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Research Article

Ultra-High-Molecular-Weight Polyethylene Rods as an Effective Design Solution for the Suspensions of a Cruiser-Class Solar Vehicle

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Ultra-high-molecular-weight polyethylene (UHMWPE) is a subgroup of the thermoplastic polyethylene characterized by extremely long chains and, as result, in a very tough and resistant material. Due to remarkable specific mechanical properties, its use is gradually being extended to multiple fields of application. This study describes, perhaps for the first time, how the UHMWPE can represent a valid material solution in the design and optimization of suspensions for automotive use, especially in the case of extremely lightweight vehicles, such as solar cars. In particular, in this design study, UHMWPE rods permitted to assure specific kinematic trajectories, functionalities, and overall performance in an exceptionally light suspension systems, developed for an innovative multioccupant solar vehicle. These rods reduced the weight by 88% with respect to the classic design solutions with similar functions, offering, at the same time, high stiffness and accuracy in the movements. An experimental campaign was conducted to evaluate the ratcheting behaviour and other mechanical properties needed for a proper design and use.

1. Introduction

In some cutting-edge structural engineering applications, such as the design of solar energy powered vehicles, the designer needs to use materials with the highest possible specific stiffness and specific strength in order to achieve the minimum weight [1, 2].

The solar vehicles are innovative prototypes destined to run for long races in extreme conditions, as, for example, the sunny and endless desert Australian roads of the World Solar Challenge [3]. Minimizing the weight permits, together with other technical details and engineering tricks, to improve the energy efficiency of the vehicle that represents a key factor for a successful solar prototype. From the perspective of the design of a suspension system for that application and apart from any other consideration proper of the traditional automotive design, the designer has to act with extreme care to reduce every sort of energy dissipations.

Therefore, the car has to run stable on the road asperity, vibrations have to be minimal, and inertia with respect to changes in speed and direction has to be limited. It means, in practice, that the design has to be direct to stiff, light, and precise suspensions. The possibility to obtain these results is also related to the material choice.

Considering the well-known Ashby charts [4] leads to the conclusion that the choice should be limited to Carbon Fiber Reinforced Plastic (CFRP) sandwiches, in the presence of bending load or for energy absorption, and laminates in the other cases, with the possibility of using metals where other conditions may suggest not to use composites (e.g., high contact stresses, transversal loading, and exposure). In very specific cases, where geometrical of functional constrains is present, like in the suspension system, other kinds of materials, such as high performance polymers, can be taken into consideration by the designer.

The studies presented in [5, 6] were preliminary to the design of a full CFRP suspension for the solar vehicle named *Emilia 4*, a multipassenger solar car, designed and developed by the University of Bologna in collaboration with the Onda Solare Solar Car Association. This vehicle belongs to the Cruiser Class, in accordance with the World Solar Challenge regulation [7] and is a four-seat race prototype. The car

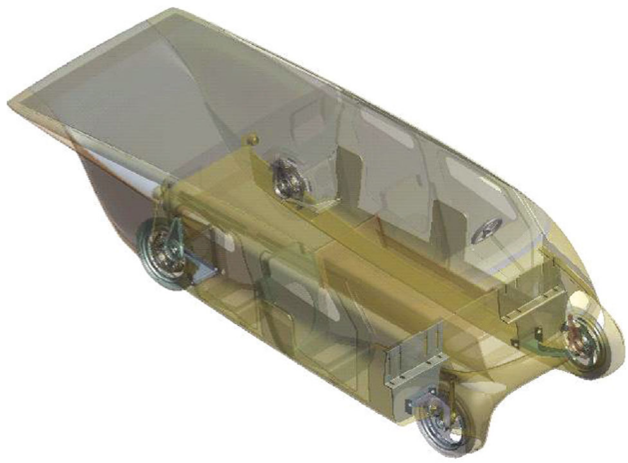


Figure 1: The Solar Cruiser Emilia 4.

model was presented in June 2018 and won the American Solar Challenge in July 2018. In this event, the vehicle ran 2700 km by means of exclusively solar energy showing a valid compromise between the different design choices. Among them, a special attention was addressed in searching effective design solutions for the suspension systems. The vehicle general shape is shown in Figure 1, where the location of the suspension systems is visible in transparency.

For additional details, the design process of the car chassis is shown in [2]. The whole vehicle body was made autoclave by CFRP/polymeric honeycomb sandwich, while all other mechanical components consist of CFRP laminates.

Differently from most engineering applications, in the case of competing vehicles, the main design directions are dictated by the rules of the race they are destined for (e.g., [8]). These requirements, in particular, regard aspects as overall dimensions, safety, visibility, drivability, and solar panel and battery characteristics. All these technical constrains, joined to the overall design goal of reducing the energy consumption, led, as regards to the mechanical and structural aspects, to the aerodynamic optimization and to a total weight of the car that was lower than 330 kg. Adding 320 kg, that is the standard weight of four passengers [7, 8], the total load on the four suspensions was of 650 kg.

The suspension system is the only moving part of the vehicle in our case, since the electric motors are located inside the rear wheels, so that no transmission shafts or differential is needed.

Generally speaking, the suspension of a car is the assembly of levers and elastically deformable elements which, by constraining the unsprung masses with the suspended masses, has the function of keeping the body in suspension of implementing a predetermined distribution of the variable forces—insistent forces on the wheels both in traction and cornering and braking—and reducing the shocks transmitted following the passage of the vehicle on the road asperity. The suspension, therefore, includes all those parts that connect the wheels to the frame. In general, it consists of three main parts: a structural part, an elastic part, and a damping part (that in our case study is not concentrated in a single element). The structural part is a set of levers that has the purpose of guiding the suspension and consequently the wheel in its motion relative to the chassis.

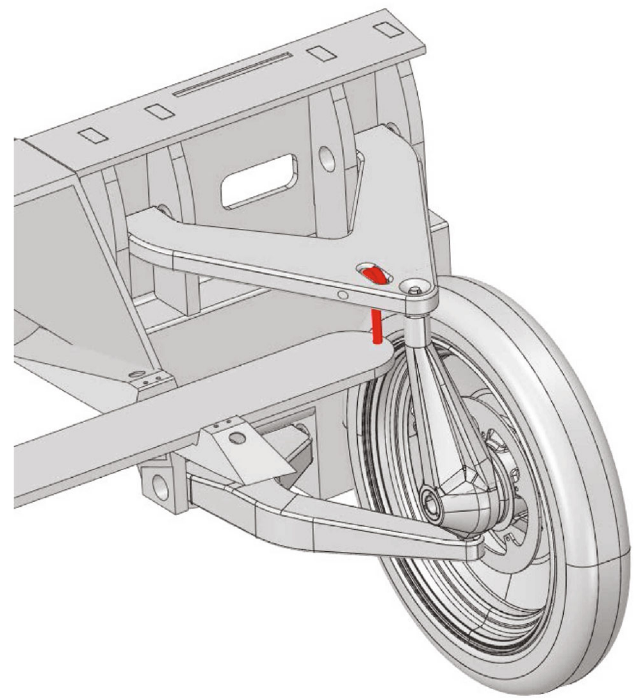


Figure 2: Design of the front suspension with the rod depicted in red.

In particular, the design chosen for the front suspension, that is the focus of this paper, is shown in Figure 2. It consists in a longitudinal arm suspension, suitable for long straight roads, like those encountered in the 3000+ km competitions, with a transverse leaf spring that has also an antiroll role since it is joined to both frontal wheels.

The suspension architecture comprehends a conrod loaded in tension that links the upper lambda shape arm (or upper arm) to the leaf spring. Basically, the vehicle is suspended to that conrod that transfers the load to the lambda element and then through a pillar, to the wheel.

This conrod needs to be very small to fit in the suspension scheme, but most of all, it needs to have spherical joints to its ends because the kinematic of the lambda element makes the upper end of the conrod move on a circle in the sagittal plane, while the lower end moves on the transversal plane during the leaf spring deformation.

Following these considerations, different possibilities were investigated and compared, including the use of ultra-high-molecular-weight polyethylene (commercial name Dyneema or Spectra) strips.

The UHMWPE fiber mechanical properties at room temperature are quite interesting for the designer, compared to metal- or composite-based solutions, and the use of these polymeric strips can lead to a much lighter and compact component.

In fact, with a density of 975 kg/m^3, a typical Dyneema yarn has an elastic modulus of 110 GPa and a tensile strength of 3400 MPa [9].

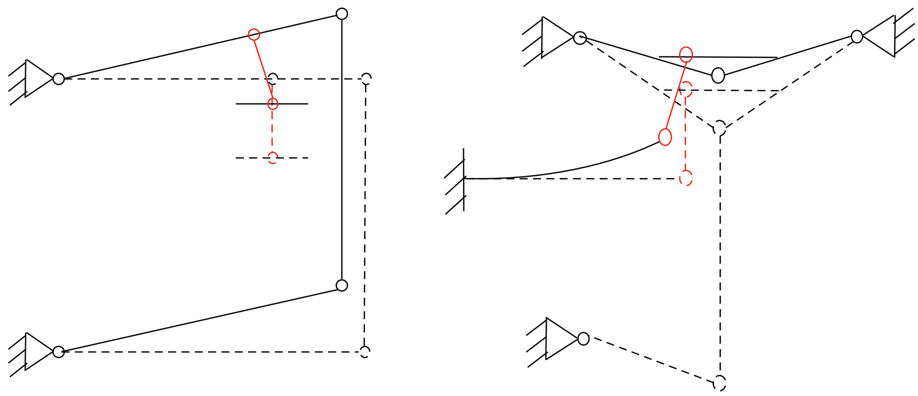


Figure 3: Schematic of the kinematic of the suspension, the rod is depicted in red.

Nowadays, these materials [10] are found in many sporting applications requiring lightweight and strength such as parasails, suspension lines for paragliders or parachutes, and in rigging used in competitive sailing. They are also used in archery or as sport fishing lines in a form of monofilaments. Finally, they are used in climbing, also because of their abrasion resistance. As regards industrial applications, UHMWPE fibers are used for rope and cordage products used in the offshore oil and gas and industrial marine industries. Moreover, their abrasion and chemical resistance make these ropes attractive alternatives to metal wires and cables in corrosive environments.

UHMWPE fibers are also used as a component in high-performance sails, often paired with a creep resistant fiber, such as carbon or Kevlar. The problem of creep, i.e., the tendency to have an increasing deformation over time in the presence of a static load, was first considered in the case of biomechanical applications [11].

In general, additional design procedures have to be employed to guarantee the resistance to creep [12] and ratcheting [13, 14].

Ratcheting is defined as the progressive accumulation of plastic deformation in materials subjected to stress-controlled cyclic loading with nonzero mean stress. This accumulation proceeds as the number of cycle increases leading possibly to failure.

A very limited number of references can be found on the characterization of thermoplastic fibers [15] or strips [16] in tensile-tensile fatigue loading.

Some research studies are available on the ratcheting behavior of bulk UHMWPE under uniaxial [13, 17–19] or biaxial [14, 20–22] loading, considering also the effect of additives [23, 24] in particular for biomechanical applications, but to the authors' knowledge, there are no studies in the scientific literature on the ratcheting behavior of UHMWPE fibers, yarns, or strips.

2. Materials and Methods

In this section, the requirements for the possible design solutions are detailed, including UHMWPE strips. For this material, the ratcheting characterization is shown and a procedure to allow its use in the suspension system is proposed.

The rod must carry a static axial load equal to the quota of the weight of the passengers and of the car that insists on the specific axis. Moreover, it is subjected to dynamic loads due to the normal vertical oscillation that occur during the vehicle motion and finally to shocks as a consequence of impact on obstacles.

As regards the front suspension, where the rods are located, it is evaluated that the static load per single wheel is 0.5 kN when the vehicle is unloaded and 1 kN when the vehicle is carrying four passengers. The dynamic load is considered a multiple of the static one, and it is set 2 kN max for the normal driving (working load) and 5 kN max in the case of shock (worst-case load). All these forces load the rods exclusively in traction.

The specifications of the negative and positive strokes of the wheel were used to design the leaf spring [2] and are not important for the choice of the rod, provided that it is significantly stiffer than the leaf spring.

In Figure 3, the kinematics of the suspension is shown, by means of the two extreme positions in lateral and frontal views.

One general requirement for this element is to be commercial and possibly certified for a specific load. This excluded the possibility to use an element made of crimped steel wire that would have been very effective, but they are not available for such high loads in small dimensions (lower than 150 mm, all included).

Differently from the metal solution, a polymeric component must be assessed as regards the time-dependent viscoplastic behavior that is what is described in the next section.

2.1. Ratcheting Assessment. As soon as the weight of the empty vehicle on the front suspension represents a very small fraction of the rupture load, due to the imminence of the first race of the solar vehicle, it was decided to skip a time-consuming creep-test campaign and the components were tested directly in ratcheting conditions.

A load-controlled cyclic test was performed on a servohydraulic Instron 8033 machine, equipped with a 25 kN load cell. The frequency was 0.5 Hz and the load ratio variable, but keeping the minimum load always at 1 kN (corresponding to a quota of the weight of vehicle and the passengers

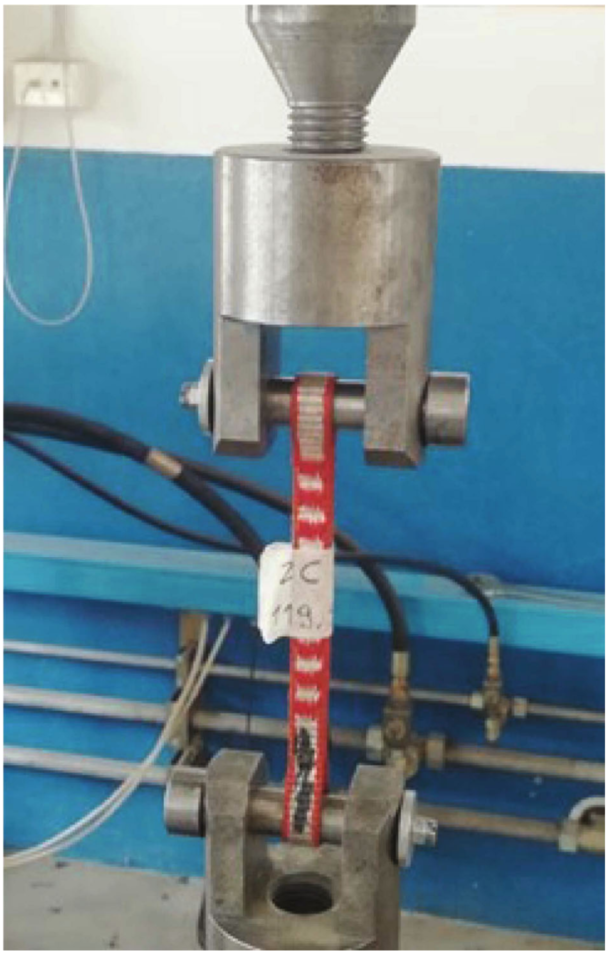


Figure 4: Polymeric specimen mounted on the grips and loaded in tension.

on a single front wheel). In Figure 4, it is possible to see the specimen loading system.

Three types of tests were conducted, all of them with sinusoidal cyclic loading, on three specimens each:

(i) Step test to rupture, in which, keeping constant the minimum load at 1 KN, the maximum load was raised to 2 kN every 10 cycles

(ii) Cyclic test between 1 and 2 kN for 10000 cycles at 0.5 Hz that is the normal driving condition during the race

(iii) Cyclic test between 1 and 5 kN for 10000 cycles at 0.5 Hz that is the worst-case condition to be faced at a very limited number of times (10-20) during the race. Then, a resting period of 7 days at a constant load of 1 kN. After that, on the same rod, a cyclic test between 1 and 2 kN for 10000 cycles at 0.5 Hz

3. Results and Discussion

3.1. Rod Design: Conventional Design by Aluminum Rods and Spherical Connections. The obvious commercial solution is an aluminum rod with two spherical connections, as can be seen in Figure 5, that is calculated according to ISO 12240-4 [25] from the catalog available, for example, in [26]. Considering the above stated loads leads to a couple of commercial spherical heads, chosen among the types shown in Table 1, joined by an aluminum pillar. The total minimum length ($2 \times l2$) of the rod becomes ranges from 78 to 108 mm and the total weight ranges from 26 to 52 grams plus few grams of the weight of the aluminum pillar.

The stiffness of the rod is dominated by the aluminum part one, but it is not an issue as soon it is much higher than the spring one.

On the other hand, in this case, the minimum length is determined by the head geometry and also the head diameter from one side may be too large to fit in the leaf spring, and from the other, the connecting pin diameter (d) is limited to 6 mm due to the size of the head hole. This could be a problem in the connection to the lambda element due to high contact pressures on the CFRP plies.

3.2. Unconventional Design by Polymeric Elements. Following these considerations, the possibility of using a commercial polymeric element was investigated. Kevlar ropes with a 12 mm diameter and nominal resistance of 20 kN were tested, but crimping had the same problems found in the case of metal wires and making knots lead to a sharp (and difficult to foresee) reduction of the nominal resistance [27], eliminating in this way the advantage of the commercial component. In Figure 6, the effect of different types of knots on the quasi-static behavior of the rope is shown. It can be seen that the knot tightening is responsible for huge displacements with very limited load. In no cases, the ultimate strength is close to the nominal one and also the overall stiffness is not suitable for the application.

Finally, a Dyneema stitched strip used for mountain climbing and rated with CE certification marking for 22 kN, shown in Figure 7, was identified as a possible solution.

Indeed, the minimum length is 100 mm, the weight is 6 grams, the width is 10 mm, and the diameter of the head is equal to the pin diameter plus two times the thickness of the strip that is 2 mm. These strips can be connected to the leaf spring and to the lambda upper element by means of 12 mm pins, leading to a fairly low contact pressure on the composite.

3.3. Ratcheting Behavior. In Figure 8, a typical step-test result is shown. A ratcheting behavior, more evident in the first cycles, can be seen, corresponding to the lower loads. Breakage load is higher than the certified load and corresponds to a displacement of 14 mm.

Figure 9 shows the maximum, in red, and minimum displacement, in blue, corresponding to the maximum (5 kN) and minimum (1 kN) load within the cycle, respectively.

It can be shown that, after a sharp increase in the first cycles, the ratcheting effect tends to slow down.

In Figure 10, the typical results of the three tests are shown (note that in this case the number of cycles is in a logarithmic scale). It is possible to appreciate the stabilizing effect on the 1-2 kN loaded specimens of a previous 1-5 kN

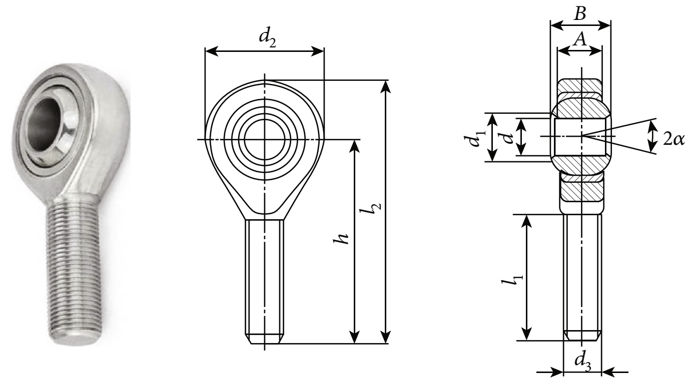


Figure 5: Conventional metal solution.

Table 1: Possible commercial spherical connections.

Type	d_2 (mm)	d_3 (mm)	h (mm)	l_1 (mm)	l_2 (mm)	B (mm)	Dynamic load (kN)	Static load (kN)	Weight (g)
Steel on bronze	18	M6x1	30	13	39	9	4.3	5.3	26
Steel on steel	21	M5x0.8	30	11	42	6	3.4	8.1	13
Steel on metal/PTFE	20	M6x1	30	25	54	9	4.3	5.3	21
Steel on PTFE	18	M6x1	36	22	45	9	4.3	5.3	19

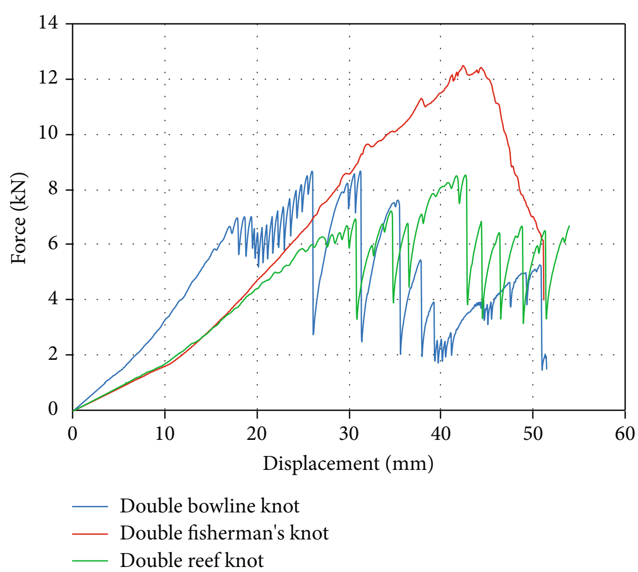


Figure 6: Mechanical behavior of a Kevlar rope with different types of knots.

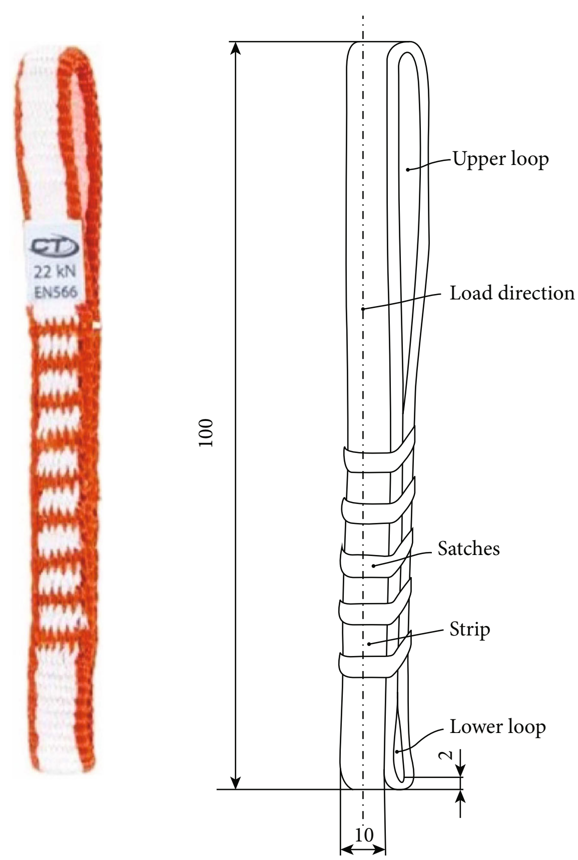


Figure 7: 22 kN rated commercial Dyneema stitched strip.

loading. So, the preloaded strips start from a length of 2.6 mm higher than the commercial one, but the ratcheting behavior due to the service load (1-2 kN) is dramatically reduced. This can be explained through two different phenomena that occur during the loading between 1 and 5 kN at two different dimensional scales. At the molecular level, the long polyethylene chains of the single strand get aligned along the load direction. While at a microscopic level, the strands of the weft and warp of the strip get compacted and aligned along the load direction, as shown in the scanning electron micrographs of Figure 11, where virgin and trained strips are compared.

The results show that it is possible to use the UHMWPE rod, taking the precaution of training it before mounting at a higher load than the nominal one, in order to register the suspension with the right initial length.

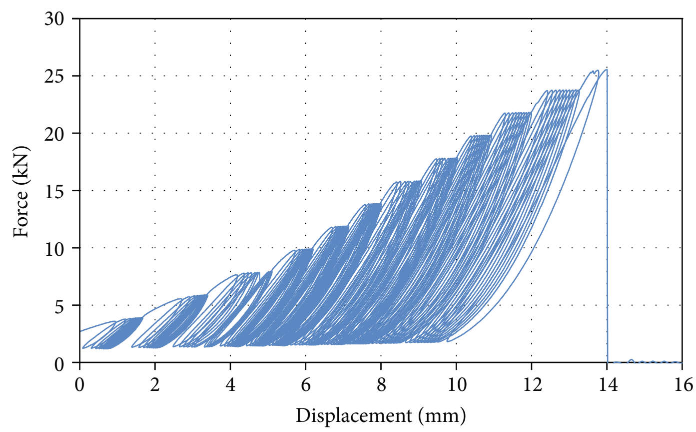


Figure 8: Step-test results.

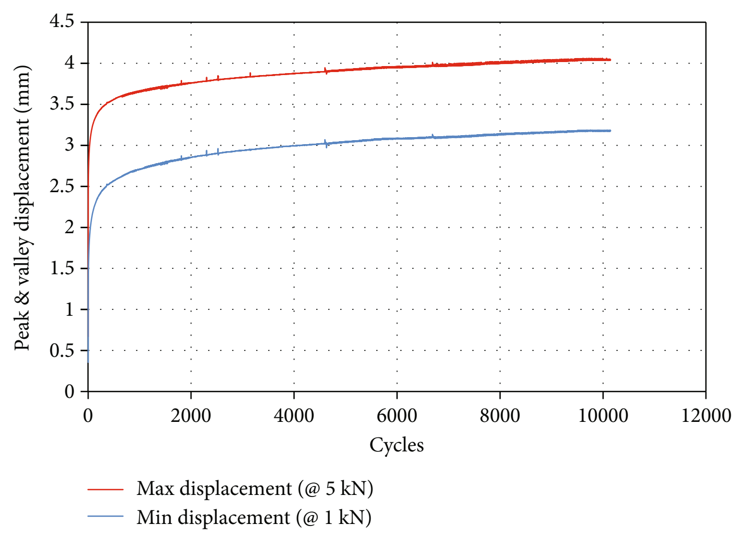


Figure 9: Ratcheting test results 1-5 kN.

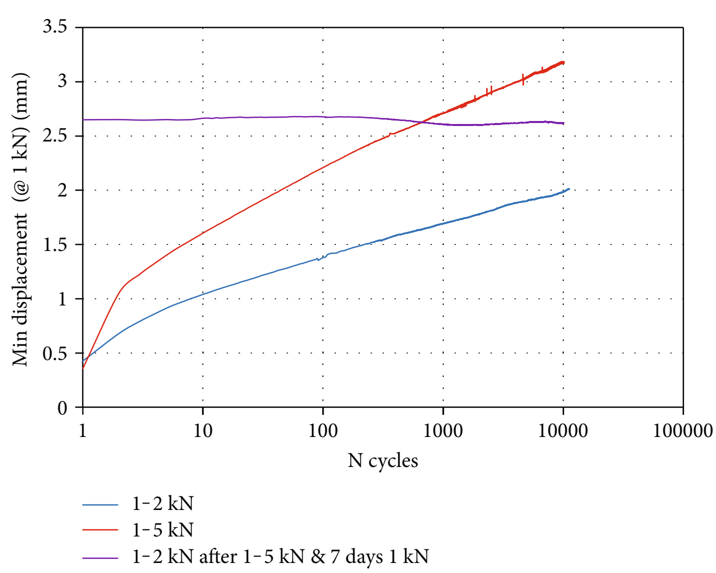
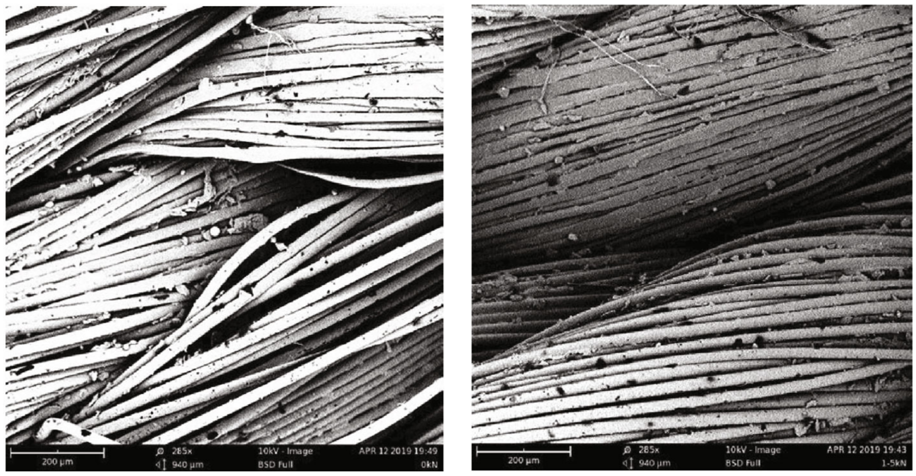


Figure 10: Ratcheting test results in different loading sequences.



(a) (b)

Figure 11: Scanning electron microscope images: (a) virgin specimen, (b) specimen after a 1-5 kN test.

The suggested training protocol is the following:

(i) verify that the maximum worst-case load is lower than the maximum rated load divided by a suitable safety factor (the higher the safety factor, the lower the stretching of the strip in the training phase)

(ii) apply the maximum worst-case load for a number of cycles coherent to the component mission duration, at realistic frequency

(iii) keep the rod statically at the minimum level of the cyclic load for the same amount of time of the cyclic training

(iv) measure the rod length to adapt the mounting set-up

4. Conclusions

The design of a rod for a lightweight vehicle suspension was shown. The analysis of the possible design solutions, i.e., a conventional metal rod with commercial spherical connections and a commercial polymeric UHMWPE element, showed that the latter was able to provide some competitive advantages, in terms of weight and reduced dimensions.

Nevertheless, it was found that in this case, the creep and ratcheting behavior could be an issue, due to two main mechanisms: the alignment at the molecular level of the long polyethylene chains and the compaction and alignment in the direction of the load of the strands of the weft and warp of the strip at a microscopic level.

Suitable mechanical cyclic experimental tests demonstrated that, after the application of the working and the worst-case loading, the rod elongation at a load of 1 kN was of 2 and 3.2 mm, respectively.

By applying a specific training protocol, a full stabilization of the rod with respect to ratcheting was obtained, with a slight elongation, that needs to be taken into account, with respect to the nontrained components.

The trained UHMWPE rods were qualified for the suspension by means of the mentioned tests, both as regards the maximum load and the dimensional stability, and they were actually mounted on the Cruiser-Class Vehicle "Emilia 4" that won the 2018 edition of the American Solar Challenge.

Data Availability

The experimental data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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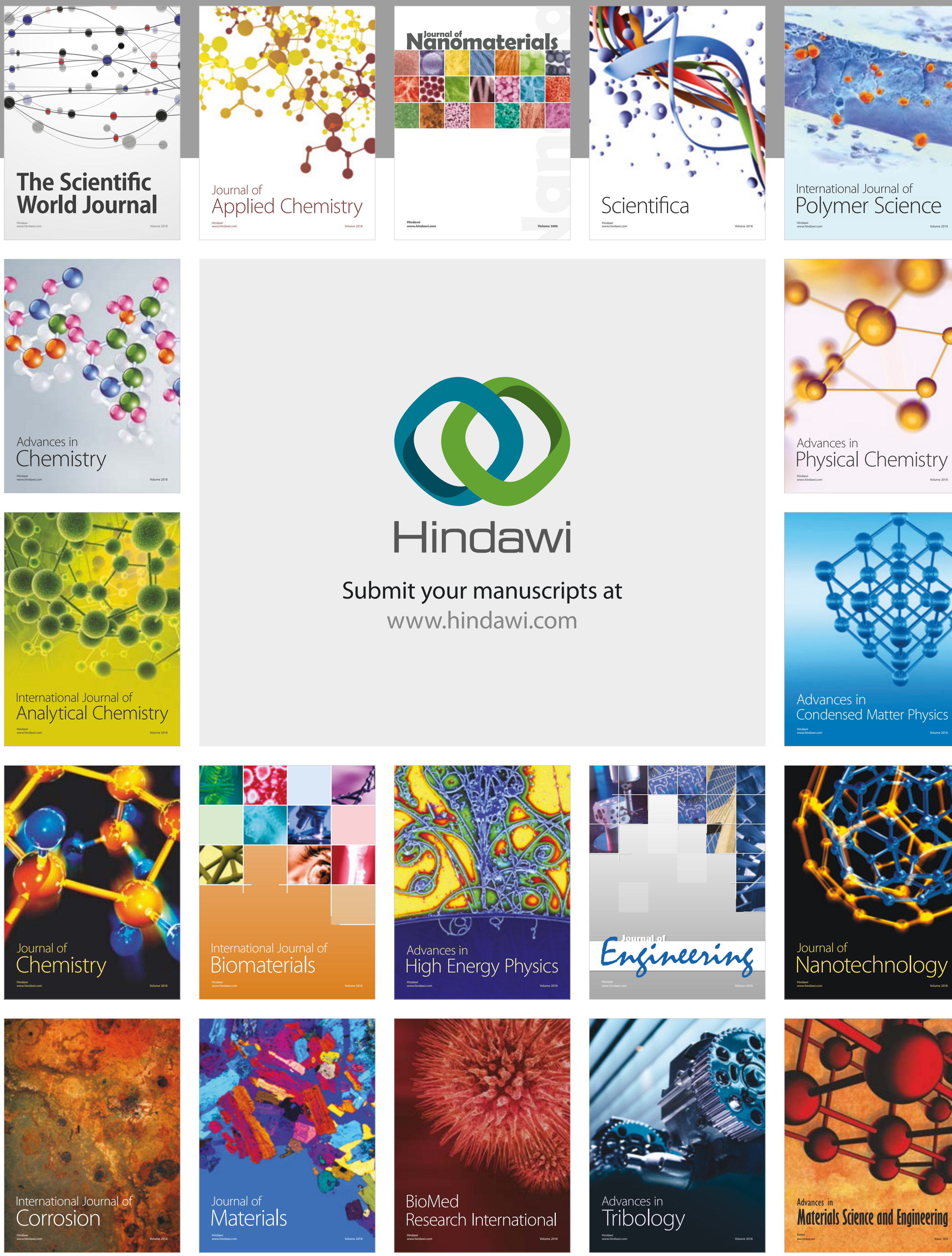
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