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Mould design for manufacturing of isogrid structures in composite material

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Abstract

In the transport industry, fuel consumption and emissions can be reduced introducing very light parts. An optimal solution to these problems consists in the construction of isogrid structures made of composite materials, whose manufacturing process is a critical step, since it can induce some damages that cause the rejection of the produced part. The forming technology, the necessary equipment and the process parameters must be carefully chosen, since they strongly affect the part quality. The mould shape has to be carefully designed since the part presents a complex geometry, due to the presence of ribs, that could present a bad compaction. The aim of this work is to introduce and verify through structural tests a design methodology for the manufacturing of isogrid structures made of composite materials. In particular, the mould groove geometry was defined in order to obtain the right compaction degree. Then, different experimental tests were carried out to determine the quality of the produced structures.

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Keywords: Isogrid structures; Composite materials; Curing; Complex shape mould.

1. Introduction

The increasingly stringent environmental regulations require that in the transport sector the fuel consumption and, consequently, the emissions must be reduced to decrease the air pollution. Among popular solutions, this objective can be achieved by reducing the weight of the parts, though without affecting their structural resistance. According to Frulloni et al. (2007), the design and manufacturing of isogrid structures made of composite materials is the best

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answer to this demanding task. These structures are composed by an isogrid lattice, formed by helical and circumferential ribs, surrounded by a thin skin: in such manner, the final product consists in a lightweight structure characterized by high mechanical performances.

In the literature there are lots of study dealing with the mechanical performance of lattice structures. The buckling failure modes of lattice structures made of composite material were studied by Totaro (2012) and (2013). In particular, he applied analytical models on both triangular and hexagonal cells system, after those models were experimentally verified on a curved lattice panel with an axial compressive load by Totaro et al. (2013). Lattice structures failure was predicted by other researchers too, that prepared several models. The higher mechanical performance of lattice structures in comparison with sandwich or stringer ones was proved in a work of Vasiliev et al. (2012).

The manufacturing process is a critical step for this kind of structure, since it can induce some damages that cause the rejection of the produced part or its failure in service. The forming technology, the necessary equipment and the process parameters must be determined with care, since they strongly affect the quality of the produced parts. In particular, the mould shape has to be carefully designed since the part presents a complex geometry, due to the presence of ribs. In fact, a common defect that usually occurs is a bad compaction of the ribs, which involves porosity and low mechanical strength.

The aim of this work is to introduce and verify through experimental tests an innovative mould design methodology for the manufacturing of isogrid structures made of composite materials. In particular, the mould groove geometry was defined in order to obtain the right compaction degree. Then, different experimental tests were carried out to determine the quality of the produced structures and so the suitability of the designed mould.

2. Materials and methods

In a previous work by Sorrentino et al. (2016), the rib geometry was designed by the Vasiliev's theory, fixing the rib thickness equal to 2 mm and the rib width to 5 mm. Other geometrical parameters of the lattice structure were: triangle width equal to 94.25 mm, triangle height to 83.33 mm, helical angle to 60.51°, structure diameter to 300 mm and structure height to 338 mm. However, only a sector equal to one fifth of the structure was considered for the purpose of this work, as visible in Fig. 1. As a first approach for the realization of the structure, after having designed the mould and chosen the stratification sequence, the lattice structure alone was produced, without the skin. The material considered for this work was a unidirectional prepreg tape made of glass fibre and epoxy resin, whose parameters of interest are reported in Table 1.

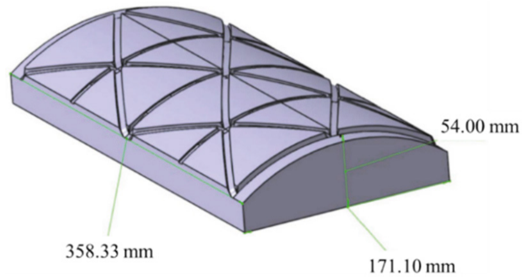

Fig. 1. Mould dimensions for one fifth of the structure.

Table 1. Material properties.

Property	value
Resin weight content	33%
Composite density	1850 kg/m^3
Fibre weight	0.66 g/m

2.1. Mould design

Not only the geometry of the lattice structure but also the manufacturing technology was considered for the design of the mould necessary for the production of the isogrid structure, because the technology inevitably determined a geometric/dimensional variation of the ribs compared to the drawn ones. Therefore, the design phases of the mould proved to be fundamental for obtaining the appropriate quality of the produced parts.

The mould channels were designed with well-defined geometry and dimensions in order to guarantee the deposition of the composite material roving and to facilitate as much as possible the compaction. The groove depth was chosen considering a uniform compaction and a rib thickness of 2 mm; therefore, the channel depth between two intersection point was 2 mm, while in the intersection point it was 6 mm, that is three times the thickness of the single rib. From a geometrical point of view, the groove bottom conceived in that manner was concave, therefore it had to be managed appropriately in order to reduce to a minimum the problems of compaction due to the fibre bridging; this means ensuring a smooth transition between these two thicknesses (2 and 6 mm).

However, this approach created a concave surface, whose negative curvature required auxiliary compaction systems, capable of making the fibres adhere to the groove surface during the material deposition. In order to overcome this question, an innovative solution was studied which delegated this task to the deposition of the circumferential ribs. For this reason, the thickness variation of the circumferential grooves was designed taking into account this purpose. The circumferential ribs also presented a depth variation from 2 mm to 6 mm and, taking into account their role of compaction system, to create a zero curvature surface was decided.

2.2. Mould production and preparation

The mould for the lattice structure was produced by machining a block of epoxy resin. This material was chosen since it had a coefficient of thermal expansion compatible with that of the composite material and it was convenient for the purpose of this experimental campaign. As concern the machining sequence, the dimensions of the raw block were defined on the mould drawing. In the first machining phase the rough shape of the mould was obtained; then, in the second machining phase, the mould surface was finished. The third machining phase consisted in the milling of the stratification groove, while in the fourth and last machining phase, a chamfer of 0.3 mm and 45° was milled on both side of each groove.

Before the stratification was carried out, to carry out treatments on the mould was considered appropriate to make it unaffected by the dimensional variations that may occur during the cure process of prepreg. Once the correspondence between the CAD model and the produced mould was verified, a size was spread on the mould to fill the surface porosity, then a release agent was put to avoid part sticking at the end of the process; a layer of liquid wax was added, which was accurately laid down on the whole mould to make it still less porous.

2.3. Design of tape stratification plan

For stratifying the tape on the mould, to follow the grooves machined on the mould surface was necessary; for this operation it had to be taken into account the fact that the helical ribs had a radial thrust lower than the circumferential ones, therefore the stratification plan provided a first step in which all the helical ribs were stratified and then the circumferential ones; this sequence was executed for each one of the calculated layers of composite material. The first step consisted in calculating the number of layers to be laid down to obtain the right structure dimensions, that were a rib thickness of 2 mm and a width of 5mm. Starting from the properties of the material used, the number of tape layers to be considered was calculated from the prepreg characteristics reported in Table 1; a number of layers equal to 20 was fixed for the structure under investigation. Considering the mould portion placed on a two-dimensional plane and numbering all the starting points trajectories as reported in Fig. 2, a first stratification sequence is described in Table 2. To better clarify the meaning of this table, some sequence steps will be explained in the following; for example, the first step describes the first helical trajectory to be executed, from point 0 up to point 6, to lay down the tape in the groove, above the mould. The second step indicates the return trajectory of the tape, which adhered to the rear of the mould from point 6 to 8; for this reason, it is defined as “below”. This choice was necessary to ensure continuity of tension and trajectory to the tape.

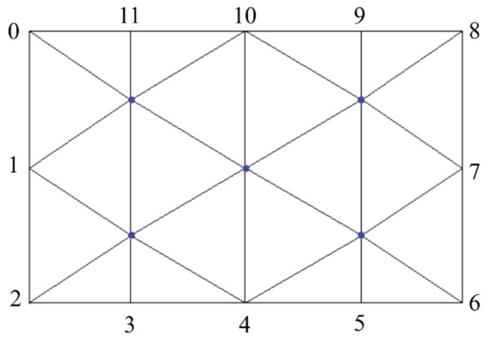

Fig. 2. First stratification sequence scheme.

Table 2. First stratification sequence.

Step	Trajectory	Position	Step	Trajectory	Position	Step	Trajectory	Position
1	0-6	Above	7	10-7	Above	13	10-4	Above
2	6-8	Below	8	7-6-8-7	Below	14	4-9	Below
3	8-2	Above	9	7-4	Above	15	9-5	Above
4	2-1	Below	10	4-10	Below	16	5-11	Below
5	1-4	Above	11	10-1	Above	17	11-3	Above
6	4-10	Below	12	1-2-10	Below	18	3-0	Below

2.4. Manufacturing of lattice structure

As aforementioned, for the aim of the present work only one fifth of the lattice structure was produced. For the ribs deposition, the mould was mounted on a turntable, by using a special equipment, and the prepreg tape was laid down by hand in the mould grooves following the sequence described in the previous paragraph. The limits and difficulties of a manual deposition were those of not being able to obtain a high repeatability. Therefore, problems such as having a constant tape tensioning, being able to have perfectly overlapping layers and avoiding neck-in and twist of the tape are typical problems that can be solved only with a robotic filament winding system, as that proposed by Sorrentino et al. (2017). Nevertheless, to reach an acceptable level of stratification was possible, obviously with a manufacturing process that required a very long time of about 3 hours.

Once the stratification process had been completed, a pre-compacting phase, known also as debulking, was carried out by vacuum bagging before the polymerization process. In this phase the stratified tape in the mould was compacted with a vacuum of -0.8 bar to make the tape adhere as much as possible to the bottom of the groove, thus increasing material consolidation, surface finish and structural solidity. For executing the debulking operation, to prepare a vacuum bag was necessary, similar to the one required by the cure process. First of all, the mould with the laid down material was wrapped with a release film to prevent it from sticking to the other ancillaries. Subsequently a layer of breather cloth was added, which was a transpiring material allowing a better distribution of vacuum on the mould surface and, consequently, increasing the homogeneity of the compaction. Finally, the vacuum bagging film, in plastic material, was deposited on the breather cloth, completing the preparation for debulking. In this last layer a valve, which was subsequently connected to a vacuum pump by means of a tube, was inserted to create the vacuum. After the compaction phase, in which the component remained for a period equal to about 4 hours, there was the polymerization phase. In this phase the part was autoclaved with all the vacuum bagging ancillaries and the mould, submitted to a cure cycle of 5 hours at 130 ° C.

2.5. Analysis of the structure quality

Characterization tests were made on the produced parts to analyse the physical and the structural strength characteristics. In particular, two tests were carried out: the former was the calcination test, that was a chemical one, and the latter was the interlaminar shear strength test, that was a mechanical one.

The resin content calculation by calcination test is suitable to determine the resin content in the part after polymerization, to understand how it is distributed and so to have an index of the areas with greater compaction. The specimens were extracted from those areas that appeared most interesting for this test, both in the intersection point and on a single rib. Six specimens were taken from the produced structures: from intersection points (specimens 2 and 6), from points between intersection (specimens 1, 3 and 5) and from a thickness transition point near the intersections (specimen 4). Through this test it was possible to calculate the resin and fibre volume content as well as the density and percentage of voids present in the specimens.

The interlaminar shear strength test, performed according to ASTM D2344, provides a goodness index of gluing between the laminae. It was carried out by performing a bending test with a ratio between the supports span length and the specimen thickness equal to 4. The specimens were taken from the most linear areas. Once the thickness had been measured, which was equal to 1.5 mm, knowing from the test specification that the ratio between length and thickness of the specimen must be equal to 6, the length of the specimen was fixed equal to 9 mm.

3. Results

Once cure process of the part had been completed and it had been extracted from the mould, the results obtained in terms of the tape stratification regularity and the polymerized composite material quality were analysed. Regarding the first point, it was seen that there were some points more involved for the tape inversion phase, in particular in the point 10 and 4 of Fig. 2. This created during the stratification phase a greater difficulty in depositing the tape, with the eventuality of neck-in or twist of the tape. Furthermore, no trajectories were foreseen to cover the head and base circumferences; therefore, an undesirable interruption in these points was found, as shown in Fig. 3.

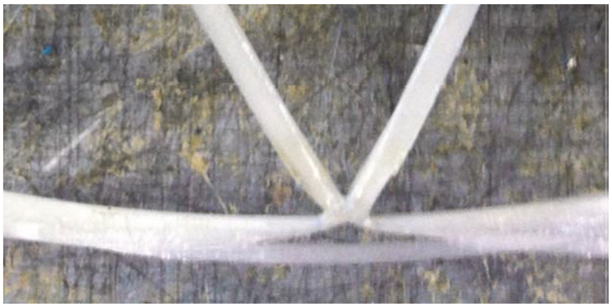

Fig. 3. Defect due to lack of circumferential head trajectory.

After the realization of the first prototypes, a non-homogeneous compaction of the tape was found; in particular, it varied in the proximity of the intersection point, where two helical trajectories intersected a circumferential one; the calculation of the groove depth in those points was made considering a triple stratification in the intersection, and therefore a triple depth than the other parts of the grooves. That is, a depth of 2 mm was considered in the zones with a single rib, while a maximum depth of 6 mm was adopted for those points where there was the intersection of the three ribs. After the demoulding of the lattice structure from the curing tool, the thickness of the ribs was measured by means of a digital calliper: the thickness of a single ribs was found equal to 2 mm, while in the intersection zone the measured thickness was 4.3 mm. Moreover, a visual analysis showed that the grooves tracts with variable depth were too long, that is the shift from 2 mm to 6 mm takes place in a too gradual manner. In fact, the tests showed a lack of compaction with a large displacement of the fibres in the radial direction and towards the inside of the groove, with a conspicuous depression of the ribs in those areas.

In order to obtain further information on the compaction level of the material in the different areas of the mould grooves, calcination tests were carried out. The results of these tests, that are reported in the Table 3, showed that the resin had a higher volumetric percentage in some parts of the structure than in others. Such a result could be expected but not to the extent that it occurred; in fact, according to the prepreg characteristics, the nominal resin contents differed considerably from those detected by experimental tests. The reason for this discrepancy was partly due to the particular piece geometry and partly to the fact that the mould grooves presented different depths, that created areas with greater compaction than others. With regard to the interlaminar shear strength tests, the relevant results are shown in the Table 4. As can be seen from these results, the interlaminar shear strength values are all above 50 MPa, which corresponds to the minimum limit given by the material specifications. It can therefore be concluded that the values obtained fall within the specifications.

Table 3. Calcination test results.

Specimen	Resin content [%]	Fibre content [%]	Void content [%]
1	39.2	59.1	1.7
2	45.4	38.6	16.0
3	35.7	59.2	5.1
4	41.4	46.5	12.1
5	36.8	59.2	4.0
6	48.8	40.0	11.2

Table 4. Interlaminar shear strength test results.

Specimen	ILLS [MPa]
1	54
2	67
3	66
4	65
5	66

The rib thickness measurement and the calcination test found some differences in terms of rib thickness between the nominal structure and the produced one, which were due to the fact that the prepreg resin underwent irregular transactions during the curing phase, filling more some areas rather than others.

4. Conclusions

The present work deals with the definition and validation of a design methodology of a mould for manufacturing isogrid structure made of composite material. In fact, some issue can arise during the production of this kind of parts, that are induced by a bad-designed process, in terms of parameters and tools. A particularly delicate area is located where the ribs intersect each other, because there the material compaction is more complicated, dangerous residual tensions can arise and the non-uniformly distributed load caused by build-up can give rise to cure induced deformation of the lattice structure.

In this work some solutions to the abovementioned issue are proposed. In particular, the mould grooves presented a variable depth to guarantee a correct compaction, since in the intersection points three times the material quantity was present than in the other parts. Also the tape stratification sequence was a parameter to be taken into consideration, as it can influence the quality of the part.

Some lattice structures were produced to assess the suitability of the design methodology. In particular, the geometry dimensions were taken from a previous work, only a sector equal to one fifth of the structure was manufactured for the purpose of this work and the lattice structure was produced without the skin, in order to highlight the rib properties, as their compaction.

Some experimental tests were carried out to assess the quality of a produced lattice structure. A visual inspection was suitable to highlight in qualitative manner the stratification induced defects and the rib compaction, while calcination tests and interlaminar shear strength tests were adopted to define in a quantitative manner the compaction degree and the quality of the ribs. The first adopted stratification sequence was found not suitable since it induced some defects in the head and at the base of the structure. As concerns the rib compaction degree, it was found uneven and consequently to design a new groove profile was deemed necessary.

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