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Structural polymer composite materials for muscle-skeletal diagnostic systems

M.F. Pernice[1], D. Annicchiarico[2], A. Petriccione[2], G. De Tommaso[1], M. Meo[1,3], V. Antonucci[2] and M. Zarrelli[2]

Abstract

The aim of the study presented herein was to investigate the possibility of employing composites in the production of medical diagnostic equipments, and their advantages in terms of costs and performances. In particular, the patient-positioning system of a magnetic resonance apparatus, comprising two elements, the bed tables, and the footrest, was examined with the main goal of enabling a wider range of population to be tested, thanks to a full re-designing of their item. An extensive variety of composites were investigated, in order to select a combination of matrix and reinforcement able to satisfy the specific requirements in terms of magnetic transparency, structural behavior, manufacturing features, and costs. Glass fiber composites were selected and characterized by experimental tests. The patient-positioning system was completely re-designed and analyzed by finite elements method; design optimization led to a simplified structure, offering a series of advantages such as light weight, manoeuvrability, thickness reduction, and cost-saving processes. Final full-scale prototypes were realized and tested according to the Medical Security procedures, achieving as main results not only a reduction of the total production cost, but also an increase in the percentage of people that can be scanned by this magnetic resonance apparatus.

Keywords

composites, finite element, magnetic resonance apparatus

Introduction

This article summarizes the activities carried out within the frame of a national research project, titled MRI (Magnetic Resonance Imaging), targeting the feasibility and the applicability of composite materials to manufacture diagnostic element parts. The project concerned the re-designing of the patient-positioning items (the bed tables and the footrest component) taking advantages of the peculiar properties of advanced composites. In particular, by employing reinforced polymer materials, the project aimed to modify a patient-positioning system of a magnets resonance apparatus widely used in medical diagnostic to perform full body and localized scan check, thanks to *ad hoc* plug-in magnets and the possibility to position the patient under its own weight, resembling the real natural life condition. The main goals of the project were a reduction of the equipment cost and an increase of the population percentage accessing the diagnostic test. Both results were achieved by reducing the thickness of the positioning bed, which necessarily leads to a decrease of the magnet dimensions considered the main costly item of the apparatus. On the other hand, a thickness reduction enables to increase the opening distance between the patient bed and the magnet, hence permitting the laying of a higher percentage of population. The right choice of composite system, compatible with the general requirements of medical equipment standards (Medical Security Rule IEC 601.1[1]) in terms of magnetic transparency performance, biocompatibility and mechanical properties, and a completely new designed geometry, led to the final accomplishment of the mentioned goals.

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A large variety of composite materials was considered for the potential application. The materials for the final prototypes were selected, firstly, according to magnetic transparency requirements, to guarantee that they do not interfere with the medical images. For this reason, long fiber glass-reinforcement systems were selected, with either thermoset or thermoplastic matrices. Mechanical tests were performed in order to determine mechanical properties of the composites for the later design and stress analysis.

Thermosetting matrix composites were employed to prototype the patient-positioning bed, while thermoplastic-based systems were considered to design the footrest. In both cases, a one-piece light weight structure was manufactured achieving a high level of part integration, fundamental for the manoeuvrability during medical exams and the safety of medical operators.

Using the experimental material properties, a structural numerical analysis was performed on the patient-positioning system, in order to evaluate the maximum deformation of the structure under the maximum load conditions scheduled by applied medical standard. Prototypes of all parts were realized by means of typical composite manufacturing techniques such as 'liquid resin infusion' and 'thermoplastic vacuum bag hot forming.' Finally, full-scale prototypes, respectively of the positioning bed and the footrest, were realized and assembled on real MRI medical machine.

In order to verify the interference level of the new items, compared with old elements, diagnostic exams were performed on the same volunteer using both a traditional system and the modified machine. Final comparison highlights negligible variation of the MRI image results according to the standards. Table 1 gives the main accomplished goals achieved by the new modified apparatus.

Material characterization

A wide range of composite materials was initially considered for the patient-positioning system and a preliminary choice was operated, based on supplier data sheets. First, materials were selected according to their cost, manufacturing process, mechanical properties, and magnetic compatibility; then, they were mechanically characterized, in order to find the best composite material solutions, according to the functional and cost requirements. At the end of this preliminary stage, two different composite systems were selected for the corresponding prototypes: the patient-positioning bed was realized by a thermosetting-based composite, while a thermoplastic matrix system was employed for the footrest element.

The thermoset composite used for the patient bed had a biaxial (0°/90°) non-crimp fabric reinforcement (SELCOM/PPG EBXS800 0°/90° Biaxial E-Glass tricot stitched), with the same amount of E-glass reinforcement in the principal directions (0° and 90°).[2] The matrix used was ENYDYNE D 20-526 TA system commercialized by Cray Valley (France), a polyester-based system specifically designed for liquid molding processes, commonly catalyzed by adding 0.5% (w/w) of methyl-ethyl-ketone peroxide (MEKP). Composite plates were manufactured by vacuum infusion process (VIP) and later trimmed to obtain suitable coupons for mechanical tests. Nominal dimensions of the manufactured composite plates were $300 \times 300\,mm^2$. The configuration adopted was a symmetric and balanced cross-ply lay-up, $[0°/90°]_S$, made by two distinct layers with a total of four unidirectional plies.

The thermoplastic composite employed for the footrest was TWINTEX® T PP, a fabric made of TWINTEX® roving, formed by commingled E-glass and polypropylene fibers.

Mechanical tests were performed on both the selected materials. Tensile, compression, and bending tests were performed using a universal testing machine INSTRON 4202 equipped with the appropriate load cell. Composite samples were also instrumented by strain gage rosettes for biaxial strain acquisition using a Vishay D5000 rack system. For statistical purpose, five different samples (or more) were tested for each set of mechanical experiments.

Tensile tests

Tensile tests were performed by using a machine INSTRON 4202 with a 2 mm/min strain rate.

Table 1. Main project aims and expected improvements compared to the current structure

Feature/performance	Current solution	Expected improvement
Patient moving system cost	–	−30%/−50%
Patient bed thickness	45 mm	−20%
Percentage of population accessible	85%	+10%
RF transparency, biocompatibility and mechanical resistance		At least the same properties of the current materials
Compatibility with the existing standards of medical equipment	Yes	Yes

The nominal dimensions of samples for the tensile characterization were chosen according to ASTM D3039 standard. As the reinforcement for the thermosetting composite used for the positioning bed was a non-crimp fabric and the unidirectional reinforcement was not available, tests were executed in 0° direction and in 90° direction, in order to evaluate possible differences. Tests in +45° and −45° directions were also performed. Figure 1 shows stress–strain graphs at 0°/90°, 90°/0°, and +45°/−45° for ENYDYNE matrix reinforced with glass fibers non-crimp fabric.

Table 2 gives the average values and the standard deviation of Young's modulus and tensile strength measured values. The measured Young's modulus for 0°/90° reinforcement was 29.4 GPa, and the tensile stress was 315.2 MPa.

According to ASTM D 3039 standard, the Poisson ratio was also measured. Strain gage rosettes were applied at 0° and 90° directions on both sides of the samples, to assure that only an in-plane load was applied during the test avoiding bending. An average value of the Poisson ratio of 0.173 was measured, with a standard deviation of 0.02.

Tensile tests were also performed on the thermoplastic composite (TWINTEX® T PP 60 745) used for the footrest. The dimensions of sample were chosen according to ASTM D 3039 standard. The same coupons were employed to determine the Poisson ratio. Figure 2 shows the stress–strain curves.

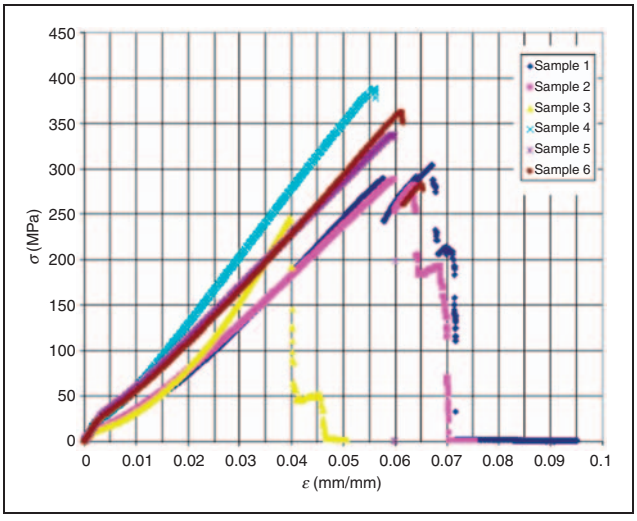

Figure 1. Stress–strain curves for ENYDYNE matrix composite samples.

Table 3 gives the Young's modulus measured for the five samples tested, the average value and the standard deviation. The measured Young's modulus was 8.33 GPa, and the tensile strength was 242.4 MPa. Finally, a Poisson ratio of 0.13 was determined for the TWINTEX® samples, with a standard deviation of 0.04.

Compression tests

Compression tests were executed on TWINTEX® samples, according to ASTM D 3410 standard, at a strain rate of 1.5 mm/min. Stress–strain curves obtained from compression tests on TWINTEX® samples are shown in Figure 3.

Table 4 gives the measured modulus for the five samples obtained by compression tests along with average value and standard deviation.

Bending tests

Bending tests were performed on ENYDYNE and TWINTEX® composite samples according to the ASTM D 790 standard. In the case of thermosetting matrix system, the span/thickness ratio was 32:1, with a distance between supports equal to 160 mm and a strain rate of 8 mm/min. Figure 4 shows the stress–strain curve obtained from the bending test on the ENYDYNE coupons.

Table 5 gives the modulus measured by the bending tests with their corresponding average value and standard deviation.

A strain rate of 5.80 mm/min was set for the TWINTEX® composite samples. Stress–strain curves obtained by bending tests for TWINTEX® are shown in Figure 5.

Table 6 gives the bending test results for TWINTEX® samples. Two of the tested samples showed critical imperfection associated to the presence of voids onto the surface; thus, the measured values for the modulus and the bending strength were taken out from the average values.

Table 2. Young's modulus and tensile strength for ENYDYNE-based composite

							Average value	Standard deviation
E (GPa)	27.36	31.70	30.56	26.92	29.84	30.00	29.4	2.0
σ_r (MPa)	245.6	272.5	290.1	387.9	361.1	336.3	315.2	30.41

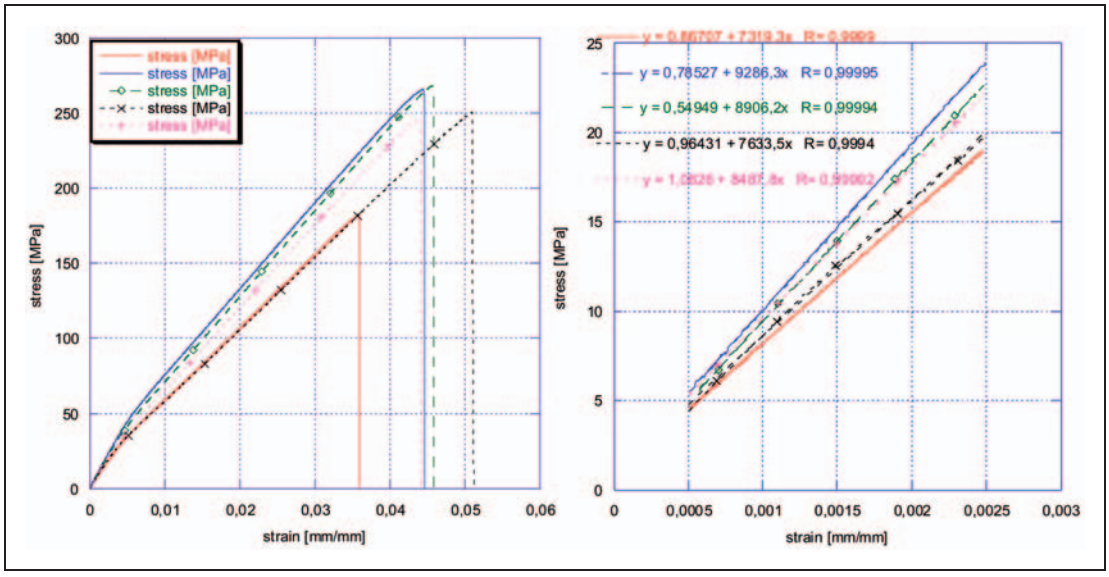

Figure 2. Stress–strain curves and Young's modulus evaluation for TWINTEX samples.

Table 3. Young's modulus and tensile strength for the TWINTEX samples

						Average value	Standard deviation
E (MPa)	7319.3	9286.3	8906.2	7633.5	8487.8	8326.6	833.36
σ_r (MPa)	180.2	265.0	270.3	245.8	250.8	242.42	36.190

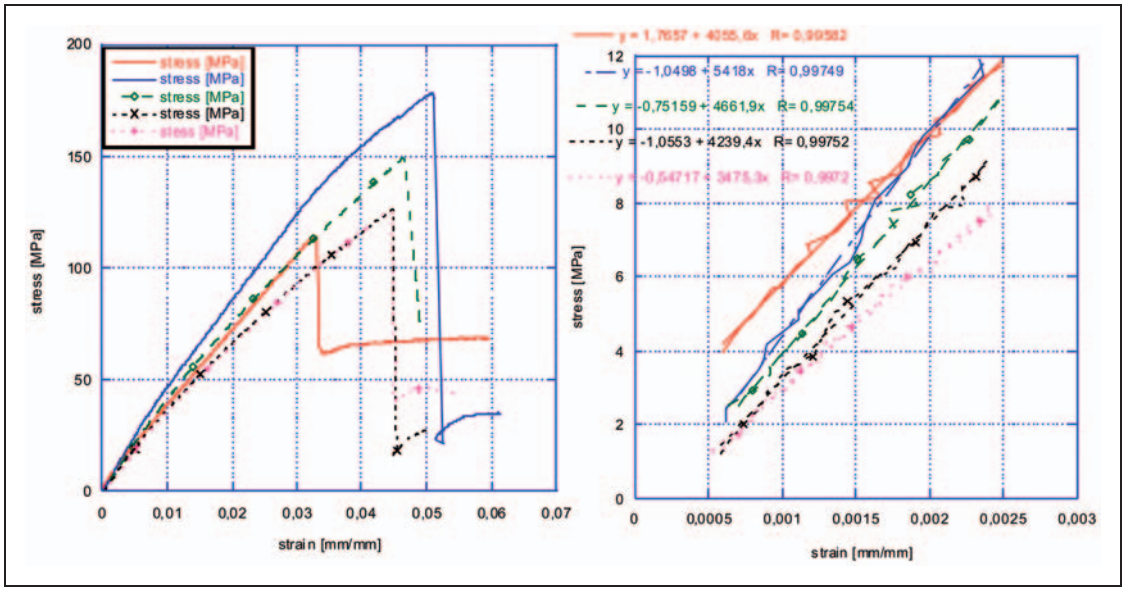

Figure 3. Stress–strain curves and modulus evaluation for TWINTEX samples by compression tests.

Geometrical design and structural analysis

Geometrical design

The patient-positioning system of the MRI machine, originally made of hybrid polymer laminate (HPL) system, was completely re-designed. Geometric shapes and dimensions of the parts were stated according to MRI machines manufacturer requirements in terms of magnetic and structural behaviors. The geometry of the patient-positioning system was changed and structural numerical

Table 4. Modulus and ultimate strength obtained by compression tests on TWINTEX samples

						Average value	Standard deviation
E_c (MPa)	4055.6	5418	4661.9	4239.4	3475.3	4370	724.5
σ_r (MPa)	113.88	177.77	149.44	125.0	125.1	138.24	25.639

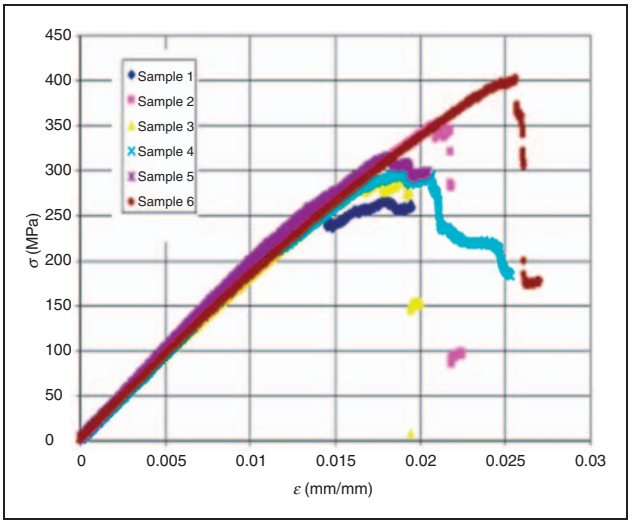

Figure 4. Stress–strain curves for ENYDYNE matrix composite samples by bending test.

analyses performed on the new geometry. Magnetic and structural performances were optimized accounting for the overall weight and cost of the structure.

The original geometry of the patient-positioning system is shown in Figure 6. It comprises two main items: the patient-positioning bed and the footrest assembly. Normally, the patient lies on the bed during medical exams and the positioning bed can either shift to center the scanned body under the magnet, or rotate to allow the diagnostic scan to be performed in vertical position. In this later configuration, the footrest assembly is required to hold the patient loaded with its own weight. The complexity and the number of the parts constituting the old version of the element are clearly highlighted in Figure 6. In the case of the patient-positioning bed, two main assemblies can be identified, namely the lower bed and the in-plane movable table.

The lower bed is connected to the main frame of the machine by means of two longitudinal struts, while the upper table is supported on the lower element simply by four rail-slides. The whole positioning bed assembly was characterized by a great number of parts and small elements.

Also, the footrest comprises different parts such as two shelves to hold the patient in sitting or standing position and a complex apparatus to connect the patient bed and to regulate the length opening according to the patient size. The existing version of the footrest element needs two different operators to perform length adjustments mainly due to the heavy weight of the component. Such difficulties were not only time consuming during normal diagnostic exam, but also unsafe for medical personnel.

Based on this starting geometry, the patient-positioning system was completely re-designed accounting for not only the structural requirements of the element, but also the processing features of composite materials. The final geometry achieved was greatly simplified for both elements accomplishing a high level of part integration (Figure 7). In the case of the positioning bed, the central slide was incorporated in the lower table, moreover, all parts of the upper table, such as handles and borders, were integrated in a single structure. The main integration was achieved in the footrest, which was reduced to a one-piece light weight component. The new footrest presented only one shelf where the patient can stay either stood or sat. The single footrest element results quite light and it can be moved easily and safely by only one medical operator without any danger. The final footrest element and the two-component positioning bed are shown in Figure 7.

Structural analysis

Structural finite element (FE) analyses were performed on the new geometry of both the positioning bed and the footrest using the commercial FE code ANSYS.[3] For both components, four-node layered SHELL elements, characterized by two different material types modeling, respectively, the ENYDYNE- and TWINTEX®-based composite systems, were used.[3]

The mechanical properties determined by experimental tests were input for the numerical analyses. Optimal composite lay-ups were determined according to the boundary conditions and the structural requirements of the analyzed structures.

The applied loading condition was determined according to the Medical Security Rule IEC 601.1[1] which prescribes a standard patient weight of about 200 kg for this kind of component and a maximum inflection value under different distributed loads.

Patient-positioning bed

The patient-positioning bed was realized by using a polyester resin matrix (ENYDYNE), reinforced by

Table 5. Bending tests results for ENYDYNE-based composite

							Average value	Standard deviation
E_f (GPa)	19.09	19.09	18.62	18.92	20.19	18.34	19.9	0.63
σ_r (MPa)	267.3	288.4	351.1	402.3	320.4	292.3	320.3	49.64

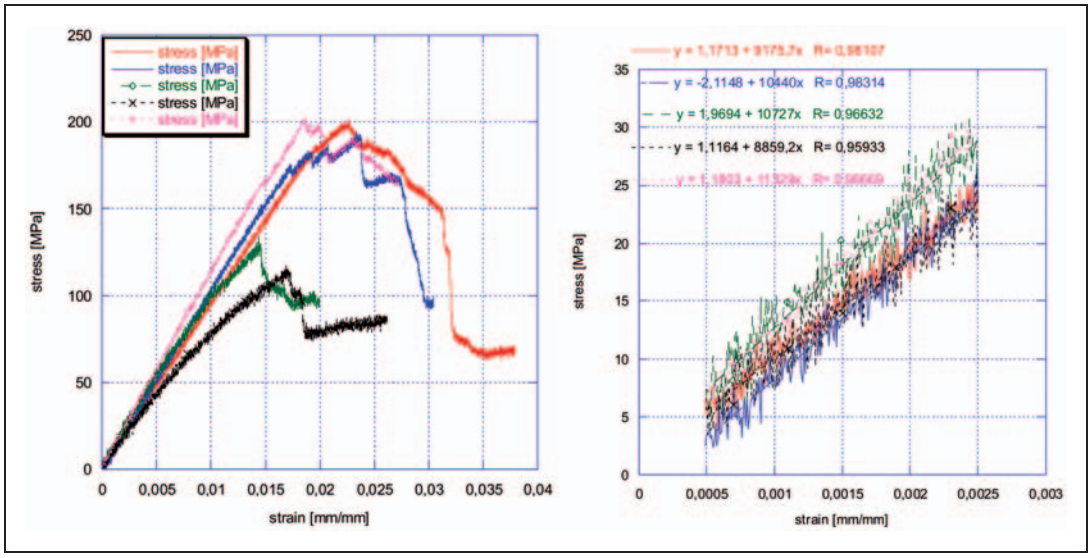

Figure 5. Stress–strain curves and bending modulus evaluation for TWINTEX samples.

Table 6. Bending test results for TWINTEX samples

						Average value	Standard deviation
E_f (MPa)	9175.7	10,440	10,727	8859.2	11,329	10,106	1050.6
σ_r (MPa)	197.91	190.97	127.77	113.19	200.02	196.3	4.739

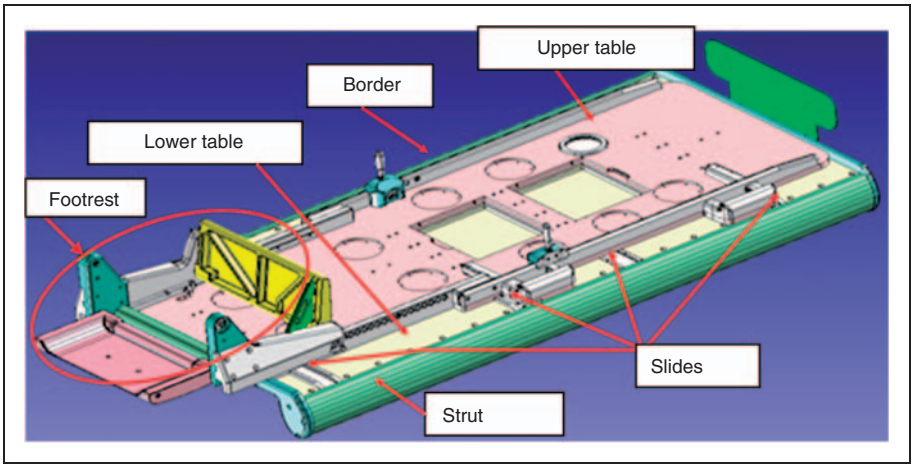

Figure 6. Old geometry of the patient-positioning system of the MRI machine.

E-glass fibers. The main target in the re-designing of the patient bed was to reduce the total thickness of the bed: starting from the old value of 45 mm, a 20% reduction was expected, so the maximum thickness allowed for each table of the positioning bed was 6.5 mm. This condition led to the selection of a 0°/90° non-crimp-fabric reinforcement with ply thickness of 0.66 mm. An eight-ply symmetric lay-up, $[(90/0)_4]_S$, was employed. For the

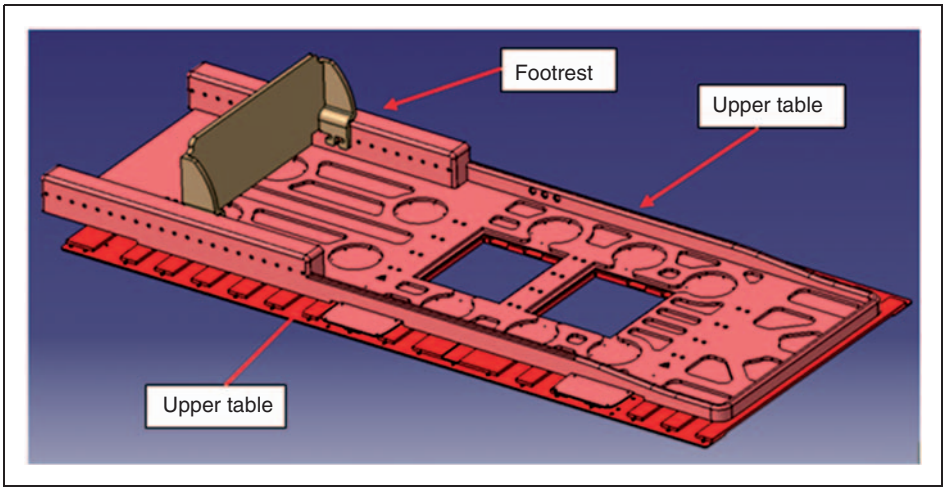

Figure 7. New geometry of the patient-positioning system.

Table 7. Mechanical properties of the ENYDYNE-based composite for the positioning bed

E_1 (GPa)	E_2 (GPa)	E_3 (GPa)	G_{12} (GPa)	G_{13} (GPa)	G_{23} (GPa)	ν_{12}	ν_{13}	ν_{23}
29.40	29.40	6.31	4.80	5.66	5.66	0.173	0.26	0.26

FE analysis, the mechanical results obtained by the experimental test campaign (Table 7) were the input.

The FE numerical model contained the lower and the upper tables of the positioning bed with different connection elements between the two table elements and the whole MRI apparatus. The lower table was fully constrained to the machine frame, whereas the upper table was joined to the lower one by means of beam elements simulating the four rail-slides.

The patient weight was simulated by means of a load on the upper table of the bed (Figure 8), distributed according to weight percentage of a laid human body.[1]

A good functioning of the patient-positioning bed is assumed when the upper table can be easily translated on the lower one by means of a limited effort by the operator on the four rail-slides. To enable this movement, even under the maximum load conditions, it is important to limit the maximum inflection of the patient bed at a value smaller than 2 mm. Figure 9 shows the displacement contour plot of the positioning bed under mentioned loads. The maximum displacement was found between the second and the third rail-slides and it was 1.8 mm, with a nominal thickness of 6.3 mm for both tables. The maximum deflection is lower than the critical value of about 20%, confirming the possibility to move the lower table also under operating loads and proofing the buoyancy of the re-designed geometry and composite dimensioning.

The nominal thickness (6.3 mm) of the lower and the upper tables of the positioning bed results to be reduced of 20%, thanks to the excellent mechanical behavior of the thermosetting matrix composite, and it confirms the possibility to increase the opening space between the magnet and the positioning bed.

Footrest

The footrest component was realized by a thermoplastic-based composite system based on TWINTEX®, a commingled yarn fabric, with polypropylene matrix and glass fibers. From an operating point of view, also for this element, it was mandatory to limit the maximum inflection at central line in its most conservative condition, i.e., with a maximum patient weight of 200 kg.

During preliminary structural analysis, it was found that the vertical displacement at footrest center line was mainly due to the rigid body movement associated with the geometry and the imposed boundary conditions. In fact, torsion was developed in the platform by the combined actions of the connection elements between footrest and patient bed and the applied loads; therefore, as a result, the vertical displacements at the front and at the rear side of the platform were different. In order to overcome this inconvenience, a non-balanced lay-up was considered for the footrest platform and the FE analysis re-computed to verify the new vertical displacements at the same center line locations.

The experimental material properties given in Table 8 for the TWINTEX® composite were the input for the numerical analysis.

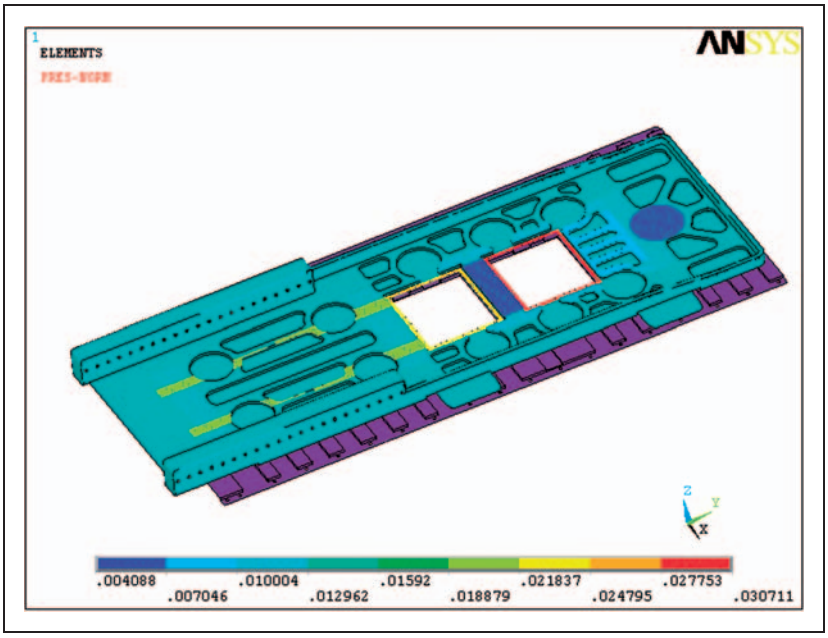

Figure 8. Load distribution on the patient-positioning bed.

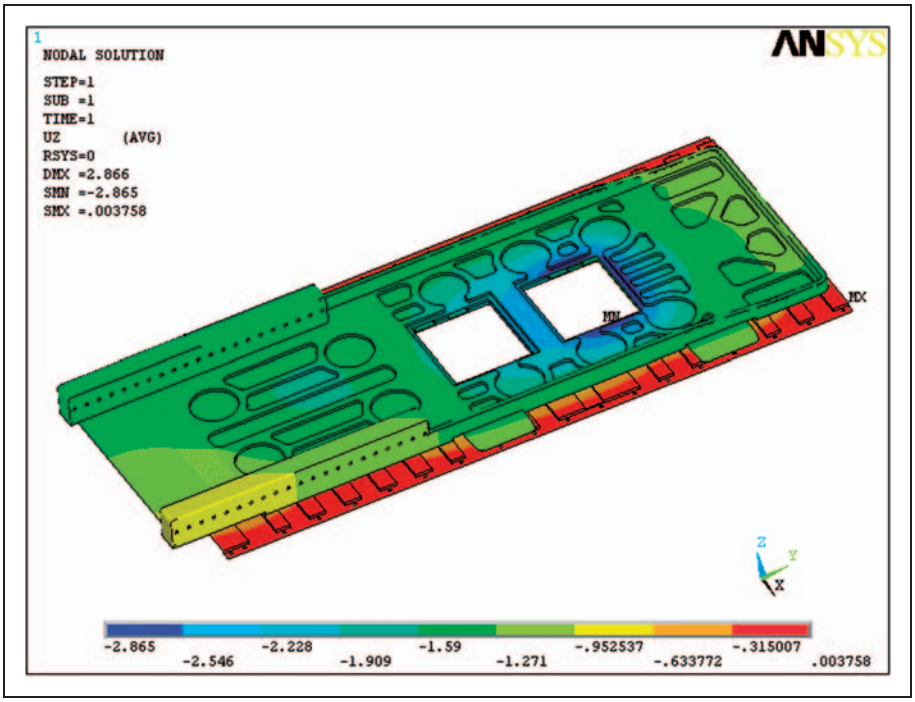

Figure 9. Plot of displacement in vertical direction on the positioning bed.

The connection between the footrest and the positioning bed, in its vertical configuration, was modeled using four later pins while a surface-to-surface contact algorithm was employed to simulate their distributed contact area, located on the sides. The load condition was determined according to the Medical Security Rule IEC 601.1 assuming a maximum patient weight of 200 kg distributed over centered and symmetrical area of 0.1 m^2. The applied loads and the imposed boundary conditions for the footrest structural analysis are shown in Figure 10.

The deflection results were evaluated, as they affect the functionality of the structure during normal operation; Figure 11 shows a contour plot of the vertical displacement as obtained by FE simulation.

Table 8. Mechanical properties of the TWINTEX composite for the footrest

E_1 (MPa)	E_2 (MPa)	E_3 (MPa)	G_{12} (MPa)	G_{13} (MPa)	G_{23} (MPa)	ν_{12}	ν_{13}	ν_{23}
8326.6	8326.6	1375.5	918.12	1661.4	1661.4	0.13	0.34	0.34

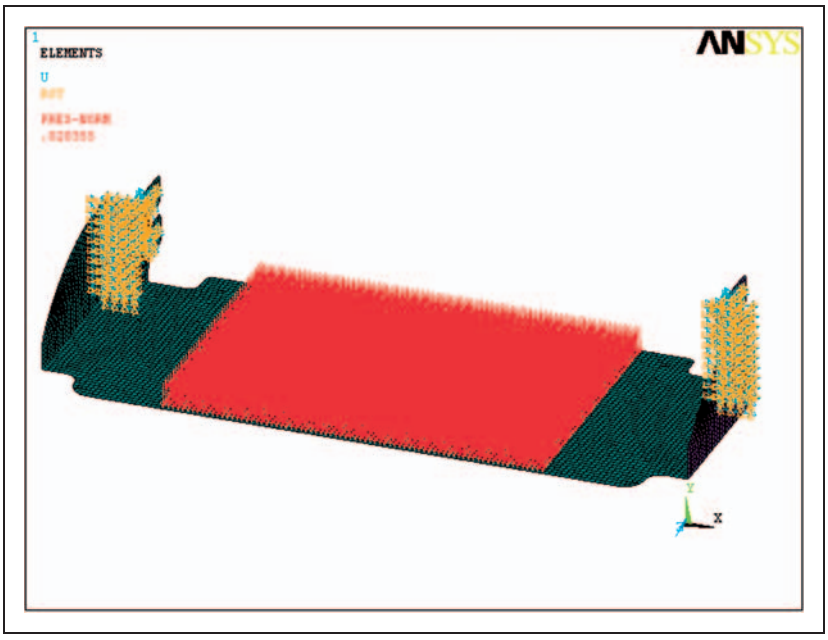

Figure 10. Boundary conditions and load distribution applied to the footrest in the FE simulation.

The maximum inflection between the central and the lateral parts of the platform was calculated as 26 mm; the found deflection allows a safe employment of this component in the MRI machine.

Prototypes manufacturing

Two different technologies were selected for prototypes manufacturing: the thermoplastic vacuum bag hot forming, to realize the thermoplastic-based footrest, and VIP, to manufacture the patient bed component by a thermosetting matrix composite.

The main difference between 'resin infusion' and 'thermoforming' is related to the matrix properties. The VIP employs dry reinforcement preforms and liquid matrix which is vacuum infused and then polymerized under a given temperature profile. In the case of thermoforming, fiber prepreg and thermoplastic matrix are used as raw materials; the final shape of the composite-thermoformed element is achieved by softening and profiling the layered system according to the design recommendations. In this latter case, no chemical reaction takes place during consolidation, and the thermoplastic prepregs can be repeatedly heated and reshaped above softening temperature without appreciable changes of its original properties.

Positioning bed prototype realization

The patient-positioning bed prototype was manufactured by vacuum infusion under flexible tool, as the size of the final item, the surface finishing, dimension interferences, and related costs of production would not justify a different manufacturing process such as resin transfer molding (RTM) or LightRTM.

The geometry of the positioning bed had been optimized by considering the following critical features:

- The laminate thickness was kept constant, in order to avoid speed variation in the resin flow, due to geometry.
- Smooth surfaces were adopted in order to avoid fabric deformation during the hand lay-up and, as a consequence, to have a uniform permeability in the whole reinforcement, and to avoid dry spots formation.
- The total geometry of the prototype was designed so that an easy and effective de-molding was guaranteed.

Process parameters were also optimized, considering both the chemical and rheological properties of the used resin; this system was injected under vacuum pressure (less than 0.1 MPa) and then cured at ambient temperature (25°C).

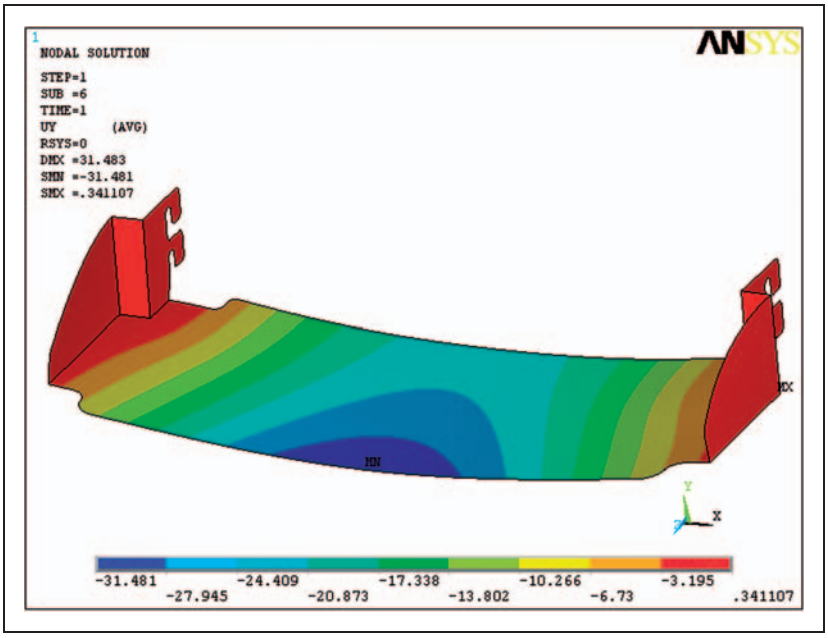

Figure 11. Vertical displacement contour plot on the footrest.

At room temperature, rheological measurements have indicated that the resin gels after 20 min, therefore, the infusion vent distribution was designed to assure a complete impregnation of the layered reinforcement system before matrix gelation occurs. A further consideration to prevent the formation of dry spots is related to the shape of the resin flows. Rightly designed gate–vent distribution will induce divergent-shaped flow, while convergent pattern would lead in some locations to poor resin area affecting the integrity of the final composite component. For these reasons, only one injection rail, passing transversally through the whole component, was employed while two vents were located on the lateral sides, as shown in Figure 12.

This injection system was applied directly on the dry reinforcement and it was not embedded in the mold. Thanks to this solution, a cost-save mold can be used, and the injection system can be easily removed from the final component.

The above process configuration was modeled numerically by employing a commercial finite volume code (PAM-RTM[4]) and also experimentally tested in order to compare results. Figure 13 shows a critical portion of the positioning bed which was realized in our lab by vacuum infusion under flexible tools. This part was selected because it contains all the main geometric features, such as in-plane curvature, maximum width, and lateral border, considered critical for the resin flow during the full-scale item injection process.

The manufacturing of the critical portion gave the possibility to develop and implement technological solution in terms of mold geometry, fillet radius, and ancillaries' material which were later transposed to the full-scale process.

Full-scale prototype molds were realized machining a polymeric material block by a four-axes computer numerical control (CNC) milling unit (Figure 14), and then their surface roughness reduced by a polishing treatment.

The positioning table prototypes were realized and assembled, as shown in Figure 15. Finally, a quality control was performed to evaluate the surface finishing, the presence of superficial dry spots, and dimensional tolerances.

Footrest prototype realization

The footrest prototype was made of a thermoplastic composite material, the TWINTEX®, by employing a thermoforming process. In order to obtain a good surface quality on the upper surface of the footrest, a male mold was used. The mold (Figure 16(a)) was realized by machining an aluminum block, ensuring good surface quality in terms of roughness, good thermal stability at process temperatures as well as durability. The inner part of the mold was hollowed with the aim to obtain a uniform thickness of the mold and, consequently, a better heat exchange between the mold and the laminate during the curing process. The laminate dimensions were higher than required, and the footrest was then cut into shape (Figure 16(b)).

Figure 17 shows a real image of the footrest prototype without gel coating on the platform surface. During the 'thermoplastic vacuum bag hot forming' process pressure is applied on layered prepregs using a flexible diaphragm (bag) and vacuum force avoiding, in this way, the involvement of a more expensive match-die system. The application of vacuum shapes the material on the die,

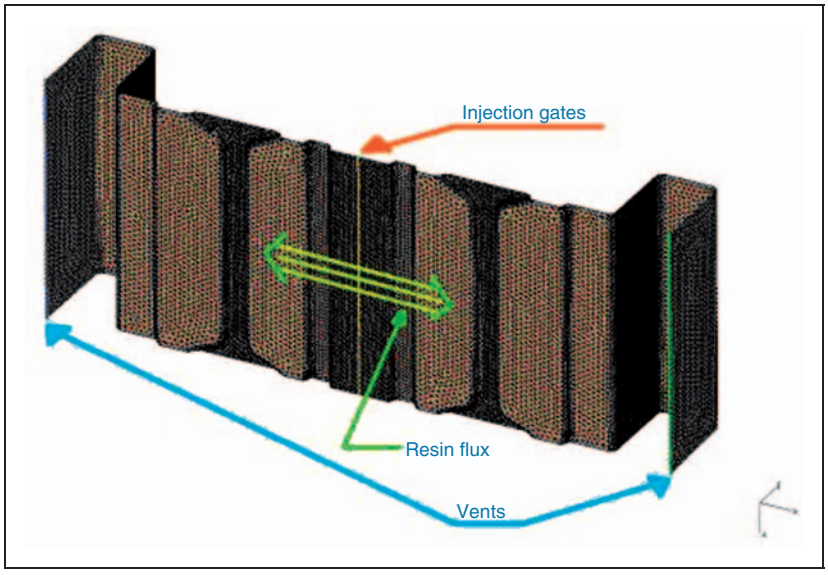

Figure 12. Resin injection points location and air exits.

compacting the plies, and promoting the evacuation of trapped air, in order to reduce any potential defects due to voids and porosity in the final component.

The stacking sequence is prepared by hand lay-up orienting the plies opportunely and then sealing the vacuum bag. After the curing cycle, the prototype is extracted from the mold and cut to its final shape.

Processing temperature and matrix consolidation time, which represents the dwell period at a temperature within the melting region, could be considered the most crucial parameters taken into account not only for optimization purpose of the manufacturing process, but also for assuring the maximum final quality of the composite materials. If the matrix is processed at higher temperature or the consolidation period is too long then degradation phenomenon can be triggered, decomposing the polymer matrix and so altering the final structural behavior of the composite system. On the other hand, if lower temperatures are set or consolidation dwell is kept short, heterogeneity are induced into the final laminate. The cooling process is generally performed at a considerably low rate to avoid 'freezing in' of residual deformations induced by the non-uniform temperature changes. Pressure should be applied throughout the forming time until solidification is reached to ensure the absence of porosity in the final composite materials.

The manufacturing process of the footrest prototype was carried out in a forced convection oven and the footrest mold was sensorized with thermocouples located in different positions in order to appreciate possible heating gradient. Figure 18 shows the position of the temperature sensors on the mold, whose signals highlight a substantial uniformity of the temperatures with a maximum variation of 1.2°C between locations TC3 and TC4.

Prototypes' performance evaluation

The performance evaluations of the manufactured prototypes were carried out, with the aim to verify their compatibility with the diagnostic system in terms of both magnetic and structural behaviors, as required by the Medical Standards.

Magnetic performances

Magnetic transparency tests were carried out in order to verify that the new positioning system does not harm the medical imaging results. For this reason, the component materials should exhibit a certain grade of magnetic transparency.[5,6] Tests, under both static and electromagnetic fields, were performed on both patient-positioning bed and footrest, and then image results were compared with data acquired by installing traditional material made components on the same MRI machine.

In the case of the static magnetic field, the following conditions were considered for comparison purpose:

- The difference between the measures, with and without the prototype, at the resonance central frequency of the magnet was required to be less than 100 Hz.
- The uniformity peak-to-peak of the static magnetic field, with and without the prototype, was required to vary less than 30 ppm.
- The expansion coefficient, with and without the prototype, was required to vary less than 10 ppm.

The result data given in Table 9 were acquired during test with static magnetic field. In the case of

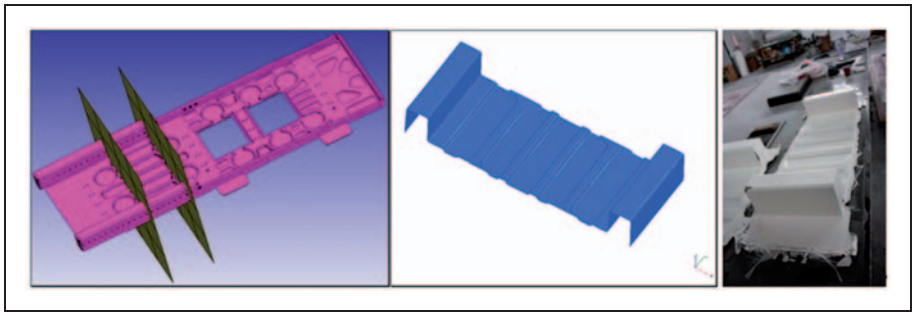

Figure 13. Critical element selected in the positioning bed prototype.

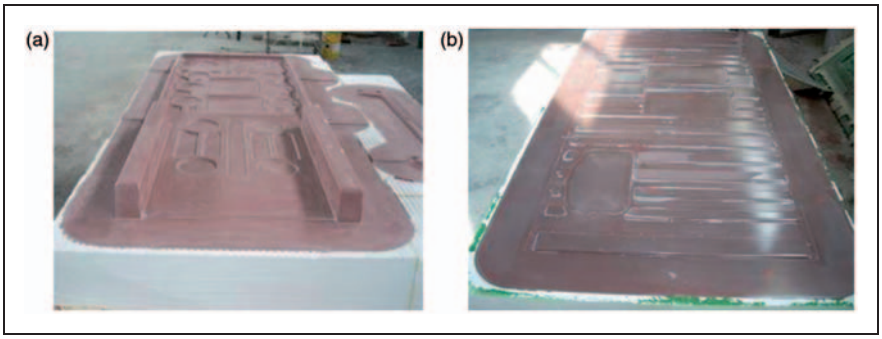

Figure 14. Patient-positioning bed molds: (a) upper table and (b) lower table.

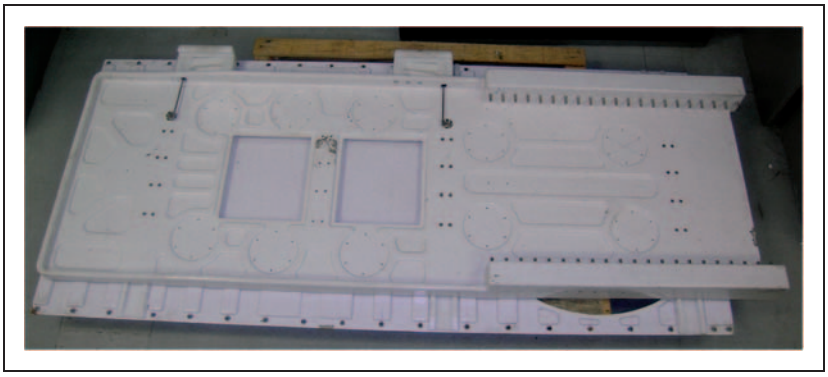

Figure 15. Patient-positioning bed prototype.

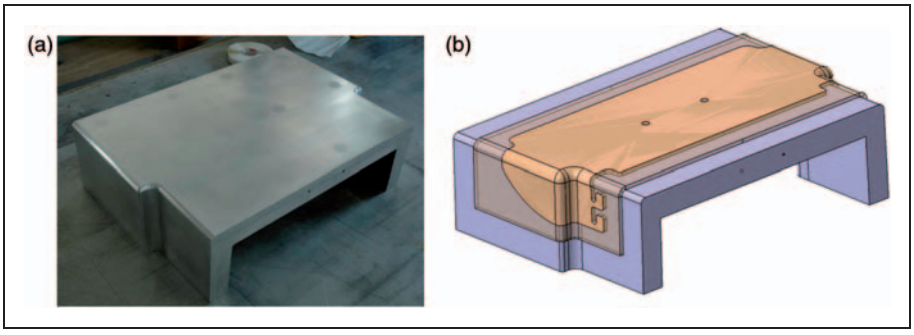

Figure 16. (a) Aluminum mold for the footrest prototype and (b) 3D model of the laminate on the mold.

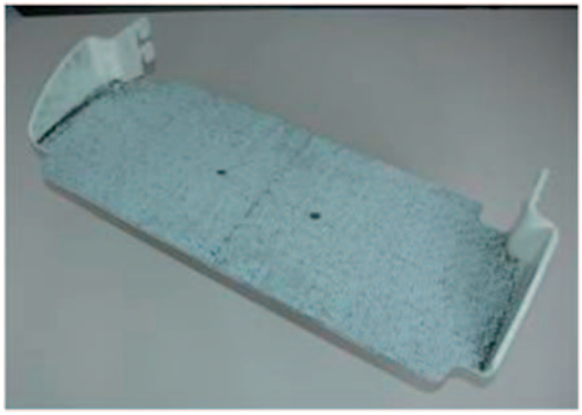

Figure 17. Footrest prototype.

the electromagnetic field, comparison was made evaluating the following conditions:

- The difference between the measures, with and without the prototype, at the resonance frequency of the transmission coil was required to be less than 10 kHz.
- Impedance, initially set at 50 Ω without the prototype at the resonance frequency of the magnet, was required to vary less than 5 Ω with the prototype.
- The difference of the intensity of electromagnetic field due to the transmission coil with and without the prototype was required not to vary more than 5%.

Obtained results are given in Table 10. Results show that variation (Δ) of the three different parameters

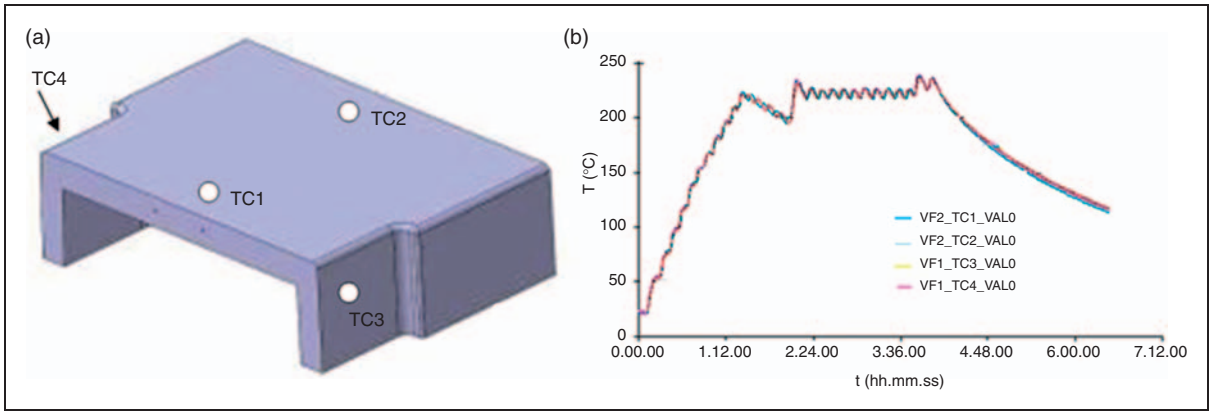

Figure 18. (a) Thermocouples location on the footrest mold and (b) signals of sensors.

Table 9. Transparency test results under static magnetic field

		Measurement				
Parameter	Δ limit	Without prototype	With patient bed	Δ	With footrest	Δ
Resonance central frequency (Hz)	100	10,188,950.3	10,189,017.9	67.60	10,188,953.0	2.7 Hz
Uniformity peak to peak (ppm)	30	19.2	19.7	0.5	19.4	0.2 ppm
Expansion coefficient (ppm)	10	16.6	18.1	Max/min 1.5/0	17.1	Max/min 0.5/0

Table 10. Transparency test results under electromagnetic field

		Measurement				
Parameter	Δ limit	Without prototype	With patient bed	Δ	With footrest	Δ
Resonance frequency coil transmission (kHz)	10	10,192.02	10,190.07	1.95	10,192.03	0.01
Impedance (Ohm)	5	53.3	52.6	0.7	53.1	0.2
Intensity of electromagnetic field (V PEP)	5%	4.42	4.40	0.5%	4.42	0%

considered in each corresponding magnetic field are within the limit range (Δ limit); thus the two composite prototypes are compatible with the transparency requirements prescribed by the Medical Standards.

Mechanical performances

The manufactured prototypes were assembled on the MRI machine, in order to perform final structural tests. According to the Medical Security Rule IEC 601.1, the prototypes were loaded with 200 kg, corresponding to the maximum patient weight, for the evaluation of the maximum inflection of the structural components.

The patient-positioning bed was assembled on real MRI machine connecting upper and lower tables as normal service operation and then loaded uniformly by means of sand sacks. A maximum inflection of 1.5 mm was measured in the central position confirming the value obtained by the FE analysis (1.8 mm). The experimental value obtained for the center line deflection proofs the possibility to substitute the HPL-made positioning bed with novel composite-made element preserving the shifting operation according to the medical exam requirements.

In the case of the footrest, the distributed loads induce a deflection of about 15 mm at center line, slightly lower than the level predicted by the numerical analysis. The differences in the deflection of the center line platform are attributed by the authors to the differences between the experimental applied loading conditions and the simulation. In fact, as during the experimental test the footrest was loaded by a oil driven cylinder acting on a rigid metallic plate put on the footrest platform, in the last stage of the test, the rigid metallic block will inevitably apply concentrated loads on the platform, whereas in the simulation analysis the loads were kept distributed through all the simulation steps.

Conclusions

The patient-positioning system of an MRI machine was re-designed, due to the employment of composite materials. A thermoset matrix composite was used for the patient-positioning bed, while a thermoplastic matrix composite was used for the footrest. Thanks to composite materials, the geometry of both elements was simplified achieving also a high level of part integration. Lightweight structures were manufactured more easily and safely, ensuring not only the magnetic and mechanical standard performances but also manoeuvrability during functional service and cost-saving limits.

The materials selected were characterized by experimental mechanical tests under tensile, compressive, and bending loads to acquire necessary input data for the numerical analyses.

Prototypes of the positioning bed and of the footrest were manufactured and tested to assess magnetic and mechanical performances during normal operation. Structural tests showed that the new composite components were suitable to be installed on MRI apparatus, as maximum deflection under prescribed load condition is within the limit according to Medical Security Rule IEC 601.1. Furthermore, medical scans were carried out with a conventional machine and with new composite component set machine in order to verify the influence on MRI medical images. Two alternative main targets were accomplished by substituting conventional materials with composite systems. In fact, the possibility to reduce the thickness of the positioning system gives arise the possibility to use a smaller magnet which indeed represents the main cost of the MRI machine. Moreover, the high level of part integration for both elements, positioning bed and footrest, leads to a cut of the production costs preserving the functionality and operability of the system. The other positive result achieved by used composite material is a marketing extension of the MRI machine in term of range of population allowed to be tested, due to the increase of the machine opening distance related with the thickness reduction of the patient bed.

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