DESINGN AND EVALUATION OF A RAIL MADE OF CARBON FIBER REINFORCED MATERAL FOR AN EXTERNAL FIXATION SYSTEM

DISEÑO Y EVALUACION DE UN RIEL HECHO DE MATERIAL REFORZADO CON FIBRA DE CARBONO PARA UN SISTEMA DE FIJACION EXTERNA

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Received for review March 11 th, 2011, accepted March 14th, 2012, final version March, 15 th, 2012

ABSTRACT: This paper introduces the design, construction, and evaluation of a rail for a unilateral external fixation system used for bone transport. The rail was made with carbon fiber/epoxy resin (CF/EP) composite material. A simple manual process was used for the construction of the element; then, the rail was evaluated via mechanical tests under axial load, bending, and torsion. The stiffness of the new element was compared with the stiffness of a commercial rail and good results were obtained.

KEYWORDS: Carbon fiber/epoxy resin (CF/EP), External fixator, Stiffness

RESUMEN: Este articulo muestra el diseño, construcción y evaluación de un riel para un sistema de fijación externa utilizado para transporte óseo. El riel fue hecho con material compuesto CF/EP (fibra de carbono/ resina epoxica). Un proceso manual simple fue utilizado para la construcción del elemento; posteriormente, el riel fue evaluado por medio de pruebas mecánicas bajo carga axial, flexión y torsión. La rigidez del nuevo elemento fue comparada con la rigidez de un riel comercial y se obtuvieron buenos resultados.

PALABRAS CLAVE: Fibra de carbono/ resina epoxi, Fijador externo, Rigidez

1. INTRODUCTION

An external fixation system is a device used to place and hold two or more fragments of a broken bone in the right positions while the healing process takes place. Nails connect the bone fragments with external clamps, which are connected to a rail (Fig. 1). Some external fixation systems are also used widely for bone transport processes like those used for the extension of limbs.

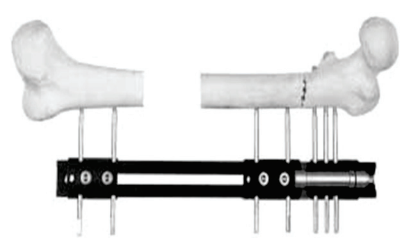


Figure 1. Assembly of bone fragments by using nails and an external fixation system

The number of applications of fibro-reinforced materials has increased in engineering applications such as the automotive and aeronautics industries due to their attractive properties of low density, high stiffness, and strength. In orthopedics, carbon fiber is an important material being used in prosthesis or external fixation systems [1] where X-ray permeability is another excellent property of this material. Such permeability enables frequent medical check-ups without having to dismantle the whole apparatus. Although these properties make carbon fiber-reinforced materials attractive, the manufacture and assembly of parts made of this material is more challenging than for metals because processes like casting and welding, which are widely applied in metals, are not applicable for carbon fiber material. Moreover, machining processes on carbon fiber pieces is not recommended if these processes break fibers in the direction of normal stresses. For the fabrication of elements with fibro-reinforced materials, specific processes exist such as resin transfer molding, the filament winding process, autoclave molding, and many others [2].

Some external fixation systems built with carbon fiber have been reported in the literature such as the unilateral fixator reported by Migliaresi et al., [1]. Rings made of carbon fiber for the Ilizarov external fixation have also been reported and studied [3,4]. In addition to external fixation systems, other orthopedic devices have been designed by using fiber-reinforced materials [5,6].

In Colombia, most of the external fixation systems are imported and too expensive for the majority of people. Therefore, it is necessary to develop this kind of orthopedic element with the advantages of the fibro-reinforced material, affordable for people in general, and with the required mechanical properties. This paper describes a manual manufacturing process for producing a 400 mm-long rail for an external fixation system. The simplicity of the process makes it a low-cost alternative for the production of these kinds of elements. The rail was evaluated with mechanical tests and compared with a commercial rail.

2. METHODOLOGY

The CF/EP rail was designed to substitute the metallic rail of a commercial system shown in Fig. 2. In this system, the clamps can slide over the rail and move the bone fragments. To use the same clamps, the cross section geometry of the new and the commercial rail must be the same. The new rail was designed to be formed by 2 segments joined at the ends by using 2 bolts. An individual element and the assembled rail are shown in Fig. 3. Each individual element was made by using a modified match molding process using a 4-part mould opened at the extremes to allow for the release of resin excess. Figure 4 shows the parts of the mould.

Plain type 3K-190 g/m^2 polyacrylonitrile (PAN) carbon fiber fabric was used as reinforcing material. Epoxy resin with shore D hardness 85-87 after curing was used as a matrix. This matrix was chosen because the curing process is produced by the chemical reaction of the resin with the hardener and no additional process is required; making the manufacturing process simpler. Initially the resin and the hardener were mixed in a 5:1 volume ratio. Then, the matrix was evenly spread on the fabric. The impregnated fabric was manually wound on a round 10 mm-diameter, 600 mm-long mandrel. After the winding, the mandrel was taken out and the impregnated fabric put on the empty section formed by the fixed parts of the mould (Fig. 4). Then, the bolts were tightened to compress the composite material with the mobile part of the mould. After the curing, the piece was removed by using extraction bolts.

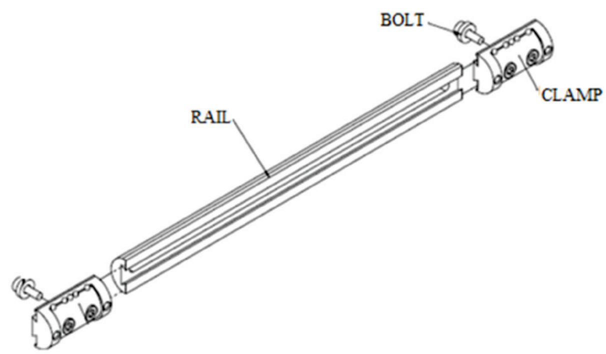


Figure 2. Rail design

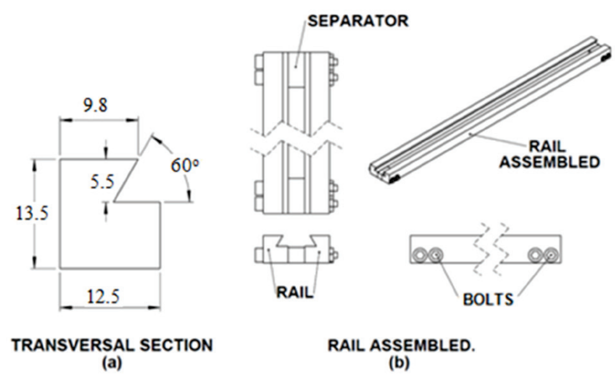
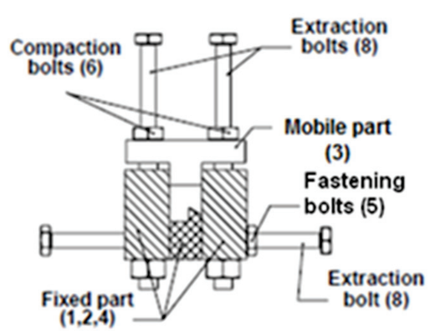


Figure 3. Scheme of the a) rail cross section, b) rail (dimensions in mm)



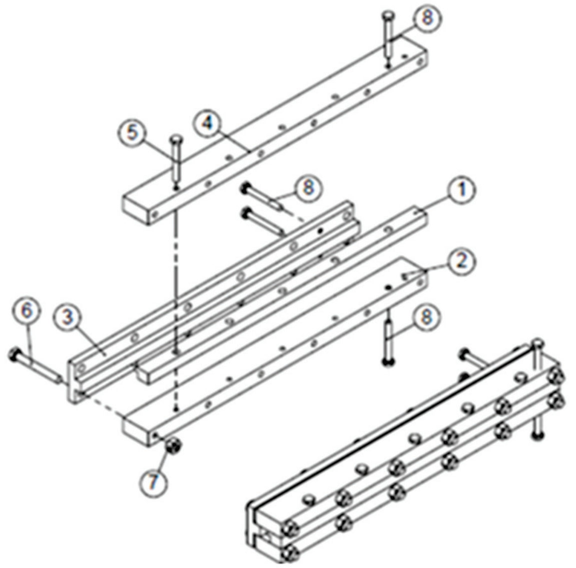
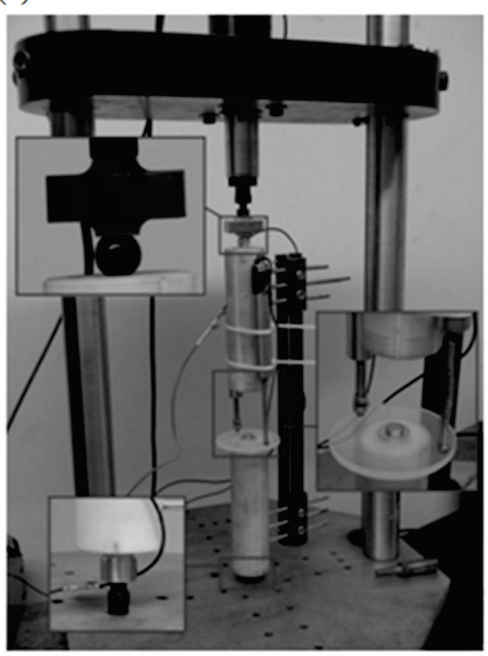


Figure 4. Parts of the mould

An adequate number of layers of fabric was calculated and implemented to reduce zones with an excess of resin or voids. The resultant fiber and resin distribution was analyzed with microscopic observations. Specimens cut from the cross section of the rail were polished using a standard metallographic procedure and then observed with an optical microscope.

(a)



(b)

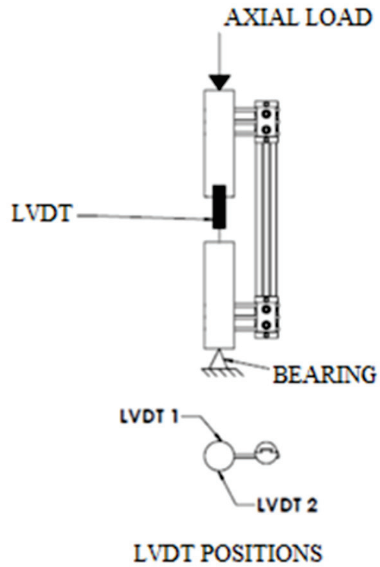


Figure 5. Arrangement for the compression axial load tests: a) actual system b) scheme, LVDT = linear variable differential transformer

Three rails were assembled and evaluated with mechanical tests. The commercial and the fiber carbon element were evaluated in tests: axial compression (AC), antero-posterior (AP) bending, medial-lateral (ML) bending, and torsion (T), under the ASTM F 1541-02 standard [5]. Figure 5 shows a scheme and the actual arrangement used for the axial compression tests. Figure 6 shows the bending and torsion tests schematically.

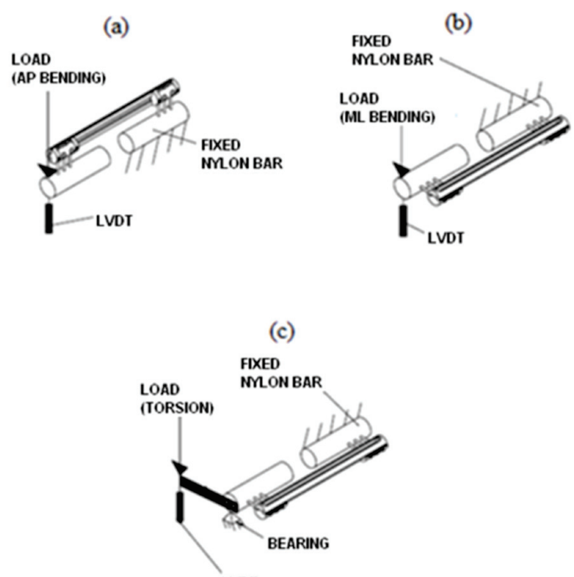
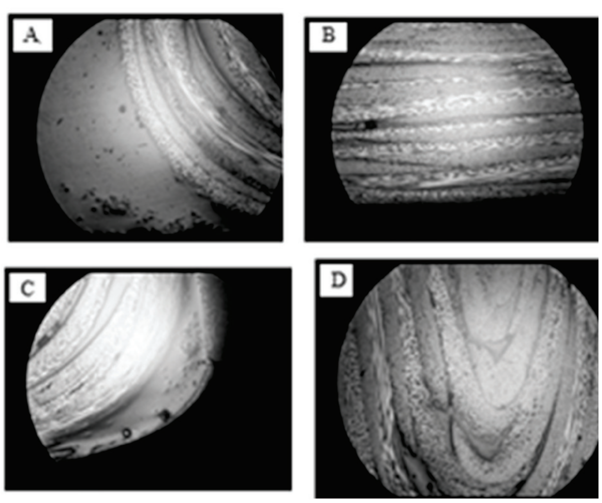


Figure 6. Arrangement for the bending and torsion tests

3. RESULTS AND ANALYSIS

3.1. Microscopic analysis

According to the literature [3,7], a fiber volume fraction between 0.4 and 0.6 is commonly used. With a fiber volume fraction of 0.6, and the thickness of the fabric at 0.1 mm, the longitude necessary to cover the whole cross section of the rail was calculated at 0.93 m. Several points on the cross section of the rail were observed microscopically. Different configurations of the fiber were observed depending on the point on the cross section. Figure 7 shows the internal structure found on the different points of the cross section. Point A is the only point with an angle lower than 90º; this caused a deficient filling of the fiber; however, the resin completely filled the section and completed the geometry. An acceptable presence of fiber was found on the 90º corners (point C). A good arrangement of the fiber was observed on the straight borders (point B) and in the middle of the section (points D, E, and F). An excellent distribution of the fiber was observed on the angle higher than 90º (point G). Some voids were also found, especially in the middle of the section (points B, E, and F). Fortunately, at the borders (like point B), which are the points with the highest tensile stresses, voids were not observed. Of course, small voids not observable under an optical microscope may be present, but if the voids are too small to be observed by microscope, then it is also expected that the influence of such small voids on the mechanical properties of the rail is not important. Figure 8 shows a fixation system assembled with one of the rails constructed.



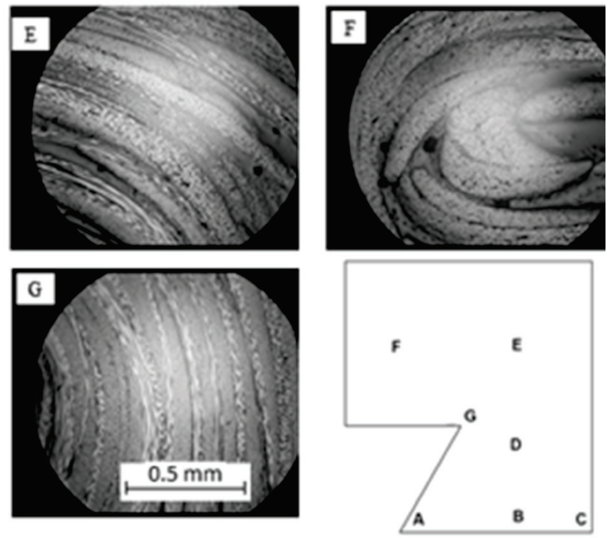


Figure 7. Structure inside the cross-section of the rail (all photographs are at the same scale)

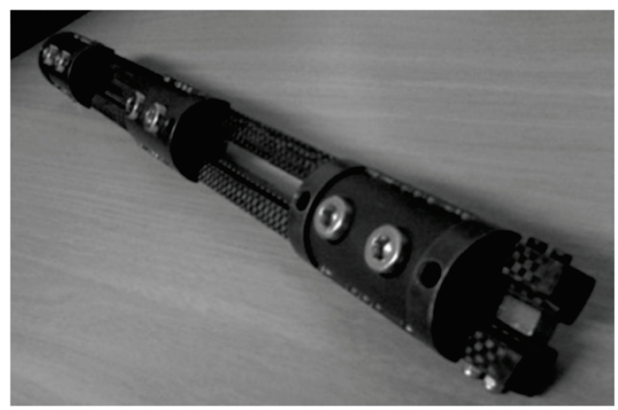


Figure 8. External fixation system assembled with the CF/EP rail

3.2. Mechanical tests

Each axial compression test was started by applying a preload followed by a controlled cyclic displacement test. After each compression, the displacement was held on for 1 min; then the load was released and the cycle started again after 1 min. Figure 9 shows a typical load vs. displacement curve. After each cycle, the fixator retains a residual displacement when the load was released. The cyclic tests continue until the difference between the last 2 stiffness values were less than 5% (usually at 5 cycles). The last stiffness value and residual displacement were taken as a result of the test.

Figure 10 shows a load vs. time curve. Relaxation behavior is observed after each load cycle. The last difference between the peak load and the load after a minute was taken and reported as the relaxation load. The relaxation percentage is calculated as:

$$R = \frac{Pp - Ps}{Pp} * 100$$

where R is the relaxation percentage, Pp is the peak load, and Ps is the load after relaxation for 1 min. Bending and torsion tests presented similar behaviors.

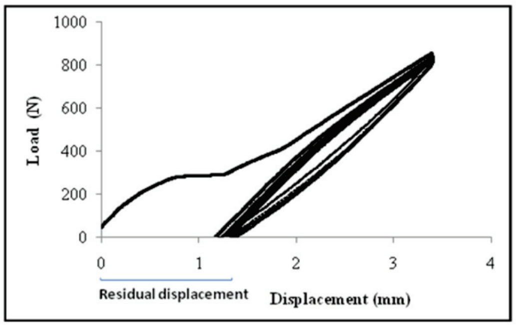


Figure 9. Load as a function of displacement for the axial compression test

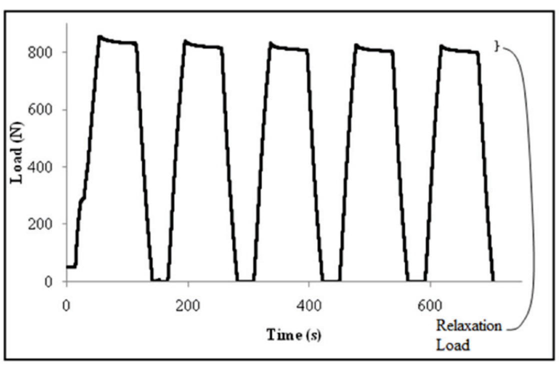


Figure 10. Load as a function of time for the axial compression test

The stiffness results for the 4 test conditions are shown in Fig. 11**,** which shows that under axial load and bending, the 2 fixers have similar stiffness; however, under torsion, the FC/EP fixator has lower stiffness. We think that this could be due to the arrangement of the carbon fiber layers of the composed rail which are all extended in an axial direction; therefore, between layers, the shear stresses generated by torsion load are transferred only through the resin that has less stiffness than the carbon fiber. Fibers are oriented mainly in the longitudinal direction; axial and bending tests mainly produce normal stresses in that direction; that is the reason for the good stiffness under axial load and bending load.

Although the torsion stiffness of the systems formed with the composite rail was lower than that of the commercial rail, it was comparable to or even higher than the stiffness reported in other studies [8–10]. Therefore, we consider that the composite rail can be successfully used in an external fixation system.

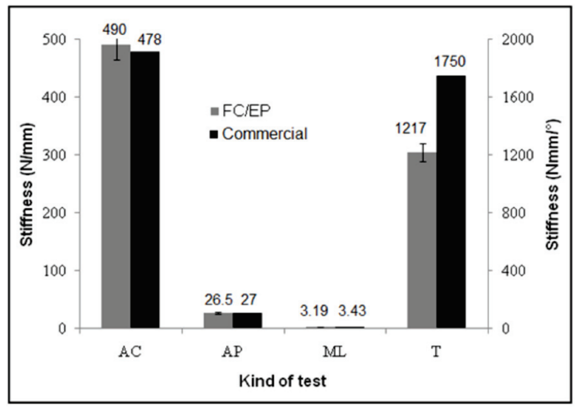


Figure 11. Stiffness values of the external fixation systems

While the commercial rail is formed from a single part, the CF/EP rail is assembled by 2 sections using bolts; maybe not enough contact area exists at the joint or not enough preload was applied on the bolts and relative movement could have occurred between the 2 parts of the composite rail. Also, permanent sliding could have happened among the assembled parts. This would explain the higher residual displacement found for the FC/EP system shown in Fig. 12.

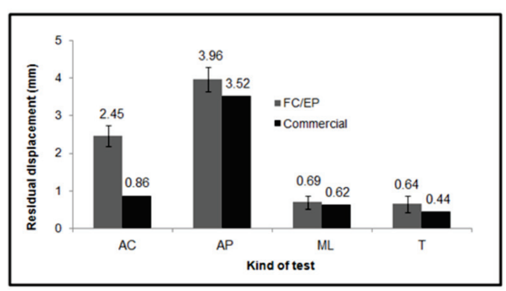


Figure 12. Residual displacement of the external fixation systems

Although a comparable relaxation percentage is observed under axial and load bending, this was higher for FC/EP under torsion load–as can be appreciated in

Fig. 13. Again, the geometric disposition of the carbon fiber layers that produce zones between layers where only resin takes shear stresses is the most probable reason for the high percentage of relaxation of the composite material with respect to the isotropic metallic material (commercial rail). Then, if the fraction of fiber is decreased, it is expected that the torsional stiffness and the relaxation percentage will increase; therefore, we think that our choice of 0.6 rather than 0.4 for fiber volume fraction was appropriate.

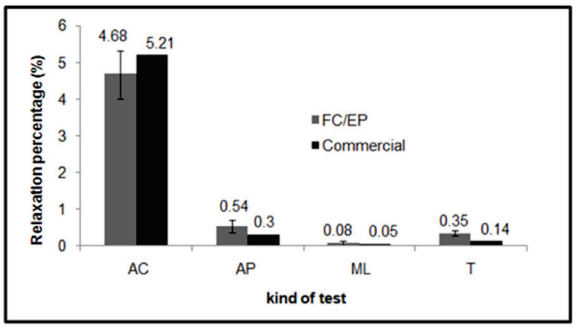


Figure 13. Relaxation percentage

Considering only the materials used, the cost of each fixator was not greater than US$150. Of course the global cost of the fixator reported in this study was much higher because is a prototype and all the design and evaluation considerably increase the costs. Moreover, the clinical evaluation is still pending which will increase the costs even more. However, the cost of the material and the simplicity of the manufacturing process suggest that when the fixator reaches the production stage, it will be economically competitive.

3. CONCLUSIONS

A manual technique was successfully applied to produce a rail using fiber-reinforced material with acceptable results and reproducibility among its properties. The simple manufacturing process can reasonably reduce the costs of external fixation systems.

The CF/EP rail revealed similar mechanical properties under axial and bending loads with the commercial rail. Although the rail made of composite material has lower torsion stiffness with respect to the reference fixator, these properties are still higher than those in many other fixators currently used; this makes the new rail suitable for being submitted to clinical tests.

ACKNOWLEGMENTS

Authors thank COLCIENCIAS and the Vice-rectory of research of the *Universidad del Valle* for the support given for the development of this paper.

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