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Comparison between the mechanical properties and environmental sustainability of basalt and carbon fiber reinforced polymers hoop filament wound components

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Abstract. Filament Winding (FW) is one of the most effective composites manufacturing processes used to produce structural axisymmetric components in fiber reinforced polymers (FRPs), such as pipes, tubular parts and vessels. Among FRPs, basalt fibers (BFs) reinforced composites are gaining an increasing interest in many industrial fields, such as aerospace, automotive and nautical ones, since BFs are natural fibers characterized by good mechanical properties, thermal and chemical stability, as well as reduced costs, compared to synthetic carbon fibers (CFs). In this context, the present research aims at evaluating and comparing the mechanical properties, in terms of hoop tensile strength and compressive strength, of Basalt Fiber Reinforced Polymer (BFRP) and Carbon Fiber Reinforced Polymer (CFRP) tubular components obtained by FW process. Furthermore, a Life Cycle Assessment analysis was performed to evaluate the environmental impacts associated to the different composite materials. The comparison between the impacts obtained using BFRCs and CFRPs has highlighted the ecological benefits of BFRPs.

Introduction

In the last decades, Fiber Reinforced Polymers composites have been widely used in many different applications in several engineering industries due to their physical, chemical and mechanical properties combined with their low weights [1]. Specifically, Carbon Fibers are the most used fibers to reinforce polymeric matrixes, in order to achieve lightweight structures characterized by high performances [2]. Unfortunately, the CF production involves relevant CO_2 emissions and energy intensive phases, resulting in CFRP parts characterized by both elevated costs and high carbon footprint [2]. Consequently, the study of natural fibers, as a sustainable alternative to reinforce composite materials, is gaining an increasing interest in many industrial fields [3,4]. In this context, basalt fibers have emerged as one of the most promising alternatives due to their good mechanical properties, high resistance to corrosion, low thermal conductivity, chemical inertness, and low environmental impacts [5,6].

Many industries, in particular aerospace and automotive ones, require tubular reinforced composite components. In scientific literature, many researchers have focused on the evaluation of mechanical performances of FRP tubular structures manufactured by Filament Winding [7], a process based on the winding of fiber reinforced polymer tows or tapes on a rotating mandrel [8].

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Lapena et al. and Kessler et al. [9–11] evaluated the tensile strength, elastic modulus and thermal properties of Glass Fiber (GFRPs), Basalt Fiber (BFRPs), and Carbon Fiber Reinforced Polymers (CFRPs) wound components using unidirectional flat specimens realized by winding the composite material on a planar mandrel. Lapena et al. [12] and Amula et al. [7] compared the mechanical properties of BFRPs and GFRPs rings realized with different winding angles in terms of hoop tensile strength (HTS), by means of split-ring tests performed according to ASTM D2290. Özbek et al. [13] investigated the radial and axial compressive properties of BFRP samples realized using polar and helicoidal windings. Unfortunately, no scientific papers that provide a comprehensive comparison of the hoop tensile strength and axial compressive strength of BFRP and CFRP filament wound tubular components are available.

In this framework, the present investigation aims at evaluating and comparing the mechanical properties, in terms of hoop tensile strength and axial compression strength, of BFRP and CFRP tubular components obtained by FW process. Furthermore, a comparative analysis of the environmental impacts of reinforced composite wound components was performed by means of the Life Cycle Assessment (LCA) methodology to identify the most environmentally sustainable alternative.

Materials and Methods

Materials

Composite tubular specimens were manufactured using both basalt fiber and carbon fiber towpregs. Unidirectional fiber tows were impregnated with an epoxy resin using an automated process [14]. A Huntsman International LLC epoxy resin, characterized by a gel temperature (T_{gel}) of 90°C and a glass transition temperature (T_g) of 120°C, was used. To prevent degradation of the resin or premature curing, the towpregs spools were stored in an industrial refrigerator at -18°C.

The Basaltex 1200 was used as reinforcement of basalt tows used in the present research consider were characterized by a width equal to 6 mm. The BF towpreg resulted in a resin weight fraction (w_m%) equal to 28.2%. As far as the carbon fiber towpregs are concerned, TRH 50 Mitsubishi 30K CF filaments, with a width equal to 10 mm, were used. The CF towpreg resulted in a resin weight fraction equal to 28.2%. By assuming zero voids content of the towpregs, the fiber content for both CFRP and BFRP is equal to 71.8%.

Manufacturing process and mechanical characterization

Composite tubular specimens were manufactured using a laboratory-scale filament winding machine (X-Winder, 4X-23). The machine has four controlled axis and four stepper motors that allow the rotation of the mandrel, the translation of the deposition head along the longitudinal section of the mandrel (w-axis) and towards it (z-axis) and the rotation of the deposition head.

The towpreg spools were removed from the refrigerator 12 hours before the winding process to reach room temperature and obtain an optimal resin tack. Hence, different tubular specimens were produced to evaluate and compare the mechanical properties of the two investigated materials. In all cases, hoop winding was used, and three layers were deposited for each specimen. A winding angle equal to 88° was imposed to allow a correct tow deposition, without having excessive overlap during the winding process. A FALC muffle furnace (FM 8.2 Lt) was used to cure the tubular components. In line with the resin producer recommendations, the parts were cured at 120°C for 2 h and at 150°C for 2 hours before air cooling.

In order to characterize the mechanical behaviour of the wound components in BFRP and CFRP composite materials, ring tensile test (Figure 1a) and axial compression test (Figure 1b) were carried out. For the ring tensile test, specimens were prepared and tested according to ASTM D2290 [15]. The initial tubular components were transversally cut and then drilled so that ring specimens had a width of 25 mm, with a notch radius of 5 mm. Five specimens for each material

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were realized and tested. A dedicated split-disk fixture, consisting of two semicircular supports, was used for the test in the MTS 810 universal testing machine. A crosshead speed equal to 0.1 mm/s was set for the test, within the range defined by the ASTM D2290 standard.

For the axial compression test, two tubular specimens were cut at both extremities to remove irregular thickness of the turning zones obtained during the winding process. According to the ASTM D695 standard, tubular specimens were 70 mm in the inner diameter and 150 mm in height [16]. The axial compression tests were performed using the MTS 810 universal testing machine equipped with compression plates. Load vs displacement curves were obtained as well as the compressive stress on the parts.

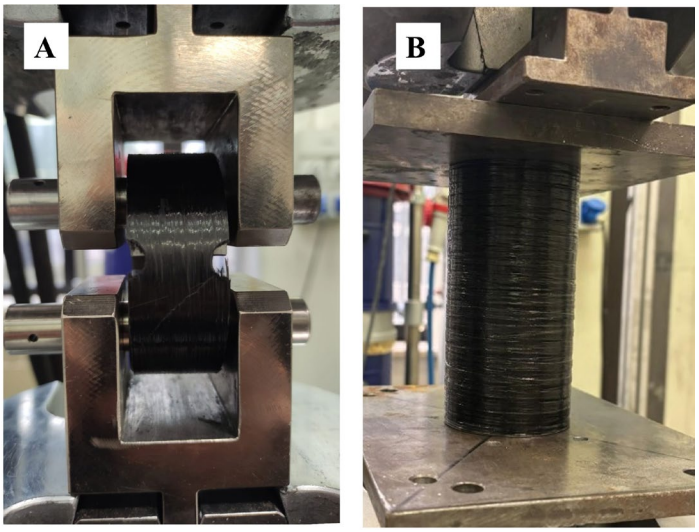


Figure 1 (a) Ring tensile test and (b) axial compression test.

Life Cycle Assessment analysis

The mechanical characterization tests were paired with a sustainability analysis to determine if the basalt fiber based composite material can provide environmental impacts reduction with respect to the synthetic alternative of CFs. To this purpose, the standardized methodology of Life Cycle Assessment, defined by the ISO 14040-14044 standard, was employed. The four iterative phases described in the standard, i.e. 1) Goal and Scope definition, 2) Life Cycle Inventory, 3) Life Cycle Impact Assessment, and 4) Results and discussion, were performed.

The Functional Unit (FU) was defined as the production of composite tubular components characterized by an inner diameter equal to 70 mm, a length equal to 150 mm and a laminate stacking sequence as that used for the mechanical characterization (i.e. 3 layers with 88° orientation); in these conditions, a composite tubular component, with thickness equal to about 2.5 mm, results. Data related to the fiber and matrix volume fraction for the composite materials were the same reported in the previous sections.

Two scenarios were hence included in the analysis to represent the production of basalt fiber (Scenario 1) and carbon fiber (Scenario 2) reinforced composite tubular parts. In order to focus on the material production and manufacturing stages, a cradle to gate approach was adopted; impacts related to materials extraction (carbon and basalt fibers, epoxy resin, consumable materials) and preparation, transport and all the manufacturing phases (including prepreg production, filament winding and parts curing) were included within the system boundaries. The service life was not included within the system boundaries as it would be strongly influenced by the specific use of the component (e.g. in automotive or building sectors) and the analysis would have lost general value.

For the Life Cycle Inventory (LCI) phase, direct measurements and secondary data from literature analyses and commercial database (Ecoinvent) were used.

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The weight of the tubular component was directly measured and, considering the fiber and matrix fractions in the two scenarios, constituents' consumption was calculated. Whenever possible, raw materials production was modelled using the Ecoinvent database (e.g. in the case of aluminium, epoxy resin…). Carbon fibers were modelled according to literature [2]; similarly, basalt fibers were modelled according to Fort et al. [17]. The prepregging phase was modelled according to literature [14]. Refrigerated storage was also considered for the prepreg. Transport distances were estimated considering the material suppliers geographical location and the production plant in center Italy. The energy consumption of the filament winding was directly measured via a power meter. Curing energy and consumable material use were estimated according to literature analysis [18]. Ecoinvent was employed to model electric energy consumption (low voltage, Italian energy mix) and transport impacts (i.e. considering road and water routes).

The two scenarios were modelled in SimaPro and LCIA results were obtained. Impacts were evaluated in terms of Global Warming Potential (GWP, IPCC methodology); GWP quantifies the possible effects of the FU on global warming, and it is expressed in kg of CO_2 eq. This impact category was selected among the most significant and used ones for composite parts LCA analyses.

Results and discussions

Mechanical characterization results

Figure 2 shows typical specific load vs. displacement curves obtained by ring tensile tests of BFRP and CFRP samples. Irrespective of the material investigated, the specific load increases with displacement until reaching a peak value at which the ring specimen fracture occurs. However, the curves of BFRP and CFRP composite materials are characterized by different slopes: specifically, for a given displacement, the specific load of CFRP is always higher than that of BFRP composite. Furthermore, the maximum specific load value reached by the CFRP specimens, equal to about 7 kN/g, is more than three times higher than the one obtained by the BFRP ring specimens (about 2 kN/g). This result can be attributed to the higher ultimate tensile strength of CFs with respect to the one of BFs. Since the load is applied along the direction in which the fibers are oriented (hoop winding), the fibers are responsible for the mechanical response of the specimens. However, it is interesting to observe that BFRP specimens reach the fracture at a displacement of 3.5 mm, which is higher than the one reached by CFRP specimens, equal to 2.1 mm. Table 1 summarizes the mean values of weight, thickness obtained by the specimens' measurements, maximum load, specific maximum load, HTS and specific HTS resulted by the performed test.

The comparison between CFRPs and BFRPs in terms of HTS and specific HTS, calculated according to ASTM D2290 standard, shows that the CFRP specimens are characterized by higher HTS and specific HTS values than those obtained by BFRP ones, even though BFRPs fail after higher displacements than those applied to CFRPs.

Table 1 Mean geometric values of ring specimens and typical mechanical properties obtained by ring tensile tests.

	Weight [g]	Thickness [mm]	Max Load [kN]	Specific Max Load [kN/g]	HTS [MPa]	Specific HTS [MPa/g]
BFRP	29.07±4.86%	2.73±2.45%	64.74±4.08%	2.23±3.37%	720.98±4.16%	24.80±3.58%
CFRP	7.02±2.03%	1.10±4.09%	50.66±4.42%	7.22±3.71%	1358.17±4.4%	194.54±3.89%

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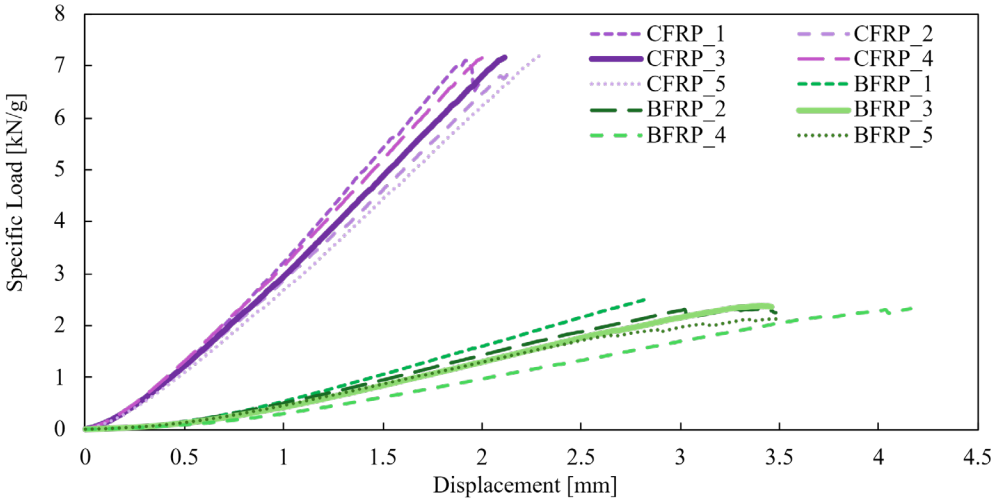


Figure 2 Typical specific load versus displacement curves of BFRP and CFRP ring specimens subjected to ring tensile tests.

To investigate the compressive behavior of BFRP and CFRP composites, axial compressive tests were performed according to ASTM D695 standard [16]. Figure 3 shows typical compressive strength vs. strain curves obtained by axial compressive tests of BFRPs and CFRPs. It can be observed that the BFRP tubular components are characterized by a different compressive behavior as compared to the CFRP ones. Specifically, the compressive strength exhibited by BFRP increases with strain until a peak value equal to about 78 MPa; then, the compressive strength vs. strain curve shows a sawtooth pattern with a gradual and slow reduction in strength until failure. The BFRP material exhibits such behavior up to a mean strain value of 6%. On the contrary, the compressive strength of CFRP specimens rises with strain until the similar peak value reached by the BFRP, at which the fracture clearly occurs, then a decrease in the compressive strength can be observed. Such result can be attributed to the different failure mechanisms of the tubular samples related to the different reinforcements used. According to Abolfazli et al. [19], the tubular component in CFRP is characterized by a fiber resin interface cracking (Figure 4a). The compressive force applied to the tubular composite part can cause the separation between fibers and resin, leading to the formation of cracks and overall failure. On the other hand, the tubular component in BFRP exhibits the end crushing, that is a type of failure mechanism where the material is crushed at the end of the structure (Figure 4b).

The similar compressive strength reached by the two materials at the first peak value of the curves can be attributed to the failure of the matrix since the direction of the applied load during tests is almost perpendicular to the fiber orientation in the hoop configuration investigated in the present study.

Table 2 summarizes both the mean values of weight and thickness obtained by the specimens' measurements, and the maximum load and maximum compressive strength obtained by the performed axial compressive tests, for both materials investigated.

Table 2 Mean geometric values of tubular specimens and typical mechanical properties obtained by axial compressive tests

	Weight [g]	Thickness [mm]	Max Load [kN]	Max Compressive strength [MPa]
BFRP	150±3.78%	2.4±4.25%	42.75±3.87%	78.34±4.09%
CFRP	130±3.23%	2.625±3.56%	44.61±4.02%	74.52±4.17%

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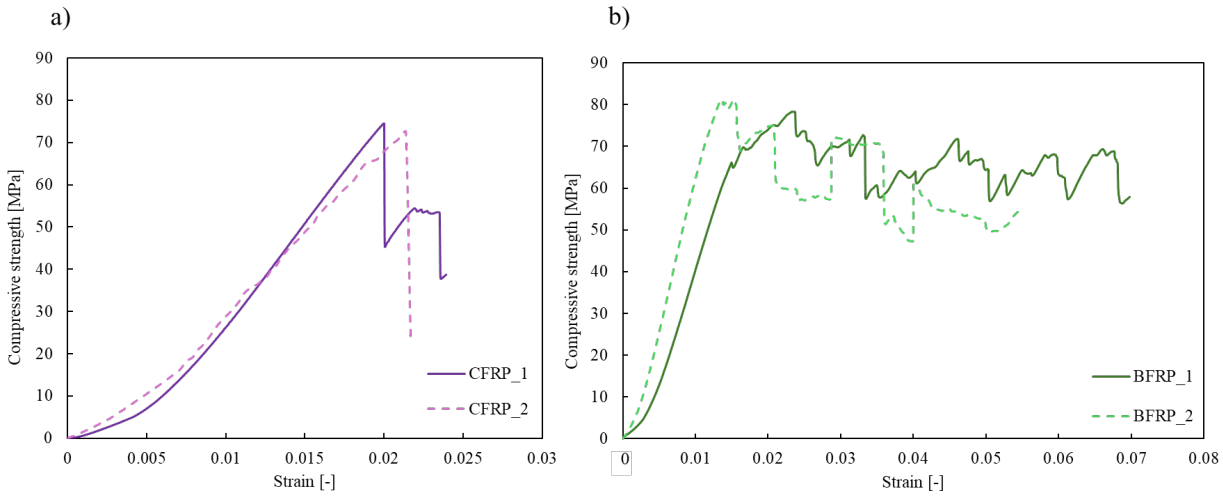


Figure 3 Typical compressive strength-strain curves obtained by (a) CFRP, and (b) BFRP specimens subjected to axial compressive tests.

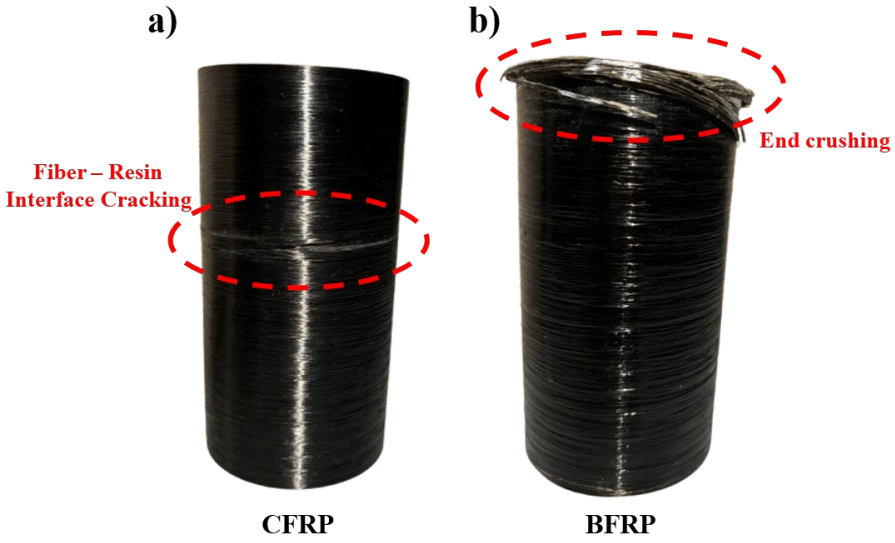


Figure 4 Fractured tubular components in (a) CFRP and (b) BFRP composite after axial compressive tests.

Life Cycle Assessment results

Figure 5 shows the results of the LCA analysis in terms of Global Warming Potential for the two considered scenarios. The Basalt Fiber composite (Scenario 1) resulted the most sustainable alternative with total footprint equal to 1.60 kg CO_2 eq whilst the Carbon Fiber one (Scenario 2) has an associated impact equal to 3.56 kg CO_2 eq.

Indeed, the main advantage associated with Scenario 1 is related to the low unitary carbon footprint of BFs with respect to the CFs (i.e. 0.4 kg CO_2 per kg vs. 39.9 kg CO_2 per kg). The production of carbon fibers represents the higher contributor in Scenario 2, accounting for about 67% of total manufacturing impact; on the contrary, the production of basalt fibers has almost a negligible impact; hence, despite the higher density of basalt fibers (and overall weight of the tubular components), they represent a sustainable alternative to synthetic materials.

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In both scenarios, the preimpregnation and filament winding phases have almost negligible impacts; this result further highlights that FW can represent a low emissions and automated production process for composites. On the other hand, the curing phase, that is the same in both scenarios as it is basically not affected by the fiber reinforcement used, is associated with relevant impacts, both for the energy requirements and the consumable materials (i.e. these phases combined account for more than 80% of Scenario 1 impacts). It follows that improvement solutions are required.

In the present analysis, the functional unit was defined only considering the geometry of the components as similar compressive behavior was assumed. Different results could be obtained as different properties are selected as benchmark for the definition of the FU; for instance, as tensile strength or modulus are considered, CFs could provide strong benefits in terms of weight reduction. These assessments will be further explored and developed in future studies.

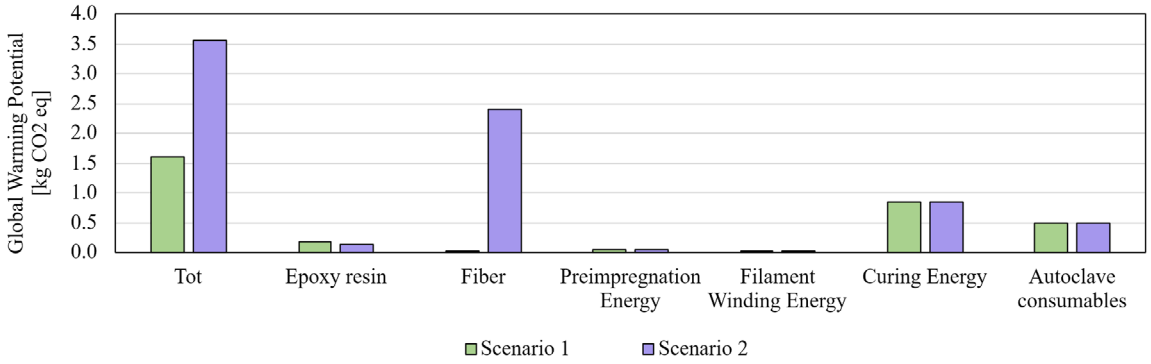


Figure 5 LCA results in terms of GWP for the two considered scenarios.

Conclusions

The present study aimed at evaluating the differences between the mechanical properties of CFRP and BFRP tubular specimens obtained by FW process, in terms of hoop tensile strength and axial compressive strength. In addition, the environmental impacts of both materials were evaluated by means of LCA methodology. The main results can be summarized as follows:

- Irrespective of the material investigated, the specific load measured by means of ring tensile tests on specimens increases with displacement until reaching a peak value at which the fracture of the specimen occurs.
- The maximum specific load, as well as the maximum specific HTS value, reached by the CFRP specimens (respectively 7.22 kN/g and 194.54 MPa/g) are relevantly higher than those obtained by BFRP specimens (respectively 2.23 kN/g 24.80 MPa/g).
- The compressive behaviour of the tubular components can be attributed to the different failure mechanisms related to the different reinforcements used. In particular, the tubular component in CFRP is characterized by a fiber resin interface cracking whilst the part in BFRP exhibits an end crushing mechanism.
- A negligible discrepancy in the maximum axial compressive strength obtained by CFRP and BFRP specimens can be observed due to the failure of the matrix since the direction of the applied load during tests is almost perpendicular to the fiber orientation in the hoop configuration investigated in the present study.
- The environmental impacts related to the production of a BFRP tubular component are significantly lower (1.60 kg CO_2 eq) than those of CFRP one (3.56 kg CO_2 eq). The main difference is due to the impacts related to the fibers: the unitary carbon footprint of CF is relevantly higher than the one of BF.

Future works will concern the study of other mechanical properties of both BFRP and CFRP, such as the radial compressive strength. In addition, the effect of different winding angles and FW parameters on mechanical behaviour and environmental impact will be investigated to optimize the performances of the BFRP components produced using FW process.

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