were with or without reinforcing. Samples without reinforcing have been produced alternating layer oriented at 45 and 135°. For samples reinforced with Kevlar, the onyx/Kevlar distribution was set as follows:

- A layer package (LP) equal to four layers was set such that the specimen was considered as comprising nine LPs.
- All the specimens included five LPs of the matrix and four LPs of Kevlar, i.e., 20 layers of matrix and 16 layers of Kevlar. Therefore, the proportion of the fibre layer was equal to 45%.
- In all the onyx LPs, a full solid infill was set, and the wire orientation was equal to a sequence of 45 and 135°.
- In all the Kevlar LPs the fibre orientation was equal to a sequence of 0, 45, 90 and 135°.

The specimen cross-section onyx/Kevlar distribution is shown in Fig. 2, the list of layer/filler configurations is reported in Table 4 while Fig. 3 plots onyx and Kevlar volume used for samples production.

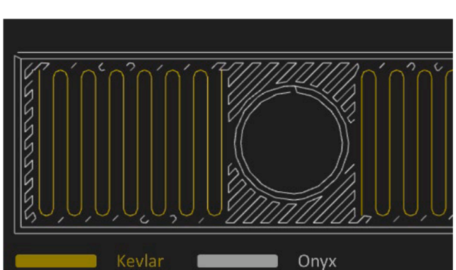


Fig. 1b. Fibre distribution in sample having D = 6 mm and W/D = 3.

Table 2
Geometry designed for the experimental tests.

L [mm]	W [mm]	D [mm]	E [mm]	t [mm]	W/D	E/D
135	36	6	18	3.6	6	3
135	33	6	18	3.6	5.5	3
135	30	6	18	3.6	5	3
135	27	6	18	3.6	4.5	3
135	24	6	18	3.6	4	3
135	21	6	18	3.6	3.5	3
135	43.2	7.2	21.6	3.6	6	3
135	39.6	7.2	21.6	3.6	5.5	3
135	36	7.2	21.6	3.6	5	3
135	32.4	7.2	21.6	3.6	4.5	3
135	25.2	7.2	21.6	3.6	3.5	3
135	25.2	7.2	21.6	3.6	3.5	3
135	25.2	7.2	21.6	3.6	3.5	3

Table 3
Mechanical properties of the matrix and reinforcement.

Properties	Onyx	Kevlar
Tensile Modulus (GPa)	2.4	27
Tensile Strength (MPa)	40	610
Tensile Stress at Failure (MPa)	37	/
Tensile Strain at Failure (%)	25	/
Flexural Modulus (GPa)	3	26
Flexural Strength (MPa)	71	240
Flexural Strain at Failure (%)	/	2.1
Compressive Modulus (GPa)	/	28
Compressive Strength (MPa)	/	97
Compressive Strain at Break (%)	/	15
Density (g/cm^3)	1.2	1.2

2.3. Sample testing

The machine employed is a QUASAR 50 (Galdabini SPA, Italy), load cell of 50 kN, testing speed of 3 mm/min. The experimental setup is shown in Fig. 4a, and 4b illustrates the bearing test apparatus based on

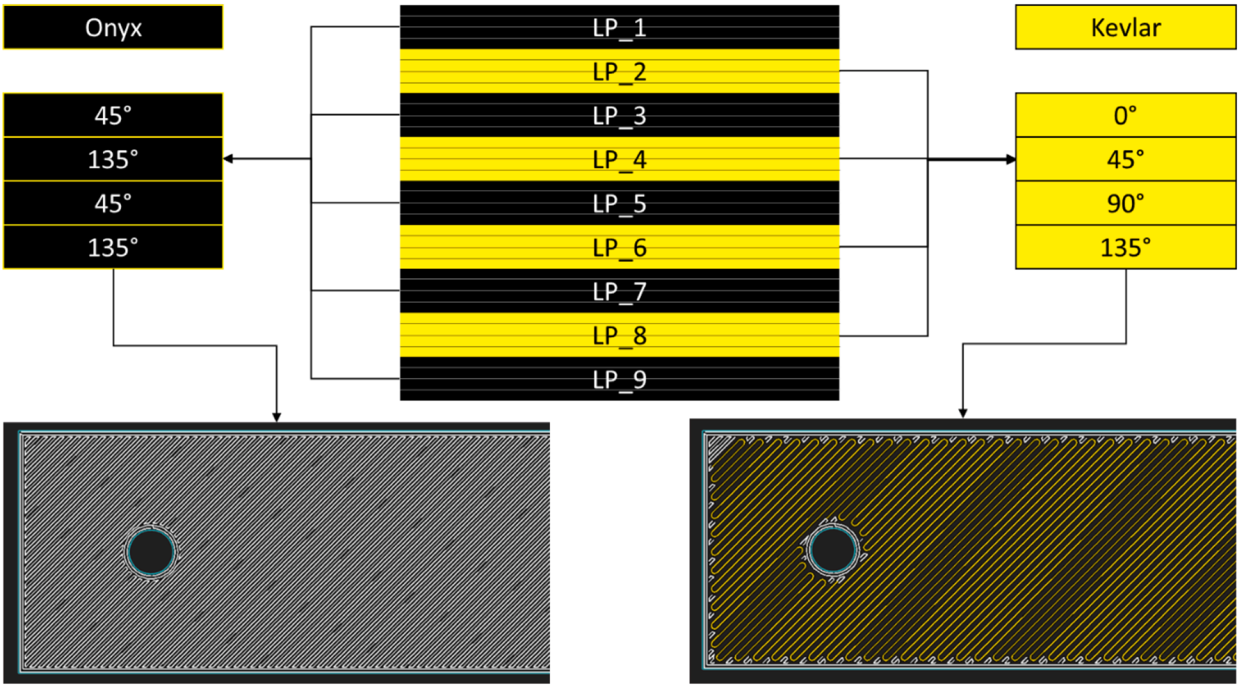


Fig. 2. Specimen cross-section configuration as a function of the layer package (LP).

Table 4
Material and pattern configuration as a function of layer.

Layer	Material	Pattern sequence
01–04	Onyx	45 / 135 / 45 / 135
05–08	Kevlar	0 / 45 / 90 / 135
09–12	Onyx	45 / 135 / 45 / 135
13–16	Kevlar	0 / 45 / 90 / 135
17–20	Onyx	45 / 135 / 45 / 135
21–24	Kevlar	0 / 45 / 90 / 135
25–28	Onyx	45 / 135 / 45 / 135
29–32	Kevlar	0 / 45 / 90 / 135
33–36	Onyx	45 / 135 / 45 / 135

ASTM D5961 [30].

$$\text{Ï¬}_{br} = \frac{P}{DT} \quad (1)$$

where P represents the bearing load, D indicates the hole diameter, and T the specimen thickness.

The most common types of failure in bearing are net tension, shear out, cleavage and bearing, among these only the last one can be considered an acceptable failure mode for the standard [26,30]. Conventionally, the bearing failure is not a catastrophic failure, but the final physical condition of the specimen after the test is subjected to whether the test method was interrupted shortly after the maximum force was reached. If the test is not stopped, the test machine will continue to deform the specimen, hiding the primary failure mode (bearing failure) by producing secondary failures. Therefore, beyond the conventional bearing failure established by the standard, in this work, the failure mode will be considered Bearing also if the maximum force occurs for a displacement equal or greater than the hole diameter. The bearing stiffness of the samples, indicated as K_p, is calculated as indicated in the authors' previous work [27].

The methods followed for the results analysis is here described:

- load vs pin displacement curves have been compared as a function of filler and pin diameter for the different levels of W/D ratios.

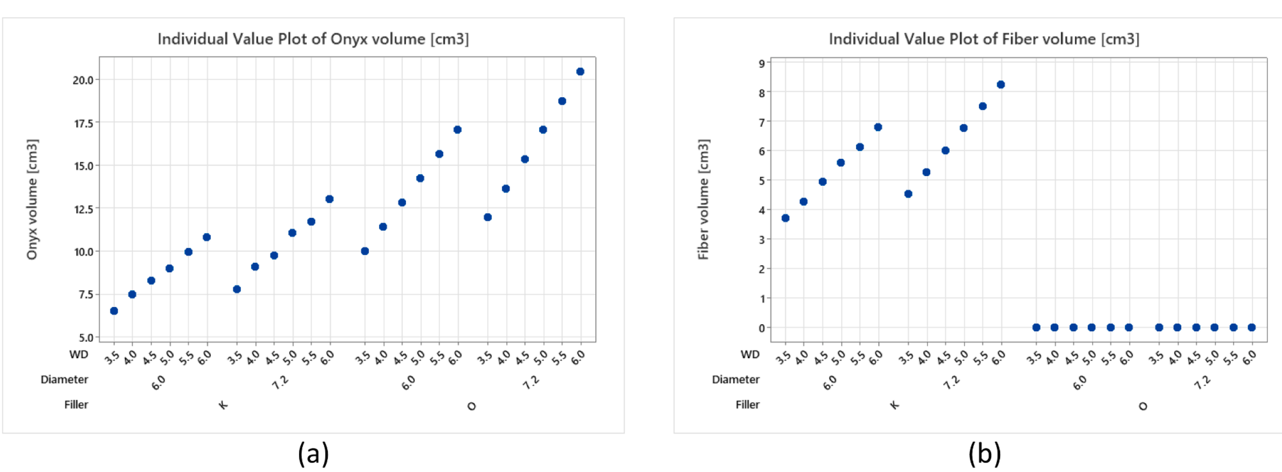


Fig. 3. Onyx (a) and Kevlar (b) volume used for samples production as a function of W/D ratio, pin diameter and sample filler.

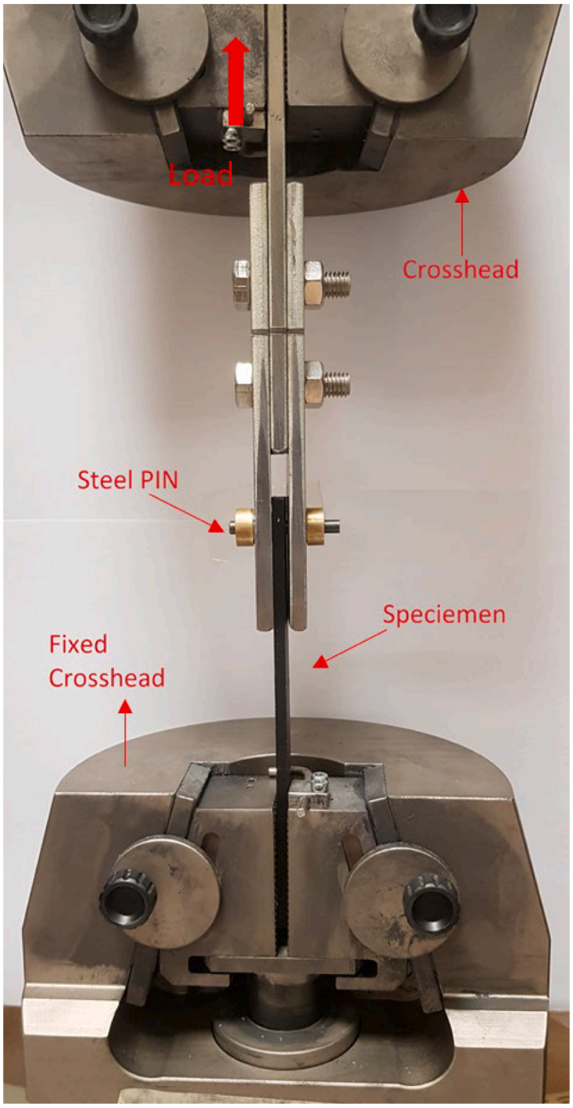


Fig. 4. Pin bearing experimental setup.

- A magnify picture of hole deformation to highlight and identify the failure mechanism.
- Analysis of Variance (AnoVa) of the maximum stress measured from the experiments (σ_{max}) and the samples stiffness (K_p) was evaluated to study the results recorded from all tests. Furthermore, Tukey range test was applied to find means that are appreciably different from conditions tested.

3. Results and discussions

Fig. 5 shows the main results of load vs pin displacement analysis for both onyx (O) and Kevlar (K) reinforced samples having pin diameter equal to 6 mm (Fig. 5.a, Fig. 5.b). For a sake of clarity, only one curve for the test is reported. However, all tests showed good accuracy, as observed by the example reported in Fig. 5.c.

As shown in Fig. 5.a, the mechanical behaviour is the same for onyx samples in all the conditions tested, but the maximum load does not follow a clear trend by varying the W/D ratio. Nevertheless, it is possible to note in Fig. 5.a that the maximum force carried by test specimen prior to failure occurs for a displacement at least twice the Diameter of the hole, and for the above-mentioned reasons, all the failure modes are considered bearing.

The reinforced specimens exhibit a different mechanical behaviour (Fig. 6.b), reaching as a maximum force value almost double the previous case, but reducing the failure displacement. For W/D equal to 3.5, the Kevlar sample collapse in a catastrophic mode (Fig. 5.d) and before displacement equal to the hole diameter (6 mm), for these reasons it is considered net tension. In the other cases, the maximum force is reached beyond 6 mm, and the samples experienced a different failure: the curve is almost stable in correspondence with the maximum force and in a certain time range and then collapses. In these cases, the failure mode is bearing. Moreover, even if there is not a clear trend of the maximum force by varying the W/D ratio in the reinforced case, the range is 3500 N–3900 N. This result indicates a higher stability of the reinforced specimens. Moreover, in this case, it is possible to note a greater bearing stiffness. This increase is evident by seeing Fig. 7, in which a comparison between the Onyx and Kevlar samples is reported, and only for W/D = 3.5 for a better clarity. The first linear section of the curve recorded for the sample K_D6 is characterized by a greater slope with respect to the O_D6 one. Despite to the failure modes, the same result was noted for all the other conditions.

In Fig. 6 the magnified pictures of the hole deformation for specimen with D equal to 6 mm are shown. For brevity, three broken samples are reported, representative of the failures in this work: Net Tension, Primary Bearing and then Net Tension, and pure Bearing. The former case regards the Kevlar samples with W/D equal to 3.5 (Fig. 6a), for which a net tension failure was recorded. The second concerns many Onyx samples, where even if a partial detachment is reported in many cases, it occurs at least at a displacement higher than twice the Diameter of the hole, and so it is possible to assume it as bearing failure mode (see Fig. 6b). The latter case, the pure Bearing, is shown in Fig. 6c, indeed it is possible to see in the figure the ripples above the hole, typical of the bearing failures.

Fig. 7 shows the load vs pin displacement curves for both onyx (Fig. 7.a) and Kevlar (Fig. 7.b) reinforced samples with the pin diameter equal to 7.2 mm. Also, in this case, good tests accuracy was obtained /Fig. 7.c) so that only one curve for test is plotted. The mechanical behaviour of onyx samples is the same for all the samples, and the maximum load is reached at a displacement higher than the hole diameter, i.e., 7.2 mm. Therefore, all the conditions tested led to a bearing failure. In Kevlar specimen samples with a W/D equal to 3.5 experienced a catastrophic failure, characterized by a drop in the curve shown in Fig. 7.b. In the other cases, the failure is considered bearing in a conventional way, and so a non-catastrophic failure, even if it occurs at a displacement slightly lesser than the hole diameter. However, the onyx and Kevlar samples differ for the bearing stiffness, in Fig. 7.d comparison between them is reported for W/D equal to 3.5, in which it is clear the difference between the characterizing curve of the Bearing (onyx) and catastrophic failure mode (Kevlar), and the difference first linear section of the curves, which is translated in a difference in stiffness.

What is declared previously on D = 7.2 specimen is confirmed by observing Fig. 8, in which pictures of the hole deformation are reported for the three main failure of this work. Also, in this case, the net tension regards the Kevlar samples with W/D equal to 3.5 (Fig. 8a). Fig. 8b represents the case where the primary failure is a bearing (the hole deformation images confirmed that pin bearing corresponds to the first phenomena of material failure). Still, without stopping the test for a displacement greater than the hole diameter, it is possible to also have a net tension (in this case at 45° and not at 0° because the breakage follows the printing directions of the Onyx tracks). Finally, Fig. 8c shows an example of pure bearing failure. By merging the results of Figs. 8 and 6, it is evident that reducing the W/D ratio affects the type of failure mechanism. Specifically, a decrease in sample width, as observed in the lowest level tested (W/D = 3.5), results in the predominance of the horizontal component of loads experienced by the pin in the hole. This phenomenon leads to a net tension failure during the pin bearing test [12].

The statistical analysis highlights different results both for the maximum stress measured (σ_{max}) and the stiffness (K_b). From the AnoVA

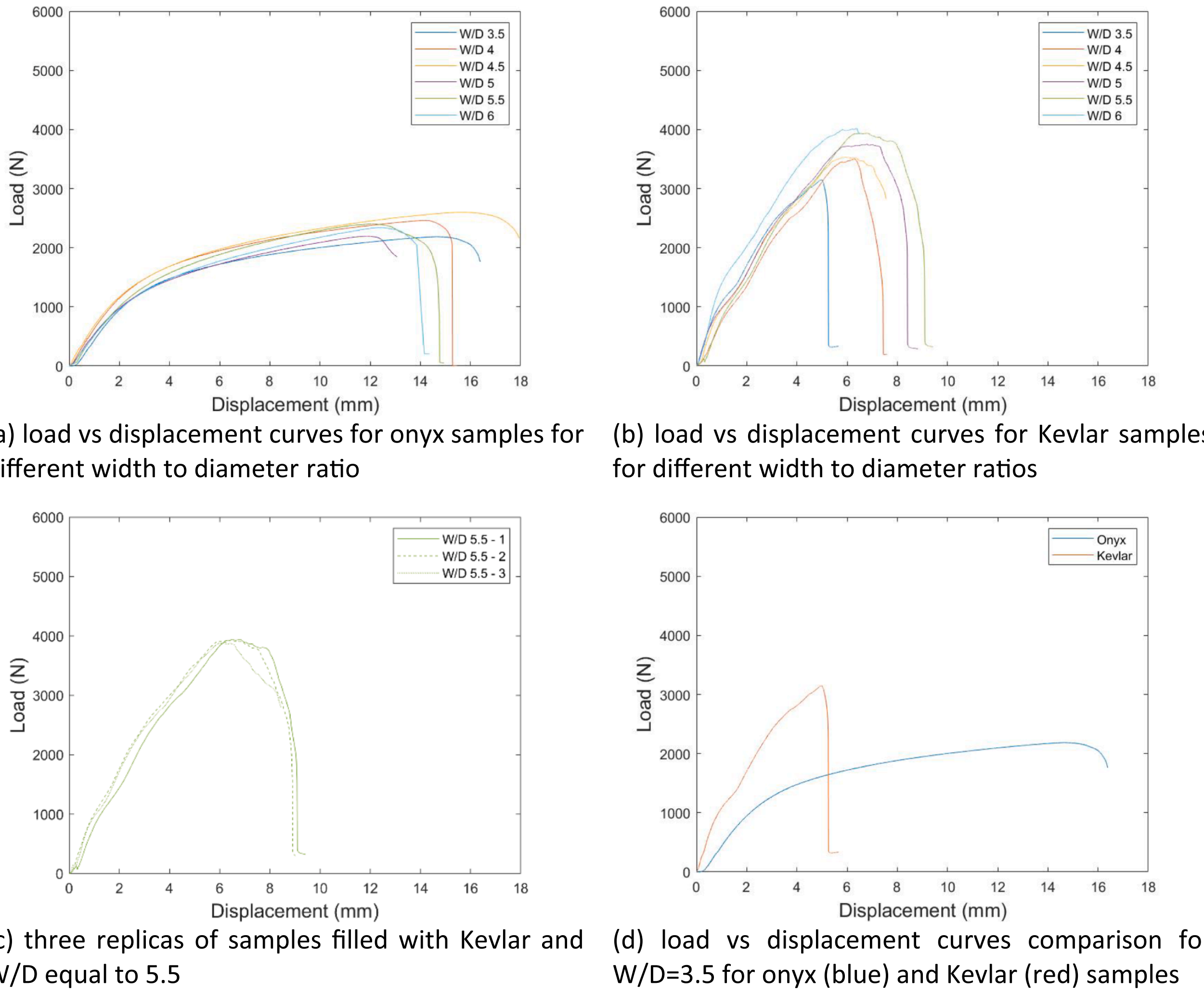


Fig. 5. Main results of samples having pin diameter equal to 6 mm.

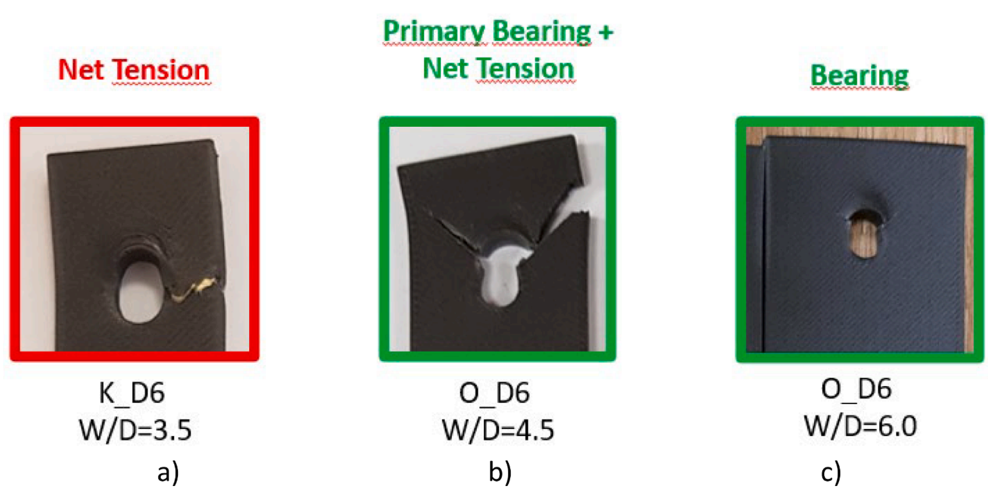
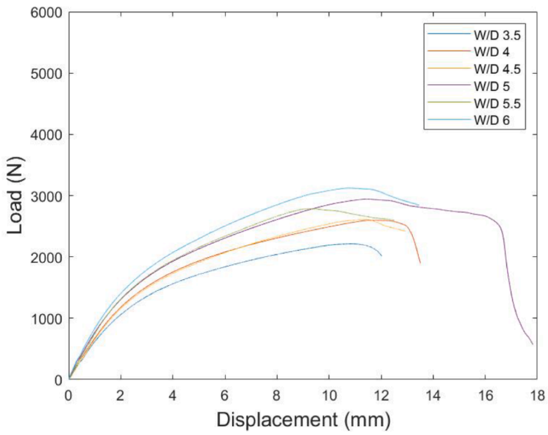
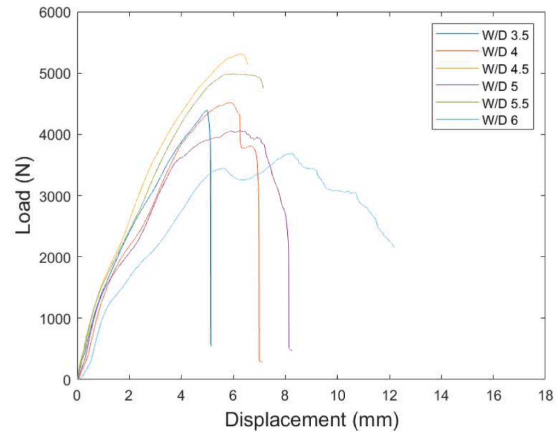


Fig. 6. Magnified pictures of tested specimens.

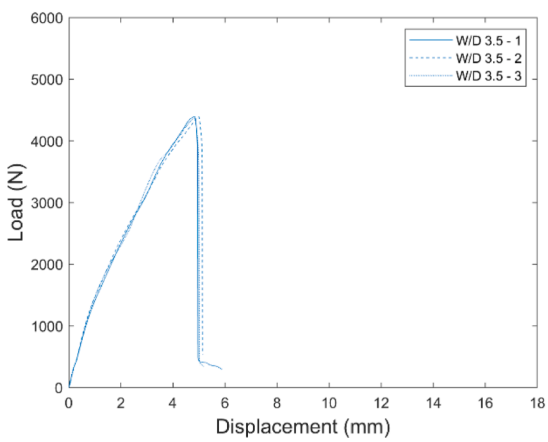
test executed on σ_{max} it is possible to record a significative effect of W/D ratio and filler (p-value greater than 0.005) while pin diameter seems to be not. About interaction it is interesting to observe a significative effect of W/D with D (Fig. 10.a). Observing the interval plot Fig. 10.b it is evident how Kevlar imposes an increase of σ_{max} values, while for the other two parameters, it is impossible to identify a trend. These considerations are confirmed from the Tukey range test in Fig. 10.c where two groups have been identified for filler and D coherent with the AnoVa



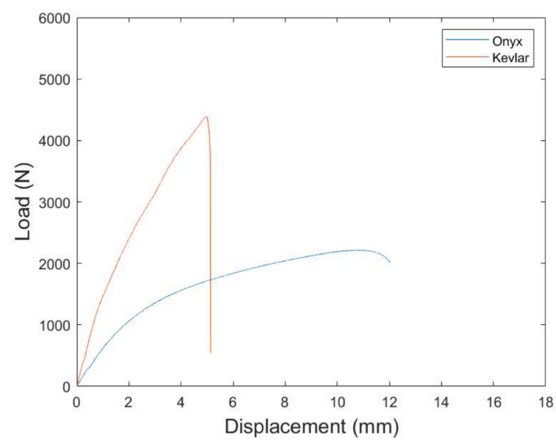
(a) load vs displacement curves for onyx samples for different width to diameter ratio



(b) load vs displacement curves for Kevlar samples for different width to diameter ratios



(c) three replicas of test K_D7.2 with W/D equal to 3.5



(d) load vs displacement curves comparison for W/D=3.5 for onyx (blue) and Kevlar (red) samples

Fig. 7. Main results of samples having pin diameter equal to 7.2 mm.

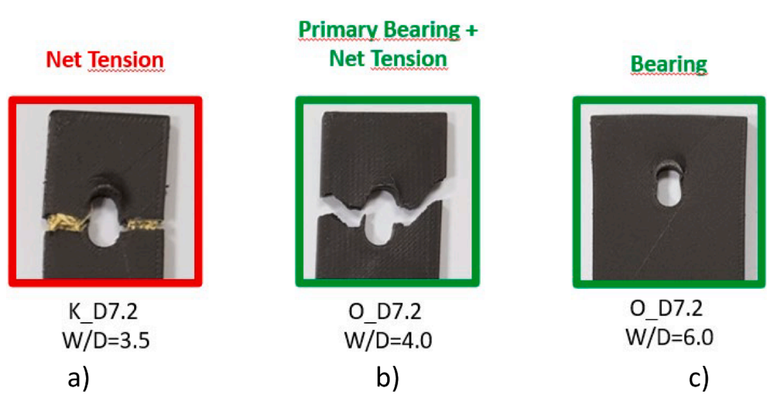


Fig. 8. Magnified pictures of tested specimens with a diameter D = 7.2: a) Onyx (O_D7.2), b) Kevlar (K_D7.2).

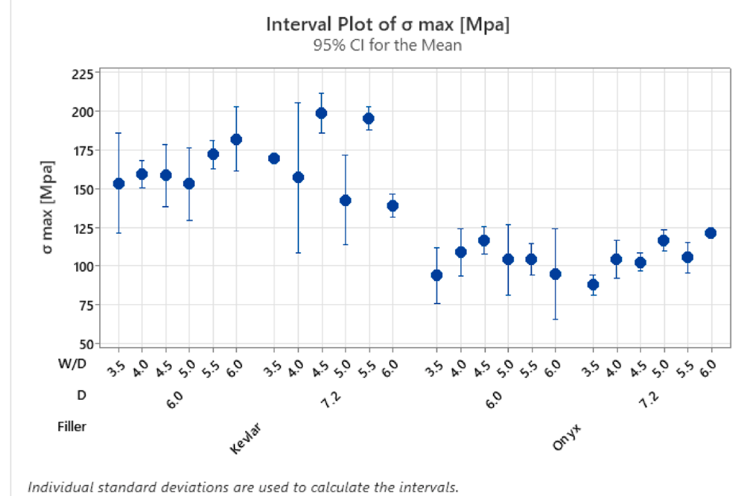
one group. Tukey test on W/D from a side confirmed a significant difference suggesting two groups, but on the other side, because group A includes W/D 5.5 and W/D 4.5 and group B the other ones it is impossible to observe a trend.

About the AnoVa test results on bearing stiffness (K_b), Fig. 11.b presents a significative effect of all factors investigated including all the interactions (p-value always < 0.005). The Interval plot shows, as observed for σ_{max} an increase of stiffness for Kevlar samples, moreover, still for these samples the increase of pin diameter results in a rise in K_b. About W/D effect Fig. 11.b highlights an increasing trend for samples in onyx with a pin diameter equal to 7.2 mm. Tukey test range reported in Fig. 7.c confirm these results dividing filler and pin diameter D parameters respectively into two groups assigning the higher-level A to Kevlar and to 7.2 mm diameter. Finally, Tukey test identified an increase of stiffness with samples having W/D ratio equal to 6, 5.5 and 5 respect to 4.5, 4 and 3.5.

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
W/D	5	3481.0	696.2	12.10	0.000
Filler	1	64798.4	64798.4	1126.28	0.000
D	1	192.2	192.2	3.34	0.074
W/D*Filler	5	3598.9	719.8	12.51	0.000
W/D*D	5	1086.0	217.2	3.78	0.006
Filler*D	1	7.1	7.1	0.12	0.727
W/D*Filler*D	5	6986.3	1397.3	24.29	0.000
Error	48	2761.6	57.5		
Total	71	82911.6			

(a)



(b)

W/D	N	Mean	Grouping	
5.5	12	144.557	A	
4.5	12	144.275	A	
6.0	12	134.417		B
4.0	12	132.697		B
5.0	12	129.286		B
3.5	12	126.349		B

Filler	N	Mean	Grouping	
Kevlar	36	165.263	A	
Onyx	36	105.264		B

D	N	Mean	Grouping
7.2	36	136.897	A
6.0	36	133.630	A

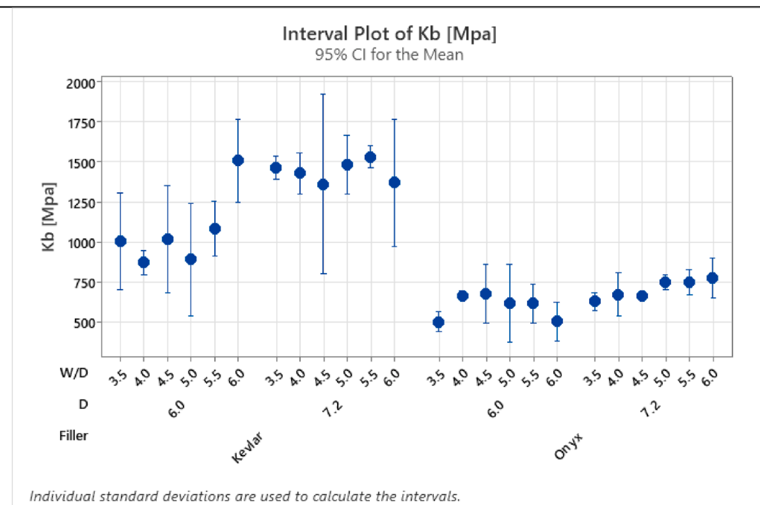
(c)

Fig. 10. AnoVa results (a), Interval plot (b) and Tukey range test (c) for σ_{max} as a function of filler, pin diameter and W/D ratio.

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
W/D	5	176380	35276	4.63	0.002
Filler	1	6471603	6471603	848.93	0.000
D	1	1070428	1070428	140.42	0.000
W/D*Filler	5	224555	44911	5.89	0.000
W/D*D	5	170868	34174	4.48	0.002
Filler*D	1	321816	321816	42.22	0.000
W/D*Filler*D	5	440422	88084	11.55	0.000
Error	48	365916	7623		
Total	71	9241989			

(a)



(b)

W/D	N	Mean	Grouping	
6.0	12	1038.90	A	
5.5	12	994.83	A	B
5.0	12	934.86	A	B
4.5	12	929.49		B
4.0	12	909.73		B
3.5	12	899.77		B

Filler	N	Mean	Grouping	
Kevlar	36	1251.07	A	
Onyx	36	651.46		B

D	N	Mean	Grouping	
7.2	36	1073.19	A	
6.0	36	829.33		B

(c)

Fig. 11. AnoVa results (a), Interval plot (b) and Tukey range test (c) for K_b as a function of filler, pin diameter and W/D ratio.

All the results obtained can be summarized plotting the σ_{max} as a function of K_b with filler and pin diameter D as variables for grouping, as reported in Fig. 12). The following considerations can be made:

- It is clear how that filling most affect both σ_{max} and K_b, onyx samples have maximum stress in a range between 50 and 125 MPa and a stiffness between 500 and 750 MPa. Kevlar samples have higher maximum stress (130–200 MPa) and stiffness (750–1600 MPa).
- The effect of pin diameter D is significant for Kevlar filler; samples having dimensions outside the standard (7.2 mm) have higher stiffness (1400–1600 MPa) but same average maximum stress respect to standard samples (6 mm). The data dispersion is higher in D 7.2 mm respect to the standard. About onyx, as demonstrated by the AnoVa and Tukey test the change of diameter parameter does not affect the mechanical behaviour.
- Ratio W/D was not included in data grouping because despite the are significative for the stiffness, a trend was not found so that their presence in Fig. 12 would not add value.

Comparing these results with the literature it is possible to note coherent and controversially trends. Different authors address a limit value of W/D under that a net tension failure occurs in the range 3.5 [11,13,16,21]. In this research, this limit was confirmed for onyx sample that presents always bearing failure on the contrary, Kevlar samples for samples having W/D ratio equal to 3.5 present net tension failure coherent with [12] where samples were polymer reinforced too. Controversially the literature [12] found that W/D ratio is not significative for maximum stress.

4. Conclusion

In the presented research the authors test the mechanical behaviour at pin bearing test of polymer samples produced via Fused Filament Fabrication technology. Samples were characterized by different infill, pin diameter and W/D ratio. Diameter with a different form with respect to the standard suggestion was chosen. Results confirm 3.5 as limit value of W/D ratio to avoid catastrophic failures for samples filled with Kevlar. Moreover, the results demonstrated that pin diameter is significative for the expected stiffness value keeping the bearing stress constant. The effect of pin diameter D is significative for Kevlar filler and samples having dimensions outside the standard exhibit higher stiffness but same average maximum stress respect to standard samples. The most interesting result is that the authors demonstrate how the pin diameter is significant for the results, particularly for the stiffness keeping constant the bearing strength. The results of this research can be used to understand and optimize the design of mechanical components that will then be connected to other components through mechanical joints and it opens the way to design bolt features as a function of desired mechanical behaviour. Ongoing activity is focusing on E/D ratio analysis.

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CRediT authorship contribution statement

Luca Giorleo: Conceptualization, Methodology, Data curation, Writing – original draft, Writing – review & editing. **Ilaria Papa:** Conceptualization, Data curation, Investigation, Writing – review & editing. **Alessia Teresa Silvestri:** Conceptualization, Data curation, Investigation, Writing – review & editing. **Antonino Squillace:** Conceptualization, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

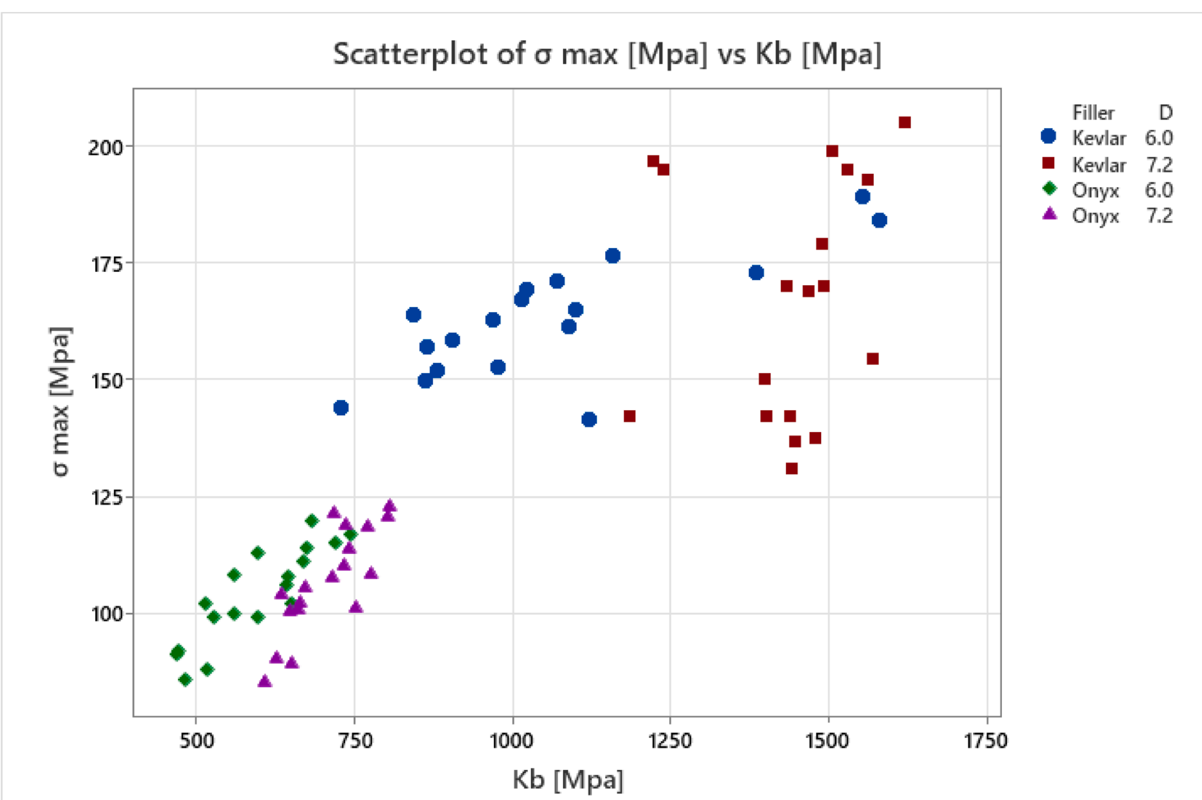

Fig. 12. Scatterplot of σmax vs Kp.

the work reported in this paper.

Data availability

Data will be made available on request.

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