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SHAPE ADAPTIVE METASTRUCTURES USING BISTABLE LAMINATES

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Abstract. Concepts involving adaptive and morphing structures offer a possibility to realise shape transformation with each shape imparting an individual functionality. However, most concepts require a "holding force" or a continuous supply of energy to maintain a targeted 3D shape. As a result, structures that can lead to shape transformation with self-locking capabilities without the requirement of any "holding forces" are more desirable, and thus an active topic of research. In this work, the concept of multistability is employed to demonstrate a novel class of metastructures that can tackle this challenge. These structures manifest shape transformation by utilising geometrical nonlinearity under a snapping load. The designed metastructure is constructed with a periodic arrangement of bistable unit cells made of anisotropic composite laminates. Each unit cell comprises multi-sectioned rectangular composite plates exhibiting bistable behaviour due to the thermal residual stresses engendered during the cooldown process from curing to room temperature. By carefully tuning the size and spacing of the unit cell, a desired response of the metastructure can be achieved. In addition, by changing the ply layup and the fibre orientation of each layer of constituent composite plates, conflicting requirements including load-carrying, shape-adaptive and lightweight, at the same time, can be addressed. Such metastructures have therefore potential applications in adaptive components of aircraft, wind turbine blades, robotics, and deployable space structures. To predict the response of the proposed metastructure, finite element investigations have been employed individually at three hierarchical levels: a single bistable element, a unit cell, and a lattice consisting of several unit cells. The minimum load to snap a unit cell and subsequently, a lattice is found through the resulting load-displacement curve from the finite element simulations. This work offers a route to the design of novel adaptive metastructures which is lightweight, load-carrying and at the same time, capable of transforming one stable shape to another, without the requirement of any "holding forces.

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Key words: Metastructures, Adaptive Structures, Multistability, fibre-reinforced composites, Thermal residual Stresses, Snap- through

1 INTRODUCTION

Metamaterials are artificially made materials engineered to exhibit extraordinary properties. They can be designed by creating repeating patterns of unit cells, so that they can exhibit tailored response that differ and surpass the performance of its constituent materials. Shape-adaptive mechanical metamaterials are a special class of mechanical materials, that employ motion, deformation or structural instabilities to change from one shape to a another desired form. Such metastructures have recently demonstrated potential for advanced functionalities, such as morphing in aircraft wings [1], adaptive flap of a wind turbine blade [2], topological wave guides [3], smart wearables [4] and biomedical devices [5]. The key to the tailored response of such metastructures lies in designing its constituent unit cells. These unit cells are engineered to react to mechanical forces by deforming, rotating, buckling, folding, and snapping, and are specifically designed to enable adjacent blocks to work in synergy to generate the desired overall behavior.

Among many strategies, multistability has been widely employed for designing shape adaptive structures as they exhibit two or more stable configurations. Multistability can be induced through different means, such as utilising the differential thermal coefficient in unsymmetric fibre-reinforced composite laminates [6], incorportating geometric features such as initially curved shells [7], origami and krigami concepts [8], or by applying prestressing [9]. By triggering snap-through in these structures, it is possible to transform from one stable shape to another, without the need for ”holding force” to maintain a configuration, making them highly design for design of efficient adaptive structures.

In the recent past, multistability has been increasingly adopted to design shape-adaptive metastructures. Shan et al. [10] developed multistable snapping metamaterials that trap energy through inclined straight beams to produce 1D, 2D, and 3D energy-trapping architectures with fully recoverable elastic buckling deformation, offering protection against impact. Chen et al. [11] utilized hierarchical frameworks and bistable actuators to fabricate multistate deployable structures via multi-material 3D printing. Ren et al. [12] designed buckling-based negative stiffness lattice metamaterials by integrating prefabricated curved beams into multidimensional rigid frameworks, and studied their mechanical behavior under multiaxial loading conditions. Ha et al. [13] introduced 3D cubic negative stiffness lattice structures capable of absorbing energy in three principal directions, representing a novel development in metamaterial technology. Researchers have also explored interlocking plugs and grooves, as well as using krigami and origami concepts to design negative stiffness structures with snapping mechanisms [14, 15].

It is well known that thin unsymmetric cross-ply fibre reinforced composite laminates can yield two cylindrical stable shapes upon cooldown from curing to room temperature, whose principal curvatures are orthogonal to each other [6]. By changing the fibre orientation angle or using curvilinear fibre paths [16], it is possible to obtain a wide variety of stable shapes.

This study presents a novel metastructure design made of fibre reinforced composites, that can achieve significant shape changes through snap-through mechanism. The proposed design consists of two rectangular bistable laminates and two monostable laminates, which are interconnected to form a unit cell (Fig. 1). Inspired from the earlier works of Haldar et al. [17], and Arrierta el. [18]), we have employed a multi-sectioned plate that exhibits two stable configurations. Previous studies have shown that constraining the edges of a bistable plate into a larger structure can result in a reduction in the net deformation and consequently loss of bistability [19, 20]. As a result,the design of such bistable elements for designing a metastructure is a non-trivial task and requires a careful design procedure.

The design of the unit cell in our proposed metastructure is guided by two key objectives: a) to achieve maximum out-of-the-plane displacement in one of the stable shapes, and thereby resulting in maximum morphing action and b) to ensure that the plate manifest straight edges in its both stable states. The second objective is critical in enabling the lattice structure to undergo shape transformation without developing excessive stresses at the connected regions, thereby preserving its bistability.

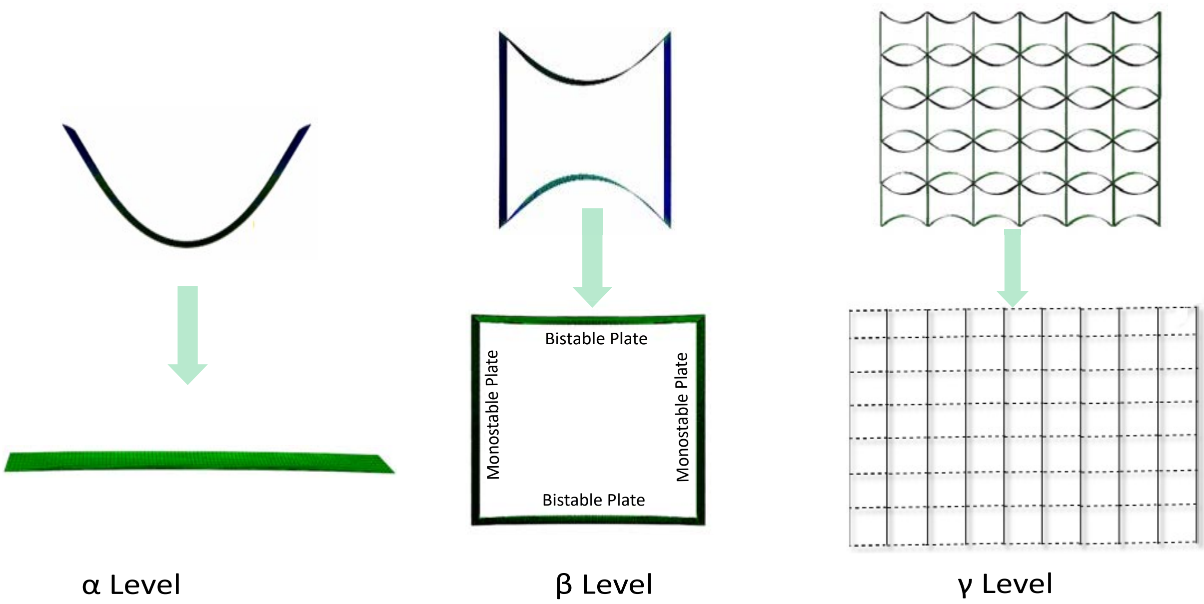

Figure 1: Concept of the proposed shape-adaptive metastructure illustrating α, β and γ levels

2 Description of the Structure

The proposed meta-structure is composed of three structural levels as illustrated in Fig. 1: a) α level which constitutes of a fundamental bistable multi-sectioned rectangular plate (as depicted in Figure 2). b) β level that represents a unit cell consisting of two bistable plates (as described at the α level) and two monostable plates made of $[0]_7$ laminate. Upon snap-through of the bistable plates, the unit cell transforms from a deployed state to a retracted configuration,

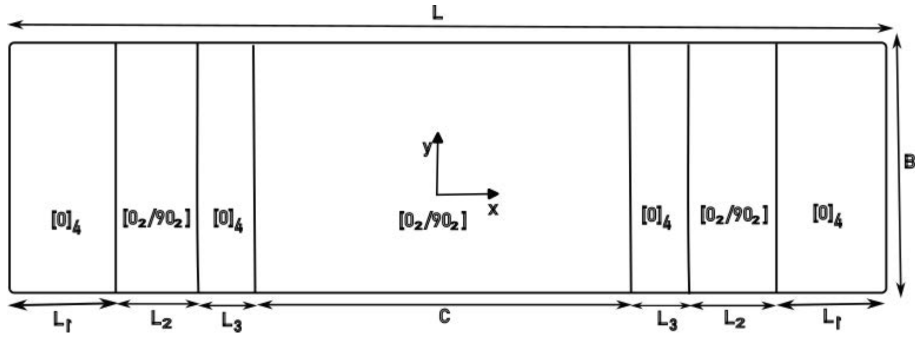

Figure 2: Dimensions and fibre orientation of multi-sectioned bistable plate

exhibiting bistability (as shown in 1. Several unit cells can be periodically linked together to further construct a γ level structure. Under snap-through forces, the metastructure can undergo shape transformation due to sequential snap-through instabilities, exhibiting deployed and retracted configurations (as depicted in Fig. 1). It must be noted that the number of plies in the monostable plate can be increased to improve the load carrying capacity of the metastructure.

3 Numerical Model

The response of the proposed metastructure unit cell made of a fibre-reinforced composite laminate is analyzed using a nonlinear finite element analysis (FEA) package ABAQUS. The numerical model to analyze a unit cell is carried out in two different levels, α and β as described in Section 2.

3.1 α level

Our objective is to design the bistable plate that can exhibit maximum out-of-the-plane displacement while maintaining straight edges in its both stable states. Therefore, a multisectioned plate is proposed that consists of symmetric and unsymmetric layups as shown in Fig. 2 with total of four layers. The length of the symmetric region is $2L_1 + 2L_3$ and the length of the unsymmetric region is $2L_2 + C$. In total, 2548 linear quadratic shell elements with reduced integration (S4R) are used to model the bistable plate. Mesh convergence studies show that the adopted mesh size yield converged results, without much change in the results on further mesh refinement. Specific boundary conditions at the edges of the plate are imposed to evaluate the plate's behavior connected in a lattice.

3.1.1 Cool Down Process

The process of cooling down from the curing temperature to room temperature for the specified composite plate is simulated. It is assumed that the temperature on the surface of the plate is evenly distributed, and a uniform temperature field is applied to the entire domain to simulate the curing process. As the plate cools from curing to room temperature ($\Delta T = 180°C$), it manifests the curved stable shape as shown in Fig. 3(b). During the cooldown process, the plate is considered fixed at its central node to prevent rigid body motion. To ensure convergence along the loading path, artificial damping or viscous forces are incorporated as a stabilising measure.

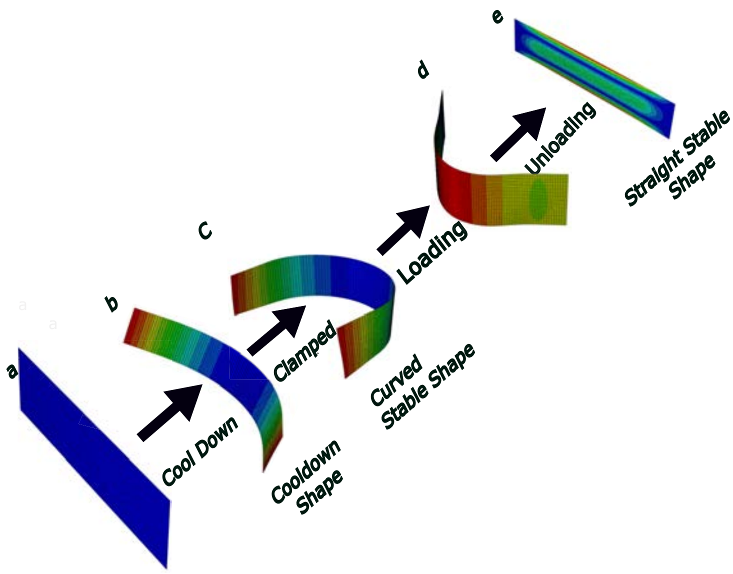

Figure 3: Stages of the numerical simulation at the α level (a) Initial shape (b) Cool down shape (c) Curved stable shape after imposing BCs at the edges (d) Shape after loading (e) Straight stable shape under the imposed BCs.

3.1.2 Snap-through Analysis

It is important to study the snap-through behavior of a multistable laminate for the purpose of designing the shape adaptive metastructure. In this work, mechanical forces applied at the centre of the plate are used to trigger snap-through, as seen in Fig. 3(e). The snap-through process involves the following steps:

1. After the cooldown step, new boundary conditions are imposed to simulate a similar boundary condition in a unit cell. One edge of the plate is constrained in translation along the x, y, and z directions and rotation along x and z directions, while the other edge is constrained in translation along the y, and z directions and rotation along x and z directions. The centre node is free to move in translation and rotational motion in all directions. The axes $x - y$ is defined in Fig. 2.

2. The next phase involves applying an external load at the centre of the first stable shape (Fig. 3(d). On applying a load higher than the snap-through load, the plate snaps to the other stable shape.

3. Finally, the applied load is removed, allowing the plate to rest in its the second stable shape 3(e).

3.2 β Level

At the β level, FEA is carried out on the unit cell comprising four laminates, of which two are bistable and the other two are monostable symmetric laminates (unit cell depicted in Fig. 4). This analysis is carried out after completing the preceding analyses at the α level and importing the residual thermal stresses in the bistable elements. The following steps are involved in the finite element analysis (FEA) of the unit cell under a snapping load:

1. The straight stable configuration (as shown in Fig. 3(e) is imported from the α level to the β level. Further, two unidirectional monostable plates are added to the bistable plate to create the unit cell. The bistable plates are connected to the monostable plates by using tie constraints in a way that only allows rotational motion, similar to the boundary condition applied in the α level (3.1.2).

2. The residual stress from the final step of the α level bistable plate (the unloading step as shown in Fig. 3(e) is imported and used as the initial state condition for the β level analysis.

3. An external load is then applied at the centre of each bistable plate to trigger snap-through. The force applied must be greater than the required snap-through force for the analysis to pass the limit point.

4. Finally the load is removed, allowing the unit cell to remain in its compressed stable shape as shown in Fig. 4.

4 Results

We have analysed a multi-sectioned laminate with dimensions $L = 0.530\ m$, $B = 0.106\ m$, $L_1 = 0.071\ m$, $L_2 = 0.038\ m$, $L_3 = 0.009\ m$ and $C = 0.294\ m$ with four-ply layups to demonstrate its bistable behavior. The dimensions are decided after conducting an extensive parametric study. The material property of the fibre-reinforced composite and the ply thickness is given in Table 1. The steps described in Fig. 3 are performed, and finally we obtain two stable configurations, straight and curved. Fig. 5 shows the load-displacement curve of an α level plate from straight to curved stable shape, when a point load is applied at the centre of curved stable shape and the displacement at the centre of the plate is recorded. Fig. 5 clearly shows the limit point after which the snap-through occurs. After applying a specific load, the bistable laminate undergoes snap-through and transforms to the curved configuration. Upon unloading, the bistable plates remain in the curved stable shape. It must be noted that there is no loss of bistability even after imposing the boundary condition at the edges, clearly indicating the advantage of the using this multi-sectioned design.

The purpose of such mono-stable elements is to carry loads in the normal direction of the element. An illustration of a unit cell is shown in Fig. 4, a concentrated force (F) in the z-direction is applied at the centre of both the bistable plates.

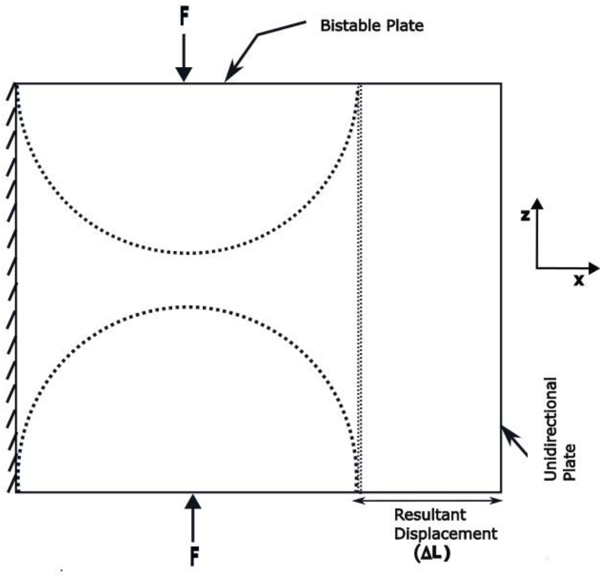

Figure 4: The two stable states of the unit cell is shown (a) Solid line is showing the straight stable shape. (b) The dashed line is showing the curved stable configuration.

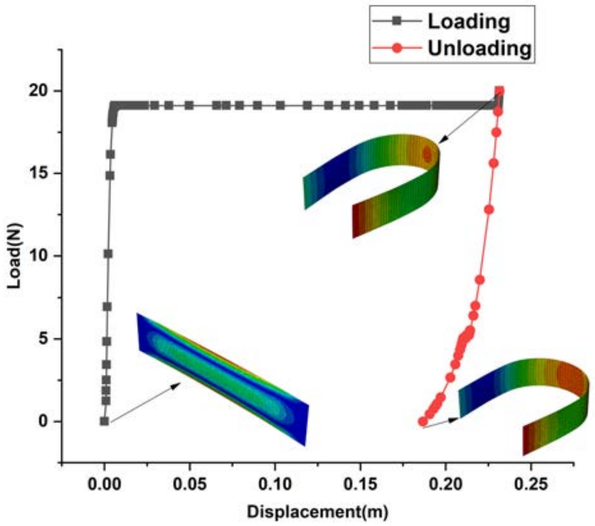

Figure 5: Load displacement curve of a bistable plate snapping from straight stable shape to the curved stable shape. The dimensions of the bistable plate are: *L* = 0.530 *m*, *B* = 0.106 *m*. The parameters L_1 = 0.071 *m*, L_2 = 0.038 *m*, L_3 = 0.009 *m* and *C* = 0.294 *m* is considered.

Table 1: Typical material properties for Carbon /Epoxy composite laminate

E_1	G_{12}	v_{12}	α_{11}	α_{22}	Thickness (m)
$16.1\ GPa$	$0.517\ GPa$	0.3	$-1.5 \times 10^{-8}/°C$	$3 \times 10^{-}8/°C$	0.131×10^{-3}

Similar FEA analysis is carried out for the unit cell at the β level. As a result of this transformation from straight to curved stable shape, the whole lattice deforms in the x-direction (as depicted in Fig. 4), and therefore the lattice itself exhibits two stable states: deployed and retracted.

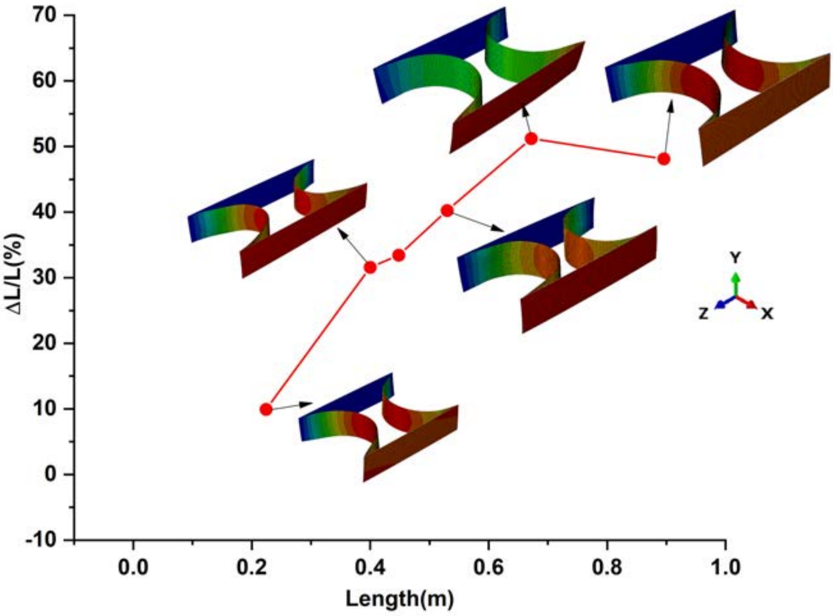

Figure 6: The resultant displacement between two stable configurations w.r.t length of the bistable plate with changing length at the constant thickness of *0.524 mm* (Four Layup) is shown.

Based on the developed Finite Element model for the β level, we carried out a parametric study to determine the percentage change in displacement of the lattice with respect to the length of the bistable element ($\Delta L/L$) with increasing length but maintaining a constant aspect ratio of $(L/B) = 5$. The change in the length parameter ΔL is depicted in Fig. 4. It is clear from Fig. 6 that as length of the bistable plates increase, the resultant displacement of the second stable configuration also increases. However, for plates with lengths more than *L* = 0.672 *m*, there is a decrease in the displacement ($\Delta L/L$) of the lattice in the x direction.

Another parametric study is carried out to analyze the effect of change of the width of the bistable plate on the deformation of the unit cell. We analyzed a bistable plate of $L = 0.530$ m and number of layers $n = 4$ with varying width values, and evaluated the % change in length of the bistable plate ($\Delta L/L$).

It can be observed from Fig. 7(a) that, as breadth increases, the resultant displacement between the two stable states (Δ L) also increases but by less than 9% as the width increases from $0.25L$ to $0.08L$. But ΔL decreases if the width is more than $0.25L$.

Further, the variation of snap-through load to transform from retracted unit cell configuration (with curved stable shapes) with the deployed configuration (with straight stable shapes), with respect to change in the aspect ratio is plotted in Fig. 7(b). The analyses is done for a constant

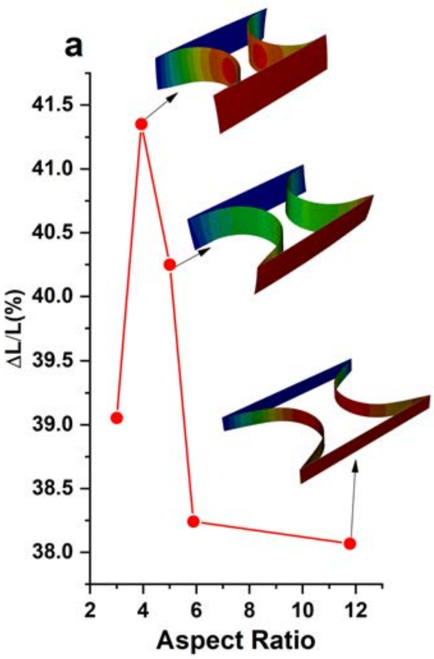

Figure 7: (a) Parametric study to depict the percentage change of displacement of the lattice with respect to the length of the bistable element ($\Delta L/L$) with increasing length L. b) Change in snap-through loads from retracted to deployed shape shape with change in the Aspect ratio.

length $L = 0.530$ m. It can be observed that as the width decreases the snap-through load also decreases. At an aspect ratio of 11, the plate snaps with a low snap-through load (1 kN), and thus is barely bistable.

After carrying out all the preceding analyses, we have selected four prospective designs of bistable plates with varying width and length, that could be used as a component of the proposed metastructure. The four models are given in Table 2. The load-displacement curve of unit cells made for these four different bistable plates is given in Fig. 8. The curve depicts how the unit cell transforms from its retracted configuration to deployed configuration.

It can be observed from the Table that Model III has 52.4% more resultant displacement at 74.7% higher snap-through force including higher length and breadth compared with Model

Table 2: The table shows four different models with different length and width, the snap-through load to transform from retracted to deployed configuration and the maximum out-of-plane displacement in the retracted configuration.

Models	Breadth (m)	Length(m)	Snap-through (N)	Max. Out-of-plane Displacement (m)
I	0.135	0.53	26.8	0.22
II	0.106	0.53	19.11	0.21
III	0.168	0.672	33.39	0.32
IV	0.135	0.672	25.93	0.34

II while Model I require more than 40.24% of snap-through force at approximately the same resultant displacement compared with Model II. Model IV is showing 5.88% less resultant displacement at 28.77% more snap-through force compared with model IV. Therefore, by suitably changing the length and width of the bistable plate, a desired design can be reached.

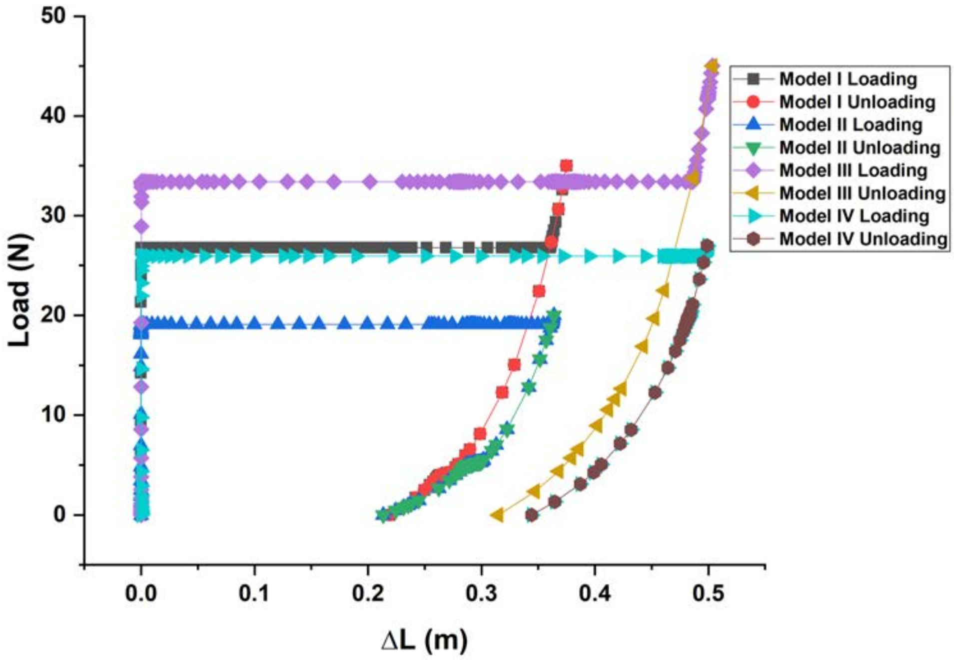

Figure 8: Load displacement curve for transforming the unit cell from deployed to retracted configuration, plotted for four test cases given in Table 2.

5 CONCLUSIONS

A shape-adaptive metamaterial with two stable configurations has been developed and analyzed at two hierarchical structural levels: α and β. Investigations on each levels were conducted out separately in a FEA package, which reveals that each component of the metamaterial is stable in both configurations without the need for any holding forces. At the α level, a multi-sectioned laminate was analysed comprising a piece-wise orientation of fibre layup that demonstrates two stable configurations: straight and curved. Both states have straight edges, enabling easy integration into a larger adaptive structure without external stressing. This stable state, along with residual stress is incorporated from the α level to the unit cell β level, which consists of two bistable and monostable laminates. A parametric analysis to optimise the dimensions of the bistable plate and thus the size of the unit cell is carried out. By placing bistable elements of different dimensions, target stable shapes of the metamaterials were achieved, thus tailoring the adaptive nature of the metastructure. Furthermore, by suitably designing the monostable element the metastructure can be designed to be load-carrying in one direction and flexible in the other.

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