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The Design of a Bistable Composite Connection Method Applied on the Low Volume Production of a Breast Board Table Connection

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Abstract. Bistable morphing composite laminates have been studied over the recent years because of their exquisite applications in energy harvesting and aerodynamic performance. A bistable laminate has two passive, stable positions that require an actuating bending moment for snap through. Different techniques have been developed to obtain bi-stability in composite laminates by using thermally or mechanically induced strain. Little study has been done around the more accessible method of laminate bi-stability through elastic buckling. This paper presents the design process of a buckling bistable composite connection method with human actuation.

1 Introduction

The use of morphing composite laminates in different applications have been studied over the recent years. Bistable laminates possess two passive stable positions, convertible by a snap-through actuator. Once settled in an equilibrium state, the bistable structure will remain there without demanding continuous power. Different techniques to obtain bi-stability in composite laminates were studied over the recent years. The following techniques are the most common:

- Asymmetrical stacking with thermally induced strain[1]
- Pre-curved asymmetric Laminates [2]
- Pre-stressed symmetric laminates [3]
- Variable Angle Tow -steering [2]
- Viscoelastic pre -stress [4]
- Hybrid composites through thermal mismatch [5]

Nowadays, the applications of bistable composite laminates are concentrated on piezoelectric energy harvesting [6] and aerodynamic optimization in for example wind turbine blades [7]. In these applications, surrounding vibration and wind are the actuators for the snap-through.

The current methods to create bi-stability are often complex and require specified machinery. Little study has been done on the more accessible technique of creating bi-stability in laminates through elastic buckling. Moreover, the applications of bistable laminates are limited to high-tech

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products. In this paper, a concept will be presented where a bistable composite laminate is used as a load-carrying connection method.

The design will be applied on the table connection of a new type of breast board, developed and researched by Ghent university in collaboration with the university hospital[8]. A breast board is a prone patient support device for breast and regional lymph node radiotherapy. The device is mounted on the treatment couch and the upper body part is hanging over the table, resulting wide range of desirable beam paths (Figure 1).

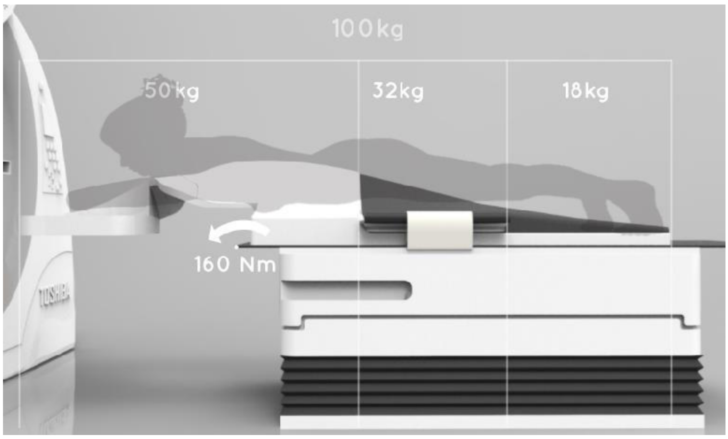

Figure 1. Prone crawl breast board with the applied forces. The clamps are subjected to a moment of 160 Nm, or 80Nm each.

The current table connection is a 3D-printed part that has to be applied manually around the table and has the following issues:

- Not safe - when the connection is not applied, the breast board can fall when the patient's weight is applied;
- Not strong enough - the current connection fails too easily because of applied moment;
- Not user friendly - There is no specific feedback when the connection is closed.

This paper presents the design process and person-interaction of a bistable buckling composite connection method. The concept will be applied on the table connection of a breast-board. The usage of fibre reinforced plastic can increase the load capacity of the connection, while the bistable behaviour improves the usability and safety.

2 Design process

2.1 Design methodology

Four main categories in the design process of a composite part will influence the characteristics of the bistable plate: shape, material, construction and production (Figure 2). Firstly, we will propose a connection design based on the buckling of a laminate. Secondly, we will determine the materialization, construction and production of this laminate. Every decision in each category, influences the other categories. Thirdly, we will perform user tests to study the person interaction. At last, the integration of the bistable connection in the breast board body will be discussed.

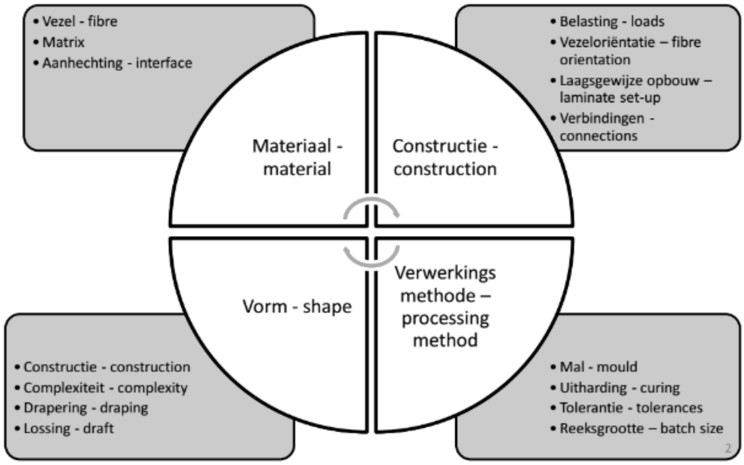

Figure 2. A composite design methodology[9].

2.2 Design principle

The concept of the proposed design is based on the simple principle of a buckling beam that is clamped between two points, because of pre-stress P (Figure 3). An actuation force F can snap-through the beam towards a second stable state.

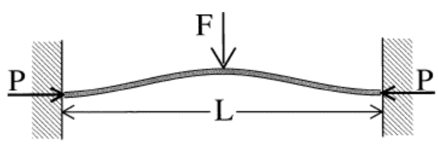

Figure 3. Simple buckling beam.

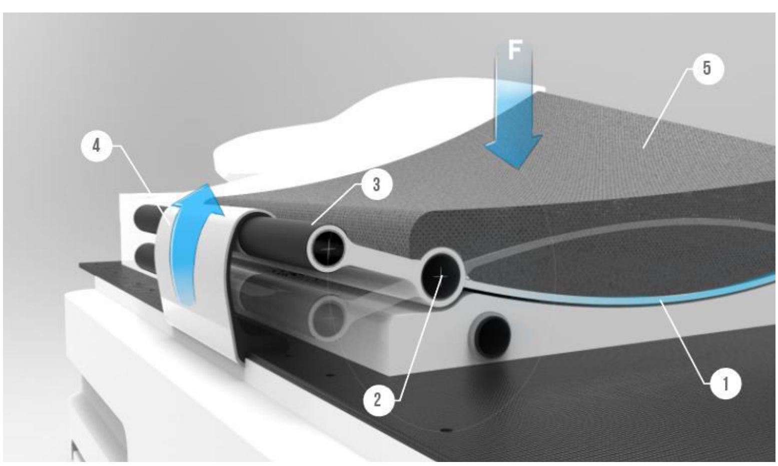

Figure 4. Proposed design for the breast board table connection.

Figure 4 gives a design solution that fits the requirements. The weight of the patient's waist (F) on the cushion (5) snaps through the bistable composite plate (1). This movement around the rotational axes (2) clamps the sides (3) against a profile (4) that is connected to the table. The connection can easily be opened by pressing on the handles (3).

Table 1 shows the parameters that can be designed in a bistable composite laminate. The second column indicates the critical parameters of the proposed design, based on the load analysis of the breast-board, material restrictions and system requirements.

Table 1. The parameters of the proposed design.

Design parameters	Critical value	Unit
Curvature	<60	mm
Snap-through moment	>16	N.m
Buckling force	/	N
Internal stress	<35	MPa
Sound intensity	Minimal	dB
Snap-through velocity	Maximal	mm/s
Service time	7	Years
Snap through vibration	Minimal	Hz
Bending characteristic	/	/

2.3 Materialisation process

Carbon fibre is often used in current applications of bistable laminates, because of its appropriate thermal properties for asymmetric [0°/90°] bistable laminates[10]. The application of the breast board requires an insulating composite, which excludes carbon fibre. Fiberglass is the most appropriate for the application because of the following reasons:

- The radiolucent characteristic ensures minimum distortion.
- The high Young’s modulus makes it possible to experiment with the flexibility.
- The integration possibility in the breast-board is better because the breast board is also made from fiberglass.

2.4 Construction

When designing a bistable composite laminate, the challenge is to balance the stiffness in order to produce a laminate that is load carrying, shape adaptable and light (Figure 5).

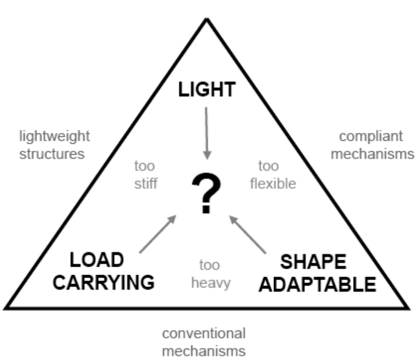

Figure 5. The design challenges of a morphing laminate [2].

In the philosophy of this design challenge, we need to consider the following issues for the construction of the laminate:

- The snap-through moment of the laminate must be able to take up the moment created by the weight of the breast board Mbb (Figure 6).
- The laminate has to be stiff enough (at the sides) to avoid that area A bends because of the moment Mbb. This would cause the sides to move downwards and the breast board to tilt over (Figure 6).
- The laminate needs to meet the critical values of the proposed design (Table 1).

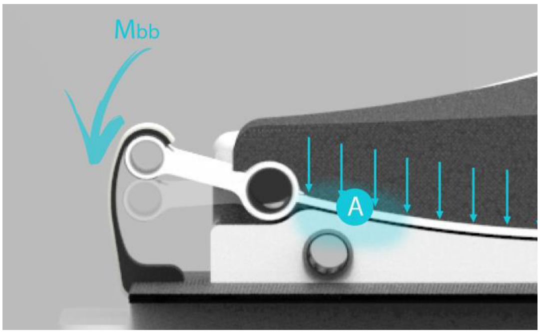

Figure 6. Forces on the bistable laminate.

2.4.1 Lay-up experiments

When applying a core in the laminate, the flexible area is reduced and will locally bend with a bigger curvature (Figure 7). Different test samples were produced to analyse the influence of the curvature change on the bistable behaviour (Figure 8)

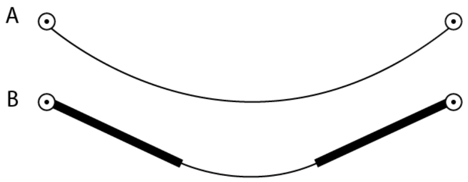

Figure 7. Layup without (A) and with (B) core.

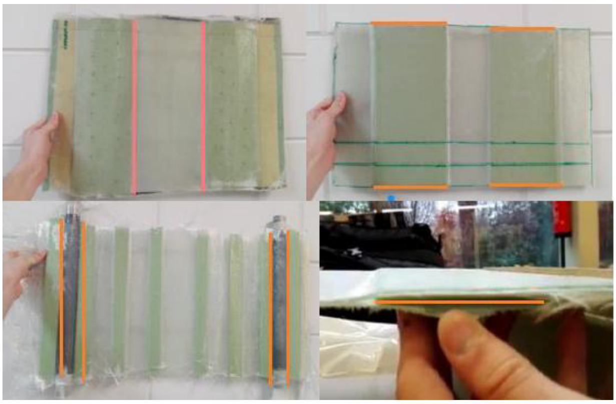

Figure 8. Laminate constructions with core variations (0°/90°/PVC/0°/90°).

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The test results showed that the snap-through moment of the laminate increased with a greater curvature because of the increasing internal stress. Secondly, every laminate with a core showed signs of shear failure at the disrupting transition from fibre to core, which causes local stress peaks.

These results point out that we need to construct the laminate as uniform as possible to avoid stress peaks and to enhance the lifetime of the laminate. To influence the snap-through load, we can variate the curvature or the stiffness of the laminate.

2.4.2 Lay-up proposal

Figure 9 shows the proposed laminate [0°/45°/0°/90°/0°/-45°/0°]. The 0°-fibers will take up the moment of the breast-board and the weight of the patient, the 45°-fibers will take up the torsional forces, and the 90°-fibers ensures stiffness in every direction. Six extra 0°-layers are placed in area 3 to soften the discontinuities and to avoid this area to bend. The fiberglass rotation axes (2) are integrated in the layup and the PVC core at the sides (1) provides extra stiffness.

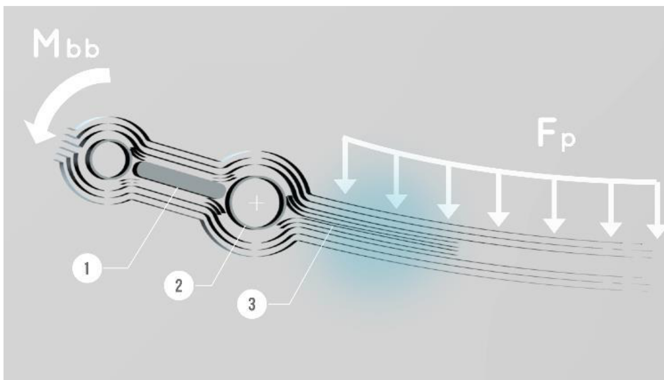

Figure 9. The layup proposal.

A test set-up was constructed (figure 10) to simulate the forces of the breast board on the bistable laminate with a curvature of 3cm. The distance of the weight of 30 kg was adjusted to gradually increase the moment M on the connection (figure 11). Two specific findings were made. Firstly, the tests results showed that the bistable laminate could easily resist a moment of 225N.m without snap-through. This is 65 N.m more than required.

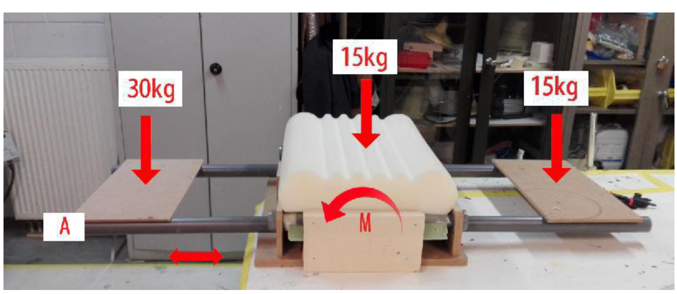

Figure 10. Test setup for load simulation on the bistable laminate with a 3cm curvature.

Secondly, the laminate showed deformation because of the bending moment M. This caused the breast board to tilt over, which is very undesirable because of calibration reasons and user comfort (Figure 11). The laminate layup needs to be constructed stiffer to minimalize this effect in future iterations.

Figure 11. The deformation of the laminate causes tilting of the prototype.

It is important to predict the behaviour of the bistable laminate over time. Specific FEM-analyses[11] and test-setups are needed to predict creep and fatigue of the laminate to propose a certain life expectancy. The following tips can be considered to minimize load capacity reduction over time:

- Avoid discontinuities in the laminate
- Design the laminate with a high safety factor (up to 10)
- Using resins with a HTD that is 20° higher than the service time.

2.4.3 Conclusion

The construction tests of the laminate confirmed the design challenge of bistable composites: the stiffness and internal stress need to be minimized to promote the life-expectancy, but we need to create enough stiffness and internal stress to meet the required snap-through moment and to minimalize the edge flexibility that causes the breast board to tilt over.

2.5 Production

2.5.1 Mould

The mould for the prototype was made in wood to reduce the costs (Figure 12). The production mould could be produced in fiberglass or aluminium, dependent from the batch size.

Fiberglass moulds are perfectly suited for low volume processes that produce less than 1000 parts a year:

- Fiberglass moulds are about 10 times cheaper than aluminum, which makes it cheaper to make adjustments
- Fiberglas moulds can last for up to 1000 parts

Figure 12. Mould for the prototype.

We need to be able to produce connections for different widths of radiotherapy tables. To achieve this, we can choose between 2 options (Figure 13). The first option is to make the clamp profile adjustable to the width of the table. The second option is adjusting the mould dimensions. A split mould has the advantage that we only need to change a small part of the mould.

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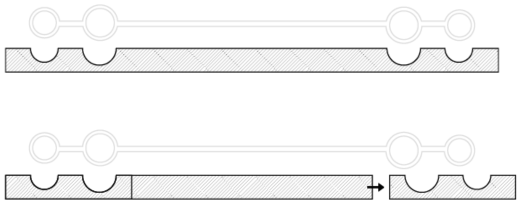

Figure 13. One-piece mould versus split mould.

2.5.2 Processing

The production of the laminate allows us to variate with different parameters.

- Fiber/matrix-ratio
- Curing
- Laminate thickness
- Air bubbles
- Surface finish

The production of a bistable laminate for professional applications requires a production process that equally distributes the matrix in the fiber. A good laminate quality is essential for the bistable behaviour over time. The test samples are produced with a resin infusion process to ensure the laminate quality (Figure 14). For professional applications, Prepreg fibers are recommended to obtain an even better resin/matrix ratio.

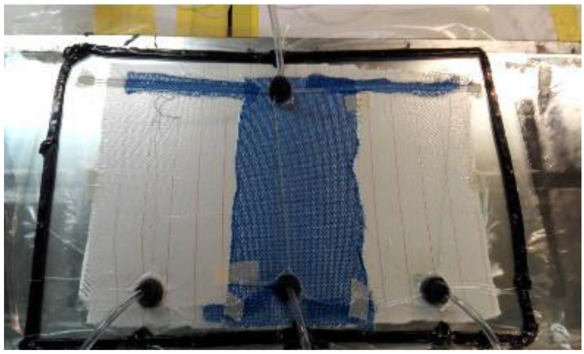

Figure 14. Infusion tests.

2.6 User tests

A prototype was built to study the person interaction with the bistable connection (Figure 15). The weight of the patient waist causes the laminate (4) to snap-through over the rotation axes (1) and bend upwards against the clamp-profile (3). The connection can be opened by pushing on the handles (2).

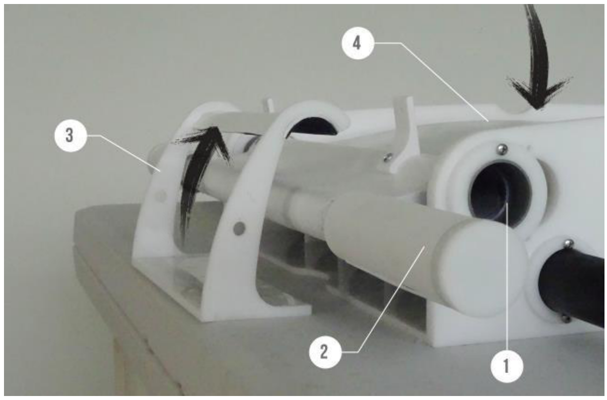

Figure 15. User test prototype.

2.6.1 Positioning

The positioning of the prototype took an average of 5.8 seconds more than the current connection. This is caused by the fact that the sides need to be positioned under the clamp profile (Figure 15). This is an issue to take into account for future development.

2.6.2 Closure

After positioning, the nurses will close the connection by pressing the cushion above the bistable plate (Figure 16). If the nurse forgets to close the connection, the system automatically closes in 0.3 seconds when a weight of 5 kg is applied above the connection. This safety factor is an important advantage in hospital environments.

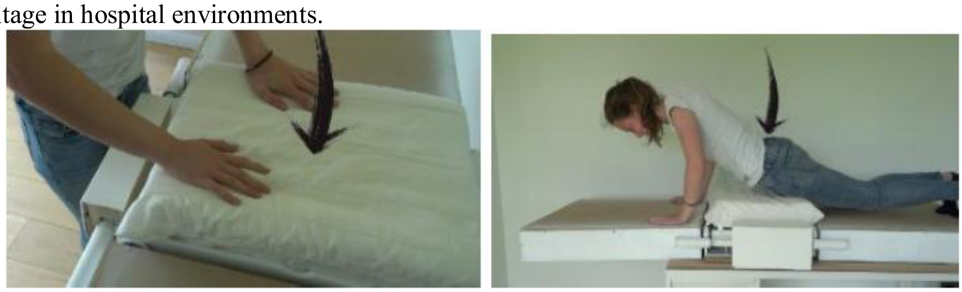

Figure 16. Closure by pushing (left) or patient's weight (right).

2.6.3 Open

The opening of the connection (figure 17.) is more intuitive: 5 out of 5 test subjects succeeds to open the connection within 5 seconds by pushing on the handles with a force of approximately 57N.

Figure 17. Opening the connection at the handles.

2.7 Integration in breast board

Figure 18 gives a CAD drawing of the overall beast board design integration.

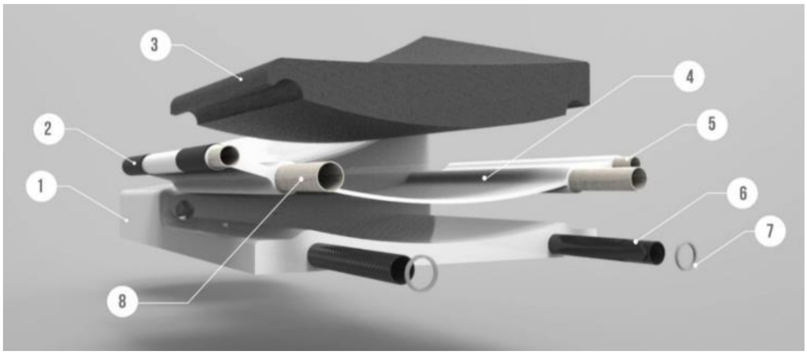

Figure 18. Assembly parts of the connection in the breast board.

The bistable composite shell (4) can be built in the breastboard body (1) with the rotation axes (8). Because the connection will have a considerable lower service time than the breast board itself, the integration has to be modular to be able to change the bistable laminate.

2 Conclusion and future vision

The bistable behaviour of the laminate shows potential towards feedback and safety in the application of the breast board. The usage of fiber reinforcement makes it easy to tailor the laminate towards the desired design parameters and takes up the load of the patient weight.

The prototype still shows some issues: the positioning of the sides under the clamp profile is too difficult and the undesired flexibility of the laminate when closed can cause the breast board to tilt over. Further study can minimize this effect by lay-up variations. These issues confirm the challenge of designing bistable laminates: they have to be flexible, but load carrying.

For the application of the breast board, extensive failure analysis and user tests are necessary to optimize the bistable laminate and to fundamentally prove that the connection meets the strict safety standards of hospital equipment.

Buckling is an accessible method of obtaining bi-stability in composite laminates, but this technique does not make use of the anisotropic properties of the laminate. Moreover, the buckling stress in the laminate causes creep and is difficult to predict.

Other techniques to obtain bistability in the composite laminate can be reconsidered for more predictability in high-tech applications. Bistable prestressed symmetric laminates [4] [12] are a good alternative because of the similar cylindrical bending characteristic. This technique shows different advantages over buckling:

- Usage of anisotropic properties to create bistability
- Better lifespan
- Better integration possibilities because no rotational axes are needed
- Minimal variability with changes in environmental conditions due to hygrothermal effects.
- Ability to prescribe laminate curvatures by control of the magnitude of applied prestress.

The technique of prestressed laminates can be considered in future work because of the numerous advantages over buckling laminates[13].

In general, bistable composite clamps can be very suitable in applications where a light, quick and heavy loaded connection is required.

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