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RESEARCH ARTICLE

Effect of fiber type and thickness on mechanical behavior of thermoplastic composite plates reinforced with fabric plies

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Abstract

Studies on weight reduction in aviation and space vehicles have gained momentum recently. Thermoplastic matrix composite materials are important alternative materials, especially due to their high specific strength, formability and recyclability. In this study, it is aimed to investigate the mechanical behavior of fiber reinforced thermoplastic composites for different fiber and layer configurations. Thermoplastic composite materials used in the study were produced by lamination technique. In composite production; Glass fiber and carbon-aramid hybrid fabrics were used as fiber, and polyethylene granules were used as matrix. Thermoplastic sheets were obtained by keeping polyethylene granules and woven fibers in the hot press for a certain period of time. The damage behavior of the composite test specimens under tensile load was tested for the number of layers and fiber type. As the number of layers increased, stiffness, damage load and deformations increased in thermoplastic composites. Using hybrid fabric instead of glass as fiber material increased the maximum damage load by 100%.

1. Introduction

Thermoset and thermoplastic matrices are used in composite materials. Composites produced with thermoset matrices are brittle and difficult to deform, while composites produced with thermoplastic matrix can deform easily. Thermoplastic materials have gained popularity in recent years, especially in the aerospace industry, due to their recycling properties. In particular, improvements in the strength properties of composites produced by reinforcing with continuous fibers can be achieved. A detailed examination of the mechanical behavior of such materials becomes important at this point.

Studies examining the mechanical behavior of continuous fiber reinforced thermoplastic composites have not spread over a wide area. Russo et al. [1] carried out impact tests with a falling dart and flexural measurements on polypropylene based laminates reinforced with glass fibers fabrics. Composite laminates have been produced by using two types of polypropylene matrices, differing for their melt flow index, and a glass fiber fabric. Their static and low velocity impact properties have been evaluated and compared to those exhibited by composite laminates produced by adding a compatibilizing agent to the matrices. Steggall-Murphy et al. [2] fabricated continuous fiber thermoplastic matrix composites using a novel powder-impregnation process that combined vacuum assisted resin transfer molding (VARTM) with compression molding. A model has been developed for the consolidation phase to predict the void fraction of the resulting composite. The model was compared to experimental values for void fraction for samples prepared using a

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range of consolidation pressures and dwell times. Van Vuure et al. [3] determined bending and tensile properties for [0/90]s silk twill weave composites, with different thermoplastic polymers and as reference epoxy resin. The choice of the polymer matrix has been a clear influence on the final mechanical properties of the silk fiber composites. Sun et al. [4] prepared poly-etherimide (PEI) composites using highly efficient injection molding technique by introducing three kinds of short carbon fibers (SCFs) treated with graphene oxide (GO), thermoplastic polyimide (TPI) and GO-TPI hybrid sizing, respectively. The effects of sizing agent on the temperature-dependent tensile behavior of SCF/PEI composites were systematically investigated. The results indicate that the tensile strength of SCF/PEI composites increases with decreasing the temperature due to the higher interfacial clamping stress at low temperature. Katti et al. [5] blended the multiwalled carbon nanotube (MWCNT) and carbon nano powder (CNP) were melt into polypropylene (PP) in the ratio of 2.5, 5 and 10 wt% using twin screw extrusion process. The extruded pellets were then injection molded using a 50 Ton injection molding machine to produce PP+CNP and PP+MWCNT composite flat test specimens according to ASTM standards and were used to carry out the tensile tests. Forsgren et al. [6] prepared the materials by extrusion mixing of either un-stabilized or stabilized polyethylene reinforced with 5 and 20 vol % cellulose content. The materials were extruded into strips and then aged at 90 °C in circulating air. The effect of accelerated ageing up to 31 days was assessed by oxidation induction time and mechanical properties in tension. Das et al. [7] presented the effect of stacking sequence on the mechanical and thermomechanical properties of composites using natural fiber (jute), glass and unsaturated polyester resin. The fabricated composite laminates were neat jute/polyester, neat glass/polyester, and hybrid jute/glass/polyester. It was revealed that neat glass/polyester laminate showed better mechanical performance than the other laminates, and glass fiber hybridization significantly affects the properties of the hybrid laminates. Obande et al. [8] explored a novel route for the fabrication of hybrid-matrix composites based on a recently developed liquid thermoplastic acrylic resin. This resin was modified using a poly phenylene ether (PPE) oligomer with vinyl functionality. Glass fiber-reinforced laminates based on acrylic and PPE-modified acrylic matrices were produced by a room-temperature vacuum infusion and in-situ polymerization process. Chukov et al. [9] used thermal treatment of carbon and glass fibers as a method of the fibers' surface modification. A polyether sulfone (PES) based composites reinforced with initial and modified carbon and glass fibers were developed using solution impregnation method followed by compression molding technique. Mechanical and thermal behavior of the composites before and after the modification was studied. It was shown that thermal treatment of the fibers results in improved interfacial interaction as well as higher strength-elastic properties of the PES based composites. Gebhardt et al. [10] presented attempts to assess the potential for re-using carbon fiber fabrics recovered from recycling infusible acrylic thermoplastic carbon fiber reinforced polymer composites (CFRPs) in a universal manner, i.e. by combining with a wide variety of matrices to manufacture 2nd generation composite laminates by resin infusion. Sathishkumar et al. [11] optimized the geometric parameters of glass fiber woven reinforced thermoplastic laminate composite for Mode-I fracture analysis with compact tension testing mode. High density polyethylene (HDPE) laminated composites were prepared by hot compression molding with three layers of HDPE and two-layer of glass fiber woven. The Mode-I fracture toughness and energy-releasing rate were calculated for all samples. Obande et al. [12] presented a comprehensive summary of recent works on room-temperature liquid thermoplastic acrylic resins and their composites. Moreover, open problems and research opportunities are identified and discussed. Saeed et al. [13] manufactured in-plane mechanical properties of continuous carbon fiber reinforced thermoplastic polyamide composite using a Markforged Two 3D printing system and they compared against predicted values from classical laminated-plate theory. Strength, stiffness and Poisson's ratio of the composite specimens were measured using tensile testing both in longitudinal and transverse direction and the shear properties were also measured. Kartikeya et al. [14] conducted tensile tests proposed in the literature and led to the evolution of a new method. Tensile test of single-ply was realized as the best representative of tensile strength of a composite than tensile test of ultra-high molecular weight polyethylene (UHMWPE) laminate. A fixture was developed for single-ply tests which increased friction and provided the mechanical constraint to slipping. Karthik et al. [15] aimed at developing new hybrid polymer matrix composites with epoxy resin as matrix material, kevlar, carbon and glass fibers as reinforcements. The fiber reinforced polymer matrix composite (FRP) laminates were prepared by hand layup method. The samples were prepared and tested by pin on disc wear tester for evaluating the wear properties, using Taguchi's Design of Experiments approach – L9 Orthogonal Array. Kazemi et al. [16] fabricated new thermoplastic-based FRP laminates consisting of: liquid Methyl methacrylate (MMA) thermoplastic resin, plain weave UHMWPE, carbon fiber, and their hybrid systems with different layups, by Vacuum Assisted Resin Infusion (VARI) method at ambient temperature. ASTM standard tests in tensile, compression, and shear were performed to obtain mechanical properties, followed the failure modes by Scanning Electron Microscope (SEM) to have a better understanding of these new thermoplastic-based laminates. Boumbimba et al. [17] prepared a laminate composite based on the new Elium acrylic matrix and glass fibres by an infusion process at ambient temperature in order to replace thermoset-based laminate composites with an equivalent recyclable thermoplastic based composites. In order to enhance the impact resistance of the composite, the acrylic resin has been toughened by adding different amounts of acrylic tri-blockcopolymers (Nanostrength). The composite plates were subjected to low velocity impact tests, per-formed at different impact energies and temperatures. Murray et al. [18] aimed to address barriers which remain to adoption of reactive thermoplastic resin transfer molding in terms of knowledge and equipment. Glass fiber reinforced polyamide composites were produced using thermoplastic resin transfer molding by injection of low viscosity monomer precursors and in-situ polymerization.

When the studies were examined, it was seen that there were no studies in which different fiber materials were used and the effect of the change in the number of layers on the mechanical behavior of thermoplastic composites. In this study, for the first time, laminated composites with polyethylene (PE) thermoplastic matrix material were produced by using glass and hybrid (HB) carbon-aramid fiber fabrics separately as reinforcement elements. Test samples were prepared from the produced plates and subjected to tensile test. The effect of the variation of the fiber layer number and fiber material type on the mechanical behavior is presented in graphs.

2. Experimental approach

In this study, woven HB carbon-aramid and glass fabric with 0^{o} fiber angle were used as the fiber, and PE was used as the matrix. Glass and HB twill woven fibers have a density of 200 g/m^2. Fibers were obtained from *Kompozitsan, Istanbul, Turkey*. PE granules were purchased from *Pistonsan Plastik, Istanbul, Turkey*.

Lamination technique was used in the production of the composite sheet. For this purpose, a mold was designed. The thickness of the composite plate was planned as 1.5 mm, but the mold depth was made as 5 mm due to the different thickness of the polyethylene granules. Holes with a diameter of 5 mm were drilled in the mold cover to dispose of the overflowing part of the melt. The mold was produced from St37 material on a CNC milling machine. The mold consists of two parts, male and female. When the female and male molds are overlapped, they are in full contact like one piece. Fig. 1 shows the assembly state of the mold. Polivaks SV-6 mold release agent was used, which allows the plates produced in the mold to be easily separated from the mold.

While producing the composite plate, it was thought that a homogeneous composite structure could not be obtained in the production of composite plate by laying the fabric and melting the granules upon placing the granules in the mold, first of all, plate was produced from pure granules. Initially, 0.5 mm thick PE layers were produced. In order to do this, the granules were placed in the mold as in Fig. 2a.

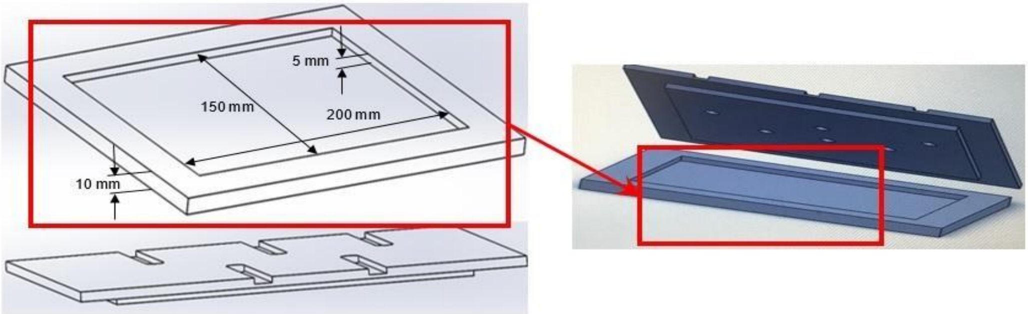
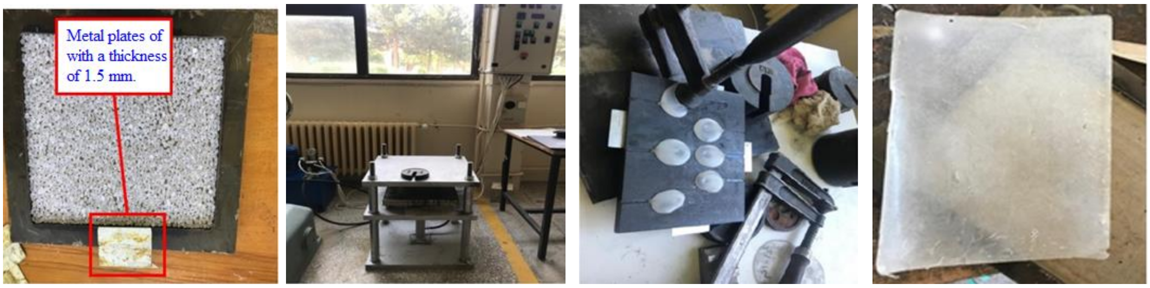


Fig. 1. Mold used in composite production.



a) b) c) d)

Fig. 2. Production stages of 0.5 mm thick pure homogeneous PE sheet: a) placing the granules in the mold, b) closing the mold, c) placing the mold in the press machine, d) obtaining the pure PE

The molds were heated up to 220 ^{o}C in the temperature controlled oven in Fig. 2b. The mold, which had been waiting for 15 minutes, was taken out of the oven, and then the desired thickness of the plate was adjusted by tightening it with the help of a vise (Fig. 2c). Metal plates with a thickness of 0.5 mm were placed between the mold covers to obtain the desired thickness (Fig. 2c). The mold was then allowed to cool at room temperature for 24 hours. As a result, a homogeneous PE layer of 0.5 mm thickness was obtained as in Fig. 2d.

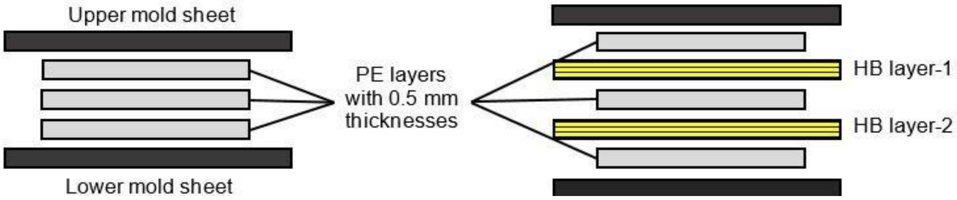
The obtained pure PE plates with a thickness of 0.5 mm were used as a matrix in the production of composites. Composite plate was produced as in Fig. 3 by using 2 and 4 layers of glass or HB fiber fabric layers and 3 layers of pure PE. The thickness of the produced composite plate was obtained as 1.5 mm. In order to obtain a 1.5 mm thick composite plate, this time 1.5 mm thick metal plates were placed between the male and female molds. While producing the composite, the temperature values and times applied in the production of pure PE were used.

In order to compare the fiber reinforced thermoplastic composites, 1.5 mm thick pure PE tensile test specimens were also produced. The dimensions of the manufactured composites are 200x150x1.5 mm (Fig. 4).

Samples of 200x15 mm dimensions were cut from pure PE, 2- and 4-layer glass fiber and carbon-aramid hybrid reinforced composite plates in a wet marble cutting machine. Then the prepared samples were tested in a tensile testing machine. The tests were carried out according to ASTM 3039 [19] test standard at a tensile speed of 0.5 mm/min.

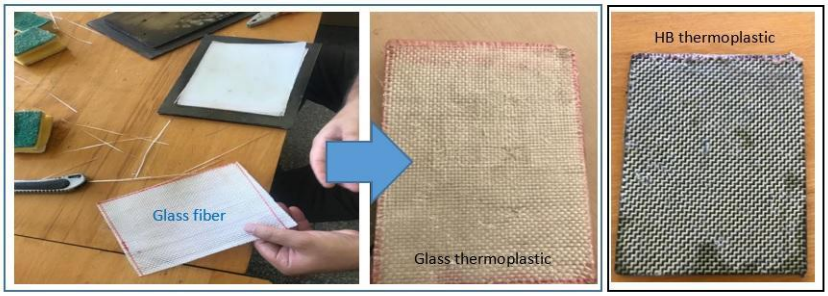
3. Results and discussion

As a result of the tensile test for composite samples, a typical graph is obtained as in Fig. 5. The force-displacement and stress-strain graphs obtained as a result of the tensile test are formed with the same characteristics. Critical points A and B can be seen on the graph.



a) b)

Fig. 3. Production of 1.5 mm thick a) pure PE, b) Production of 2 layers of HB thermoplastic composite plate



a) b)

Fig. 4. Produced a) glass fiber reinforced, b) HB thermoplastic composites

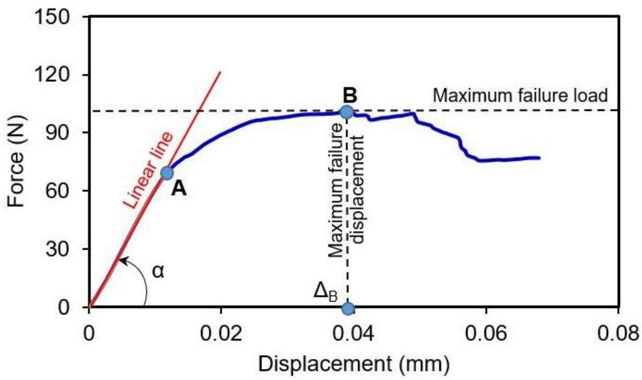


Fig. 5. Force-displacement graph for fiber-reinforced thermoplastic composite.

Point A is the point where the linear behavior ends in the force-displacement plot for the tensile test. The slope of this linear region (tanα) gives the Young's modulus for the stress-strain graph. Point B shows the maximum failure force in the tensile test. Therefore, this point is the point that gives the failure load. ΔB gives the failure displacement of the specimen against the failure load. In the study, the load and ΔB which gives the A and B points and Young's modulus were obtained for each sample.

Since the aim of the study is to examine the effect of the change of fiber type and number of layers, only the effect of these variables was examined in the experimental study. The composite plates produced are orthotropic materials. In the numerical study, the modulus of elasticity, Poisson's ratio and shear modulus of the orthotropic material should be found in three axes. Since this is the subject of another study, numerical studies were not carried out.

HB composites are shown as $[0^{HB}]_2$ for 2 layers, and glass reinforced composites as $[0^{G}]_2$ for 2 layers. The variation of the maximum failure load with the number of layers is given in Fig. 6a, and the variation with the fiber type in Fig. 6b. The increase in the number of layers exhibited similar behavior in terms of hybrid and glass fiber reinforcement, increasing the Maximum damage load and Young's modulus.

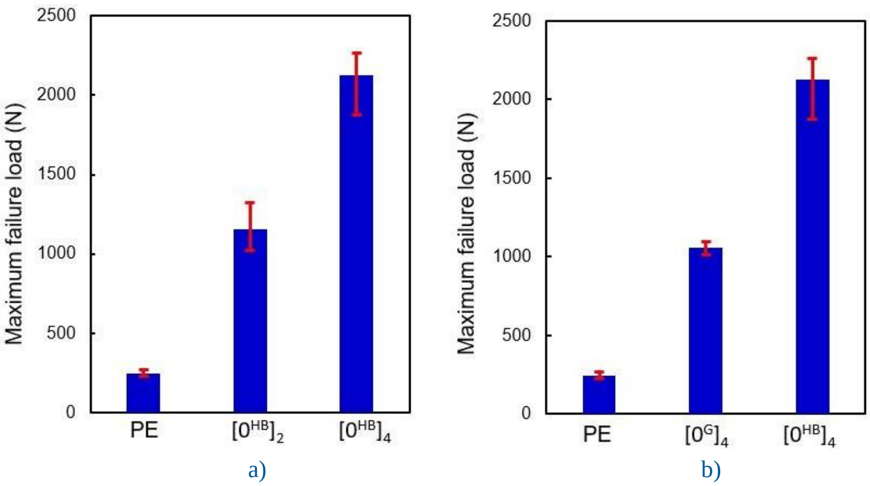


Fig. 6. Variation of maximum damage load with a) ply number, b) fiber type

Since the difference in the amount of increase can be observed more sharply, the effect of hybrid fiber reinforcement is shown in the graph. The failure load for pure PE was obtained as 246 N. As a result of adding 2 layers of HB into 3 layers of pure PE, the failure load reached 1157 N. Increasing the number of plates by 100% to 4 times increased the failure load by 84% [20]. The highest failure load was found for HB thermoplastic composite reinforced with 4 layers as opposed to glass fiber reinforced composite [15]. Both carbon and aramid filaments in HB fabric have higher tensile strengths than glass fiber [15]. It can be seen from Figure 6.b that there is a 95% increase in failure load as a result of using $[0^{HB}]_4$ instead of $[0^{G}]_4$.

The results obtained for the maximum failure load in Figure 6 are in line with the Young's modulus results in Fig. 7. In Fig. 7a, the effect of the change in the number of fiber layers on the Young's modulus of the material is shown. The Young's modulus of $[0^{HB}]_2$ composite is 2799 MPa.

In HB composites, when the number of layers is increased and doubled, a 52% increase in Young's modulus was obtained. If HB is used instead of glass fiber in 4-layer composites, a 50% increase in Young's modulus has been found (Fig. 7b). In this case, it is seen that the use of $[0^{HB}]_2$ instead of $[0^{G}]_4$ is similar in terms of Young's modulus values.

The variation of the maximum damage displacement (Δ_B) with the number of layers and fiber type is given in Fig. 8a and Fig. 8b, respectively. As a result of using pure PE, the maximum Δ_B value was obtained as 11 mm. High reductions in Δ_B values of thermoplastic composites obtained by adding fiber reinforcements to PE were obtained. While Δ_B for $[0^{HB}]_2$ is 2.4 mm, for $[0^{HB}]_4$ it is 3.1 mm. Although the number of layers increased, the displacement increased partially instead of decreasing. However, since the stress / displacement ratio, namely Young's modulus, is taken into account, there is no unexpected situation. It cannot be said that there is an obvious change in Δ_B values as a result of increasing the number of layers. The similar situation is true for the change of fiber type. As a result of using 4 layers of HB instead of 4 layers of glass, the increase in ΔB values was only 33%. Considering the use of pure PE, this increase remains at very low rates (Fig. 8b).

Fig. 9 shows the variation of the maximum damage load with Δ_B for pure PE and composite samples. It can be seen that high damage displacements are obtained for low damage loads using pure PE.

The stiffness of the composite increased with fiber reinforcement. It can be seen that high damage loads are obtained for low ΔB values. The highest strength among fiber reinforced thermoplastic composites was obtained for $[0^{HB}]_4$ composites.

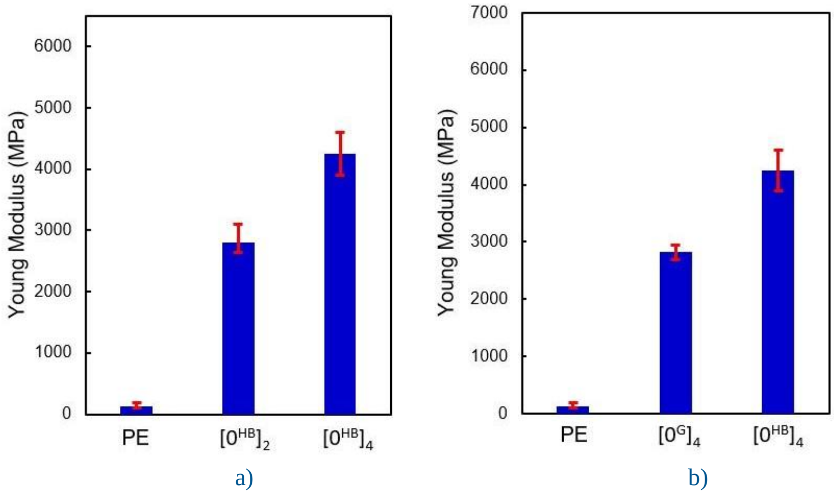


Fig. 7. Variation of Young modulus with a) ply number, b) fiber type

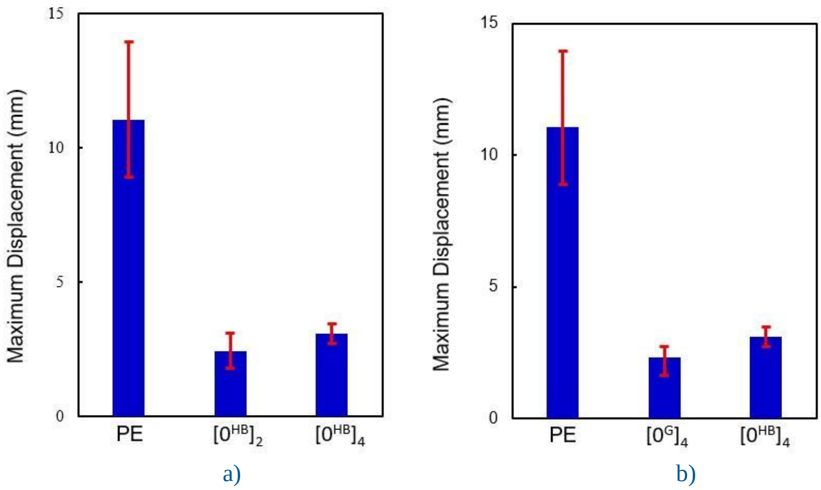


Fig. 8. Variation of maximum displacement with a) ply number, b) fiber type

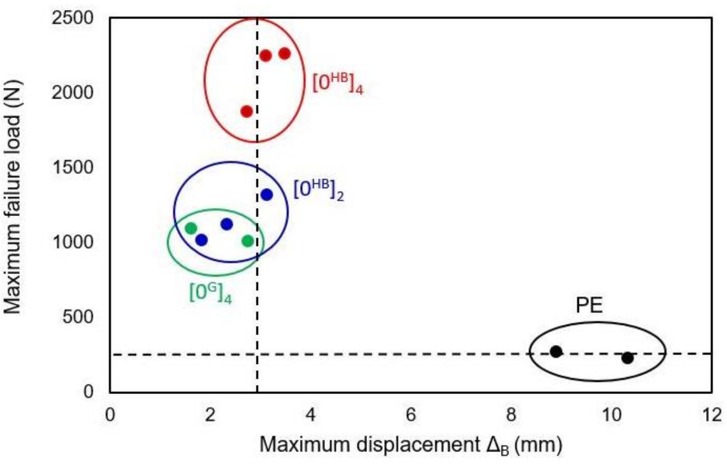


Fig. 9. Variation of maximum damage load with maximum displacement for different lamina configurations

4. Conclusion

In the study, glass fiber and HB carbon-aramid fiber reinforced, PE matrix thermoplastic composite sheets were produced by lamination technique. Test samples were prepared from these plates and tensile test was performed. As a result of this tensile test;

- It is the fiber reinforcement that supplies the damage load in composite materials. Therefore, the use of [0HB]4 fiber reinforcement increased the damage load of composites by 765% compared to pure PE. The similar situation is true for Young's modulus. If [0HB]4 fiber reinforcement is used instead of pure PE, a 32 times higher Young's modulus is obtained. However, on the contrary, approximately 4 times less elongation was obtained in damage displacement. Therefore, it has been seen that PE reinforced composites reinforced with continuous fibers provide significant gains in terms of strength.
- In the case of glass and HB fabrics, it can be seen that HB fabrics provide higher strength and rigidity. For the same number of layers, approximately 2 times more tensile strength is provided by the use of HB compared to glass fiber. However, there is no significant difference between damage displacements. On the other hand, it was determined that the use of [0HB]2 and [0G]4 exhibited similar mechanical properties. At this point, designers can consider the use of HB material in structures that require high rigidity and lightness. However, the cost calculation occurs according to glass fiber.
- In this study, composites were produced by lamination technique. The results of the tensile tests to be applied to the thermoplastic composite material produced by a different method other than the lamination technique and applied to these materials can be compared with the results obtained in this study.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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