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3D-printed highly stretchable curvy sandwich metamaterials with superior fracture resistance and energy absorption

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ABSTRACT

This paper focuses on the potential of curvy mechanical metamaterials to show how topological design can significantly enhance fracture toughness along the in-plane and out-of-plane (through-depth) directions. The conventional re-entrant unit cell is first reformulated by introducing local curvy ligaments and then additively manufactured by three-dimensional (3D) printing to form a center/edge-notch lattice metamaterial. The new conceptual design provides multi-stiffness unit cells, helping to control stress distribution within a structure under tensile load, specifically in the vicinity of the notches where stress concentrations occur. In other words, curvy unit cells are capable of arresting and blunting the notch under tensile loads and toughening the metamaterials. The crack tip opening displacement (CTOD) method calculates the fracture toughness. Not only can the fracture of lattice metamaterials be controlled along the in-plane direction by replacing unit cells in the sensitive parts of the metamaterials, but a new assembly method is also proposed. This offers that different thin plates of metamaterials with different layouts can be sandwiched to control out-of-plane fracture propagation (through-depth propagation of opening mode fracture) for the first time in fracture mechanics. This novel sandwiching method offers a multi-step fracture and significantly improves the fracture behavior of the lattice metamaterials from brittle to ductile by taking advantage of multiple through-thickness thin plates instead of considering one thick specimen. A detailed analysis of the effects of the ligament curvature value on the fracture behavior is presented. The results reveal that the more curvature, the more extension (ductility) will be realized, but too large curvature design can provide lower energy absorption capacity.

1. Introduction

Fracture mechanics is a branch of materials science that deals with the behavior of structures when subjected to external forces that can cause them to break (Anderson, 2017). It involves the study of how cracks and defects in a material lead to catastrophic failure, and how this failure can be prevented or controlled. Fracture mechanics is used in a wide range of industries, including aerospace, automotive, construction, and manufacturing. It is particularly important in the design and maintenance of critical structures such as bridges, aircraft, and nuclear power plants, where failure could have catastrophic consequences (Anderson, 2017). The importance of fracture mechanics lies in its ability to predict the behavior of materials and structures under different loading conditions, and to design safer and more reliable structures. It allows engineers to assess the safety and reliability of existing structures and to design new structures that can withstand extreme loads and conditions.

From the solid mechanics point of view, artificially designed lattice structures, so-called mechanical metamaterials (Luan et al., 2022) could be considered for fracture mechanics applications due to providing different stress states within a structure under mechanical loads. The mechanical properties of a lattice metamaterial are heavily dependent on the geometry of its fundamental elements, so-called unit cell, compared to the parent material used for fabrication. Mechanical metamaterials are also divided into several groups depending on their mechanical properties, including positive, zero, and negative Poisson's ratio lattices (Hu et al., 2023; Hamzehei, 2022; Hamzehei, 2018). Meanwhile, some lattices show negative stiffness (Pan et al., 2023) and multi-stiffness (Giorgio et al., 2020; Zolfagharian, 2022) behavior due to their unique designs. In terms of shapes, the lattice metamaterials can be seen in the form of two-dimensional (2D) plates (Rezaei, 2021), cubic (Hamzehei, 2022), and cylindrical forms (Mansoori et al., 2022;

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Hamzehei, 2023; Hamzehei, 2020).

Due to the capability of lattice metamaterials to provide different stress states under mechanical loads, many scholars have been investigating the role of nano, micro, and macro metamaterials in controlling and engineering crack propagation in a structure. In this regard, Maurizi (2022) investigated the fracture toughness of the Octet and Kagome lattice metamaterials in the nanoscale. Their results showed stable crack growth and crack resistance behavior during tensile loads. Shaikeea and Dipanka (2022) expanded upon the concepts of elastic fracture mechanics to include truss-based metamaterials and devised a universal approach for testing and designing such materials. Their framework can serve as the foundation for evaluating fractures in other types of discrete elastic-brittle materials, where the concept of fracture toughness is known to be ineffective.

In the macro scale, Manno et al. (2019) designed hybrid honeycomb metamaterials consisting of sparse and dense parts. Their hybrid design provided different stress distributions within the structure, resulting in engineering crack propagation due to the variability in stress distributions. Shu (2022) designed multi-thickness honeycomb metamaterial for engineering crack propagation and more fracture toughness. Their results showed that the differences in wall thicknesses led to different stiffnesses within a structure, resulting in engineering crack propagation. White et al. (2023) showed how interpenetrating brittle sublattices can provide ductile behavior under tensile loads. Choukir and Singh (2023) compared the fracture behavior of triply minimal surface (TPMS), strut-based, and plate-based metamaterials together. Their results showed that plate-based metamaterials exhibit the highest toughness compared to the other lattices. Gao (2020) proposed that the optical programming method via digital light processing (DLP) can engineer crack propagation.

When it comes to designing multi-stiffness lattice structures for crack propagation control, the concept of curvy lattice metamaterials is worth investigating. In this regard, the impact of strut waviness on the tensile behaviour of the honeycomb and triangular lattice structures was evaluated by Seiler et al. (2021). The research showed greater strut waviness significantly boosts the ductility of both lattice types, with a relatively modest impact on their peak tensile strength. In addition, Li et al. (2021) proposed a method of enhancing the overall strength and ductility of honeycomb and triangular lattices, showing positive Poisson's ratio behavior, with a stress-concentrating feature like a notch through the application of localized reinforcement. They showed that through the appropriate selection of the amplitude and dimensions of a wavy domain relative to the notch length, it becomes feasible to enhance both the strength and ductility considerably in the case of a hexagonal lattice, although this improvement is not achievable for a triangular lattice.

In addition, printing some pantographic sheets, uses deformable pivots and the simultaneous arrangement of the underlying structure establishes a hierarchy of resistance, allowing for a prediction of the locations and progression of crack formation and development (Ciallella, 2022; Spagnuolo, 2017).

In the study of fracture mechanics, it is essential to carefully analyze the concepts of crack arresting, blunting, or even crack deflection due to providing higher toughness and ductile fracture behavior. Researchers in the field of fracture mechanics have been endeavoring to incorporate crack-resistant structures that demonstrate concurrent ductile behavior. Due to the significant effects that mechanical metamaterials can provide on those concepts and fracture toughness, this study shows how an in-plane change in the design of a conventional re-entrant unit cell, replacing the straight ligaments with curved ligaments (curvy unit cells) leading to a highly stretchable behaviour under tensile loads (Khare, 2018), can lead to notch arresting and blunting, and cause a considerable delay in fracture which provides higher toughness. By removing the local unit cells, both center-and edge-notch lattice metamaterials are additively manufactured by 3D printing technology, where Polylactic Acid (PLA) material showing a brittle behavior is used for fabrication.

Table 1
Printing parameters.

Printing parameters	Value
Nozzle diameter	0.4 mm
Nozzle temperature	220 °C
Bed temperature	35 °C
Printing speed	200 $\frac{mm}{s}$
Infill direction	±45°
Infill percentage	100 %

The curvy unit cells can be considered in front of the notch to release stress concentration. Most notably, a new assembly method is proposed for the first time in fracture mechanics, where multiple thin plates can be sandwiched to form the same depth as the main specimen. This leads to a multi-step fracture and changes the fracture behavior from brittle to a ductile one. This novel assembly method would enable scholars to consider different metamaterial designs on separate plates and sandwich them for a specific purpose. For example, one thin plate can provide superior energy absorption capacity, while another can provide flexibility and delay in the final fracture. Consequently, the sandwich lattice metamaterials can provide both considerable toughness and extension under tensile loads.

2. Materials & methods

2.1. Materials

For the fabrication of the samples in this study, the Bambu Lab X1 carbon machine was employed with the following setup, see Table 1.

To reveal the capability of curved-based metamaterial design on fracture toughness, Polylactic Acid (PLA) as a brittle material is used for fabrication. This is important to design and introduce lattice metamaterials to engineer crack propagation using brittle materials. To extract the stress–strain curve of the considered PLA, five dog-bone samples were additively manufactured via 3D- printing technology and tested mechanically under tensile load at a speed of 5 $\frac{mm}{min}$. Fig. 1 shows the 3D printed dog-bone samples and the corresponding stress–-strain curves. From Fig. 1 c, it is apparent that the PLA material shows a linear behavior until yield stress, and a small plastic region before fracture, which approves the brittleness of the PLA material. Furthermore, it is observed that all five samples result in similar stress–strain curves.

2.2. Metamaterial design

This study considers the conventional re-entrant lattice metamaterials, then the straight ligaments are replaced with curvy ligaments. Fig. 2 shows the base structures used in this study, called "model-A", "model-B", and "model-C". Notches are added by removing the local unit cells to simulate the critical locations of an engineering structure with stress/strain concentration during operation. It is worth mentioning that the notches are considered in a symmetric position within the lattice structures. Figs. 3 and 4 show the edge and center-notch lattice structures. The red-dashed ellipses show the curvy unit cells, so-called healing areas, in the sensitive/critical parts of the lattice metamaterials. The sensitive parts are those areas with high-stress concentration due to the unit cell removal. To release stress concentration and provide fracture resistance under stretching, two approaches are considered for healing areas. Firstly, the area in front of the notch (notch tip) is confined to the curvy unit cells. Secondly, a whole row of curvy unit cells is considered in front of the notches. Table 2 provides geometrical information on the lattice metamaterials. It is worth mentioning that to have comparable results, the mass of all edge-notch and center-notched specimens are considered constant at 35 g and 32 g respectively, through variable wall thicknesses. For controlling out-of-

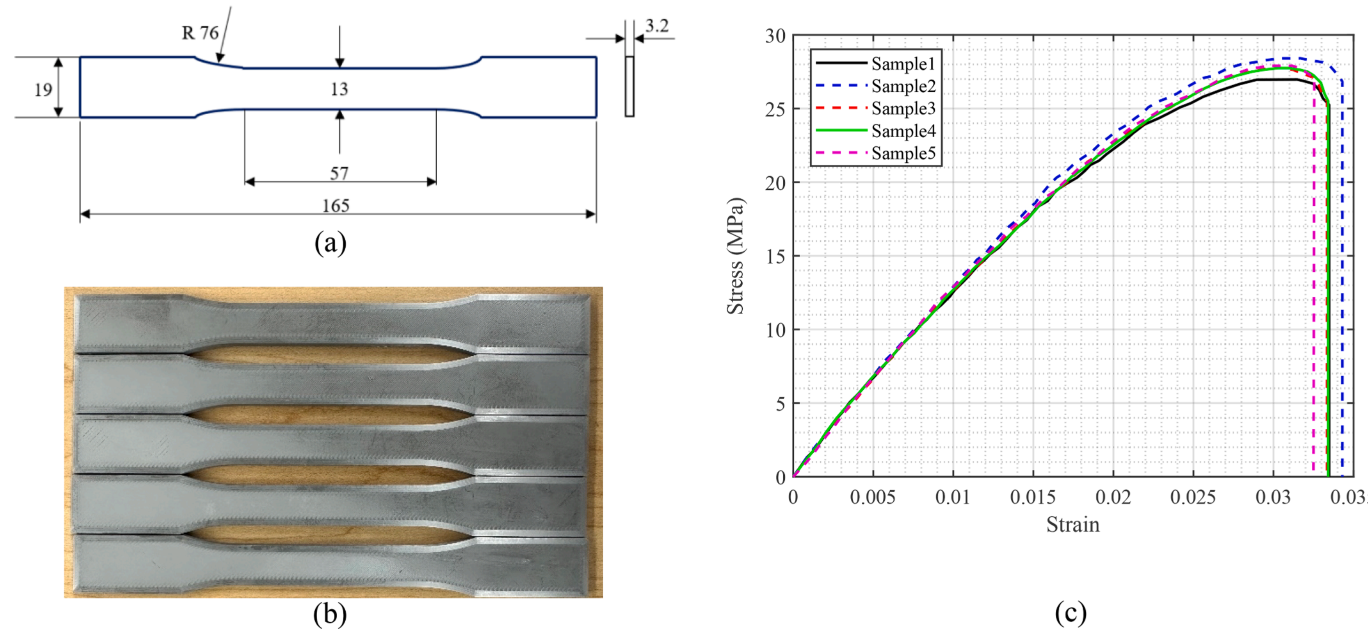


Fig. 1. (a) Schematic of the ASTM D638-14, (b) 3D-printed samples, and (c) corresponding stress–strain curves.

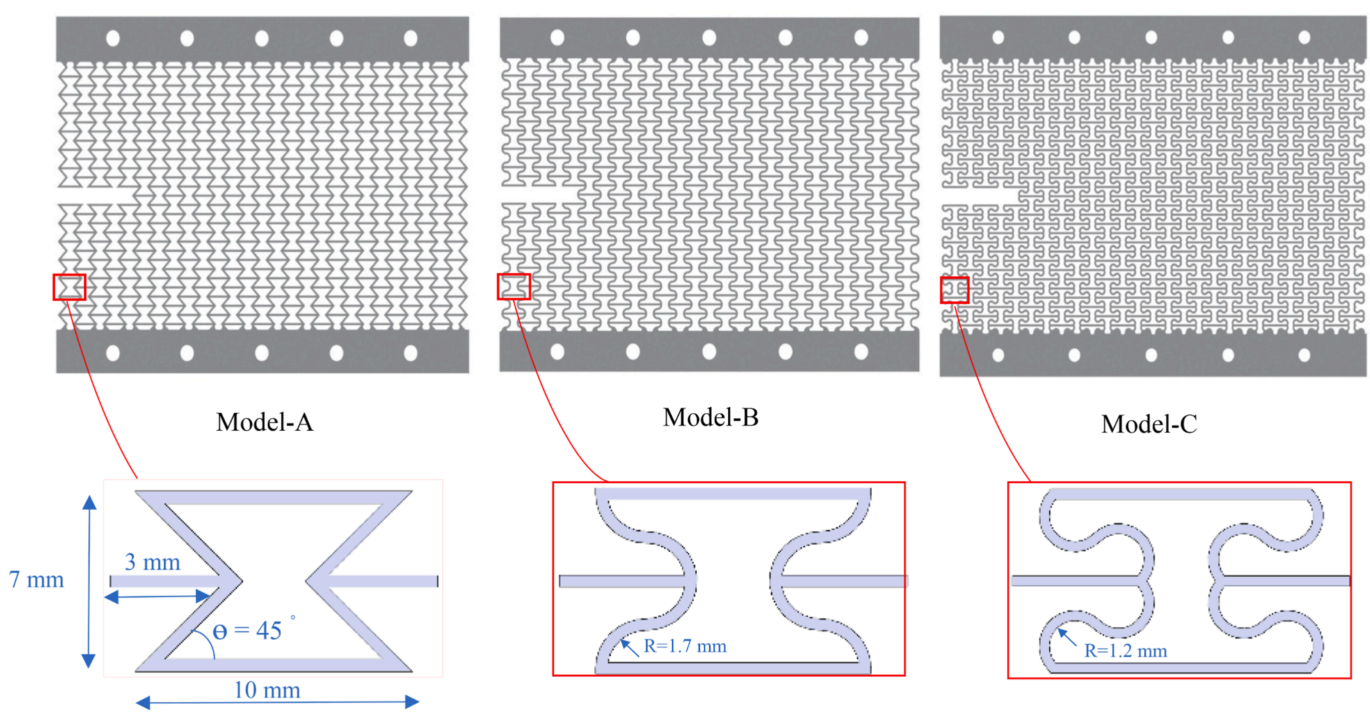


Fig. 2. Base lattice structures with the corresponding unit cells.

plane fracture propagation (through depth opening mode fracture propagation), a novel sandwich design by attaching three thin plates with the same dimensions, as the main specimen, but with a depth of 0.65 mm is proposed, see Fig. 5. Plates with different designs can be combined to study their interaction mechanism.

2.3. Experimental set-up

Tensile tests were carried out by the MTS universal machine at a constant speed of 5 $\frac{mm}{min}$ with a 50kN load cell, see Fig. 6. The lattice metamaterials are fixed between two fixtures, and a digital camera was placed in a fixed position to capture deformation patterns during the experiments.

2.4. Fracture toughness calculation

This study calculates the elastic and plastic components of the fracture toughness, “J_e” and “J_P”, respectively due to the non-linear elastic–plastic behavior that lattice structures show (the fracture behavior of the lattice metamaterials will be discussed in the next sections). Plane stress condition is considered due to the geometrical conditions of the specimens. Due to the geometrical conditions of the specimens

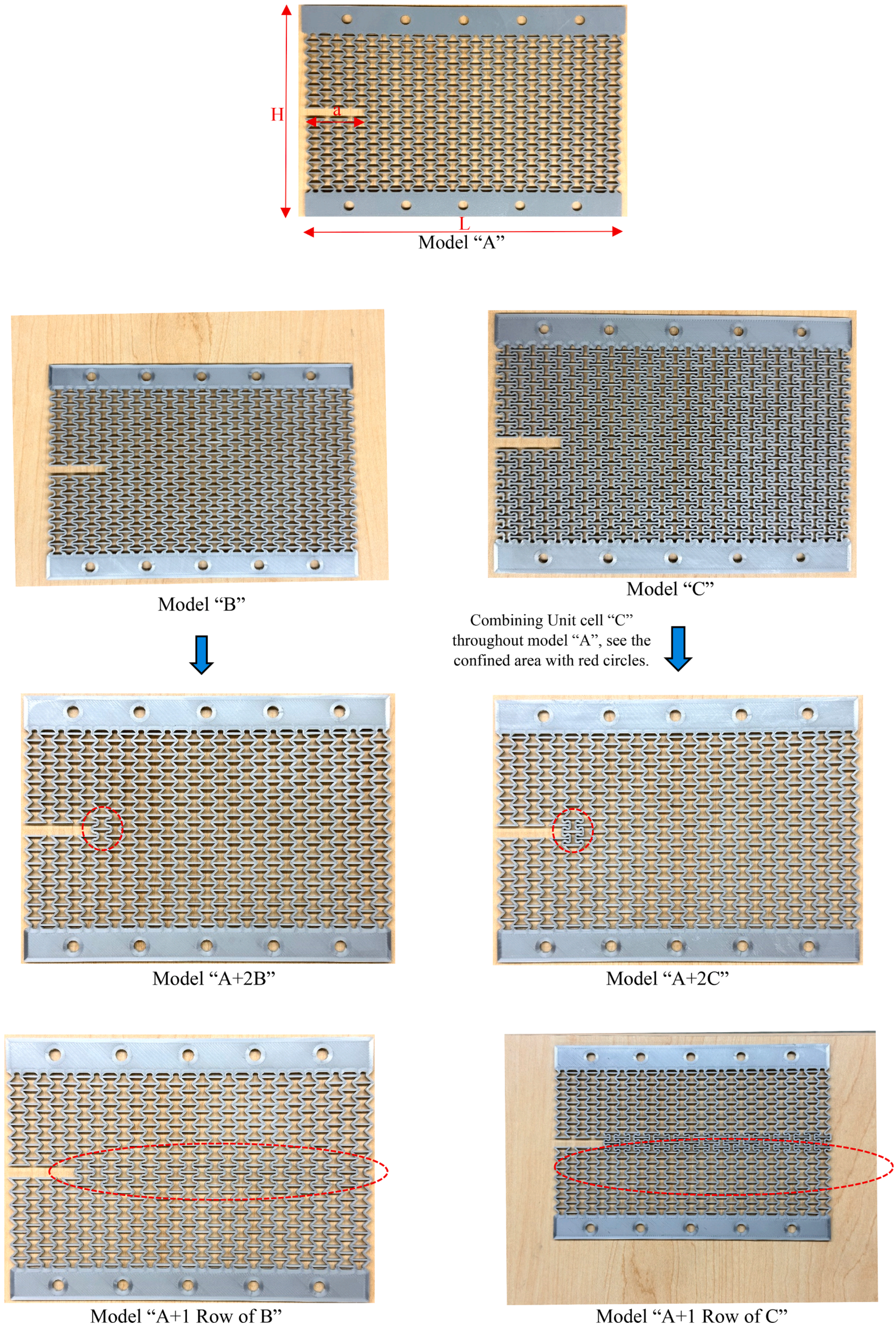


Fig. 3. 3D-printed edge-notch metamaterials.

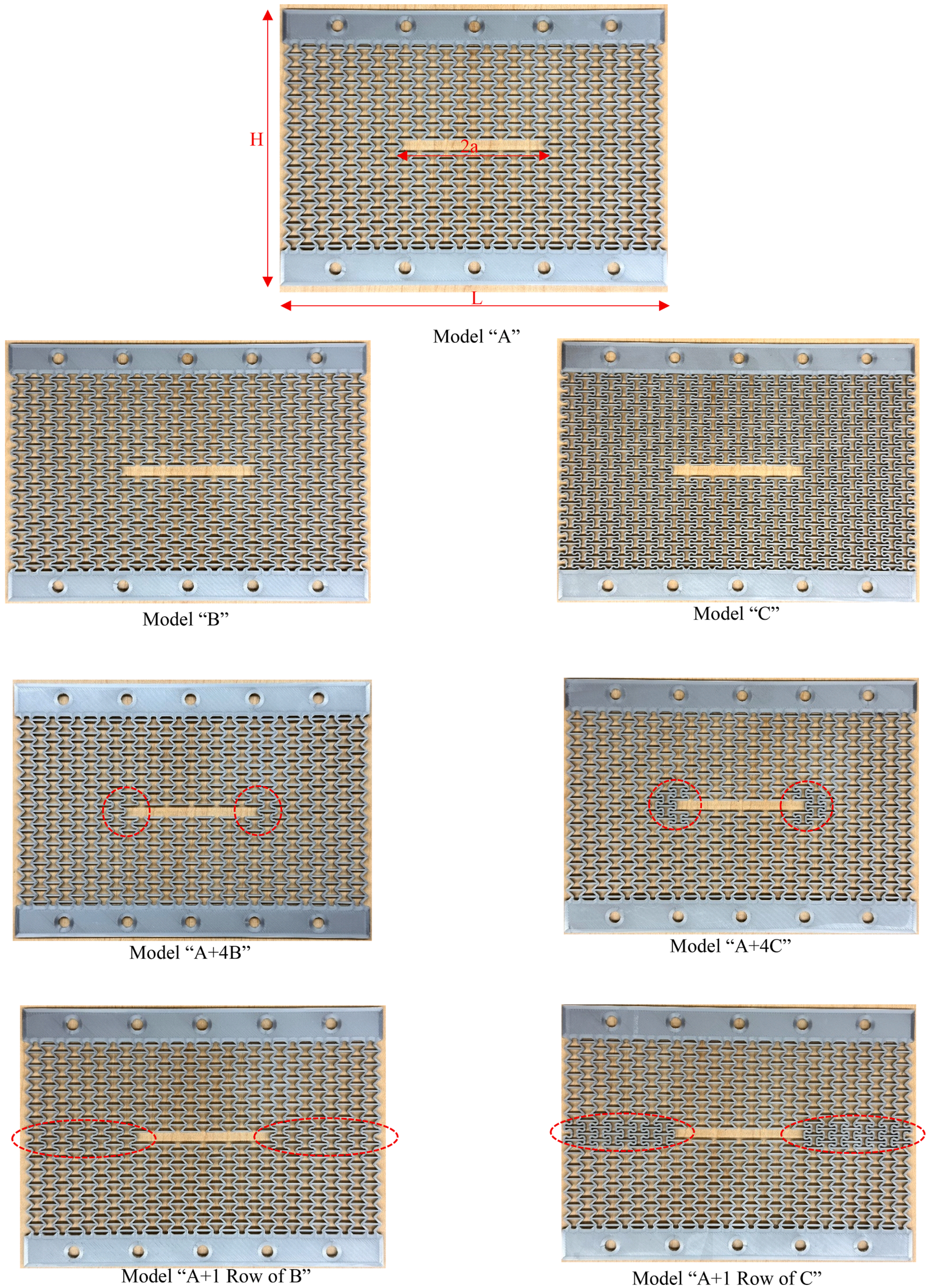


Fig. 4. 3D-printed center-notch metamaterials.

Table 2
Geometrical information of the lattice metamaterials*.

Parameter (mm) Structure	*Notch length*	*Wall thickness*	*Wall thickness (Healing part)*
Model A (Edge notch)	*35*	*0.9*	
Model A (center notch)	*70*		
Model B (Edge notch)	*35*	*0.8*	
Model B (center notch)	*70*		*0*
Model C (Edge notch)	*35*	*0.7*	
Model C (center notch)	*70*		
ModelA + 2B	*35*		*0.8*
ModelA + 2C			*0.7*
ModelA + 4B	*70*		*0.8*
ModelA + 4C		*0.9*	*0.7*
Model A + 1 Row of B (Edge notch)	*35*		*0.8*
Model A + 1 Row of B (Center notch)			
Model A + 1 Row of C (Edge notch)			
Model A + 1 Row of C (Center notch)	*70*		*0.7*

* The length (L), height (H), and depth of all samples are considered constant at 180 mm × 130 mm × 2 mm.

(symmetrical patterns), the fundamental fracture mechanics formula is considered (Gu et al., 2019; Gu et al., 2018; Fulco et al., 2022; Hsieh et al., 2020). The linear elastic fracture toughness can be calculated from Eq. (1),

$$K_I = \frac{P_i}{B\sqrt{W}} f\left(\frac{a}{W}\right) \quad (1)$$

where "P_i" denotes the force value on the force–displacement plot at an arbitrary point "i", "B" denotes the depth of the specimen, "W" denotes the width of the specimen, the parameter "a" indicates the notch length, and the factor $f\left(\frac{a}{W}\right)$ is a dimensionless shape factor depending on the notch location and the type of loading on a specimen. The shape factors for the single-edge notched tension (SENT) and center-cracked tension (CCT) are calculated as follows.

According to the formula provided in Table 3 and the geometrical information in Table 2, the $f\left(\frac{a}{W}\right)$ values for the SENT and CCT specimens would be 1.0831 and 0.6215 respectively.

At fracture load, Eq. (1) can provide the fracture toughness of a lattice metamaterial, "K_I" which can be related to "J_e" as provided in Eq. (2), where "E" is the Young's modulus of non-notched lattice structures.

$$J_e = \frac{K_I^2}{E} \quad (2)$$

To calculate the fracture toughness of a lattice metamaterial with an elastic–plastic behavior, the crack tip opening displacement (CTOD) method is used (Zhao, 2022). In this method, the opening displacement of the notches, "δ", is monitored as shown in Fig. 7. The "δ"can be calculated as follows.

$$\delta = \delta_1 - \delta_0 \quad (3)$$

Then, Eq. (4) relates the "δ" and "J", total fracture toughness ($J = J_{e+} J_P$), as follows,

$$\delta = \frac{J}{m\sigma_{ys}} \quad (4)$$

where "m" is a dimensionless constant equal to one for plane stress conditions (Anderson, 2017), and "σ_{ys}" denotes the yield stress of non-notched lattice structures. Table 4 provides information related to Young's modulus and yield strength of non-notched lattice structures.

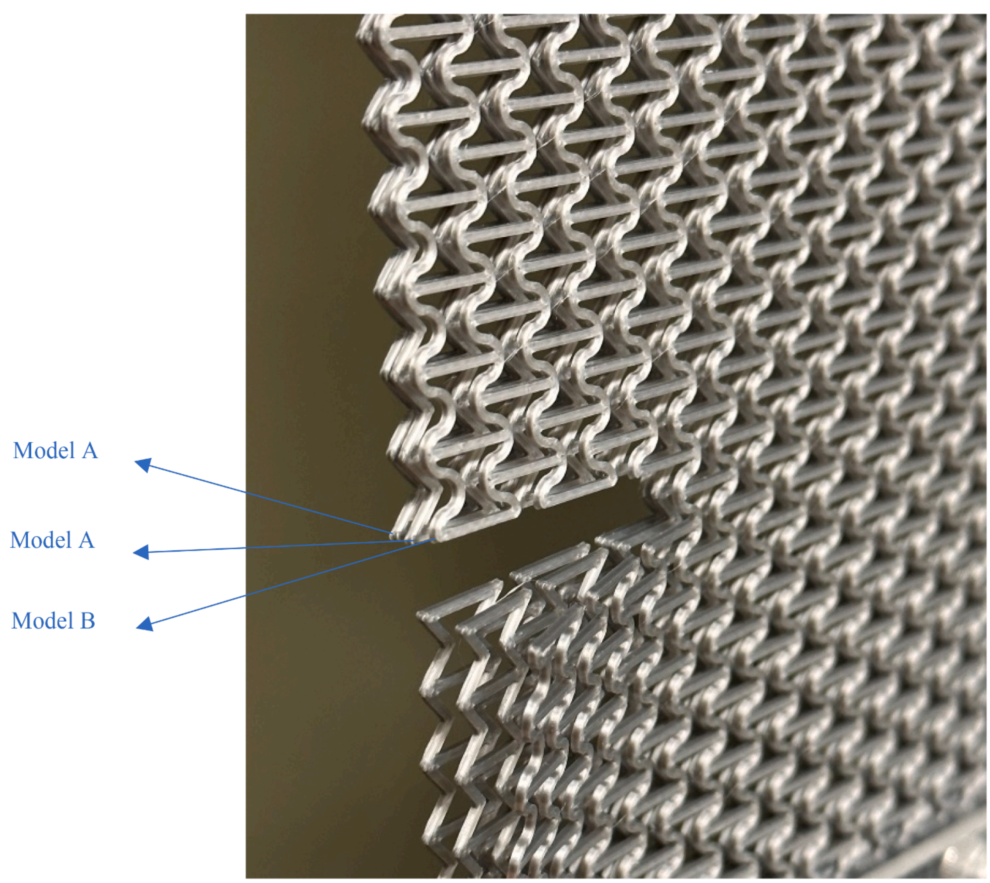


Fig. 5. Sandwich model for controlling out-of-plane (through depth opening mode) fracture.

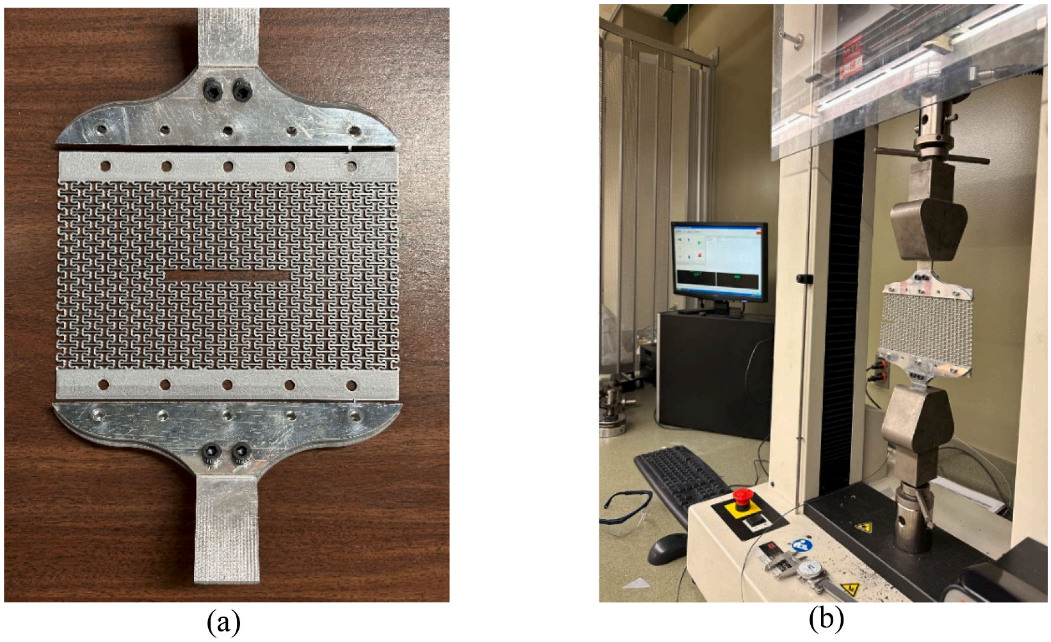
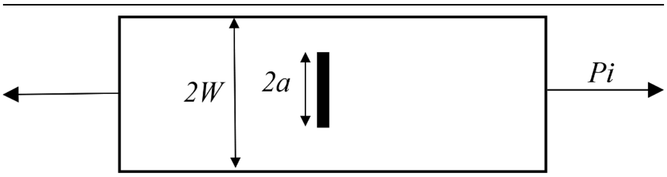
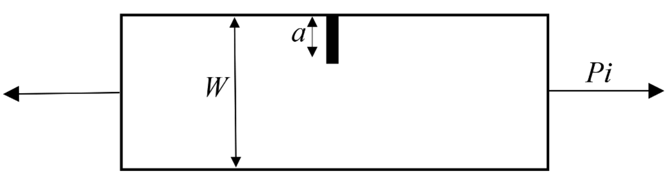


Fig. 6. (a) Tensile sample and the corresponding fixture, (b) the MTS universal machine.

Table 3
The shape factor of the edge and center-cracked specimens under tensile loads.



Since "J" contains both "J_e" and "J_P", then "J_p" can be calculated from Eqs. (2) and (4) as follows.



3. Results & discussion

3.1. In-plane fracture behavior and energy absorption capacity of edge-notch metamaterials

This section investigates the effect of curvy unit cells on the in-plane fracture behavior of lattice metamaterials. First, the homogeneous lattice metamaterials containing the same unit cells, models "A", "B" and "C" are considered. In this regard, Fig. 8 shows the deformation patterns and the corresponding force–displacement relationships under tensile loads. This is obviously seen that the lattice structures show a negative Poisson's ratio behavior, which means that showing an expansion under tensile loads. The conventional lattice metamaterial, model "A", fails at small displacements. However, the curvy lattice metamaterials, models "B", and "C" exhibit more extension (more ductility) and more energy absorption capacity compared to the conventional lattice metamaterial, model "A". The curvy unit cells "B" and "C" in homogenous lattices lead to a reduction in structural stiffness by 54 % and 91 % compared to the unit cell "A". While the elongation increases by up to 320 % and 520 % when it comes to unit cells "B" and "C". In addition, the absorbed energy increases by up to 302 % and 238 % in models "B" and "C" compared to "A", respectively. As stress concentration appears in the notch area under tensile load, the conventional re-entrant unit cells are replaced

Table 4
The Young's modulus and yield strength of the perfect (without notch) specimens.

Structure	E (MPa)	σ_{ys}(MPa)
A	52.87	0.89
B	15.43	0.48
C	4.47	0.3294
A + 2B	52.13	0.89
A + 2C	35.81	0.64
A + 4B	36.08	0.65
A + 4C	31.98	0.5
A + 1 Row of B (Edge notch)	29.66	0.72
A + 1 Row of B (Center notch)	32.25	0.53
A + 1 Row of C (Edge notch)	20.06	0.4623
A + 1 Row of C (Center notch)	28.55	0.4079

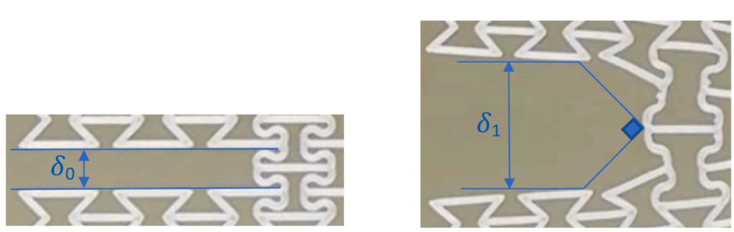


Fig. 7. CTOD method for the measurement of the displacement of notch under tensile loads.

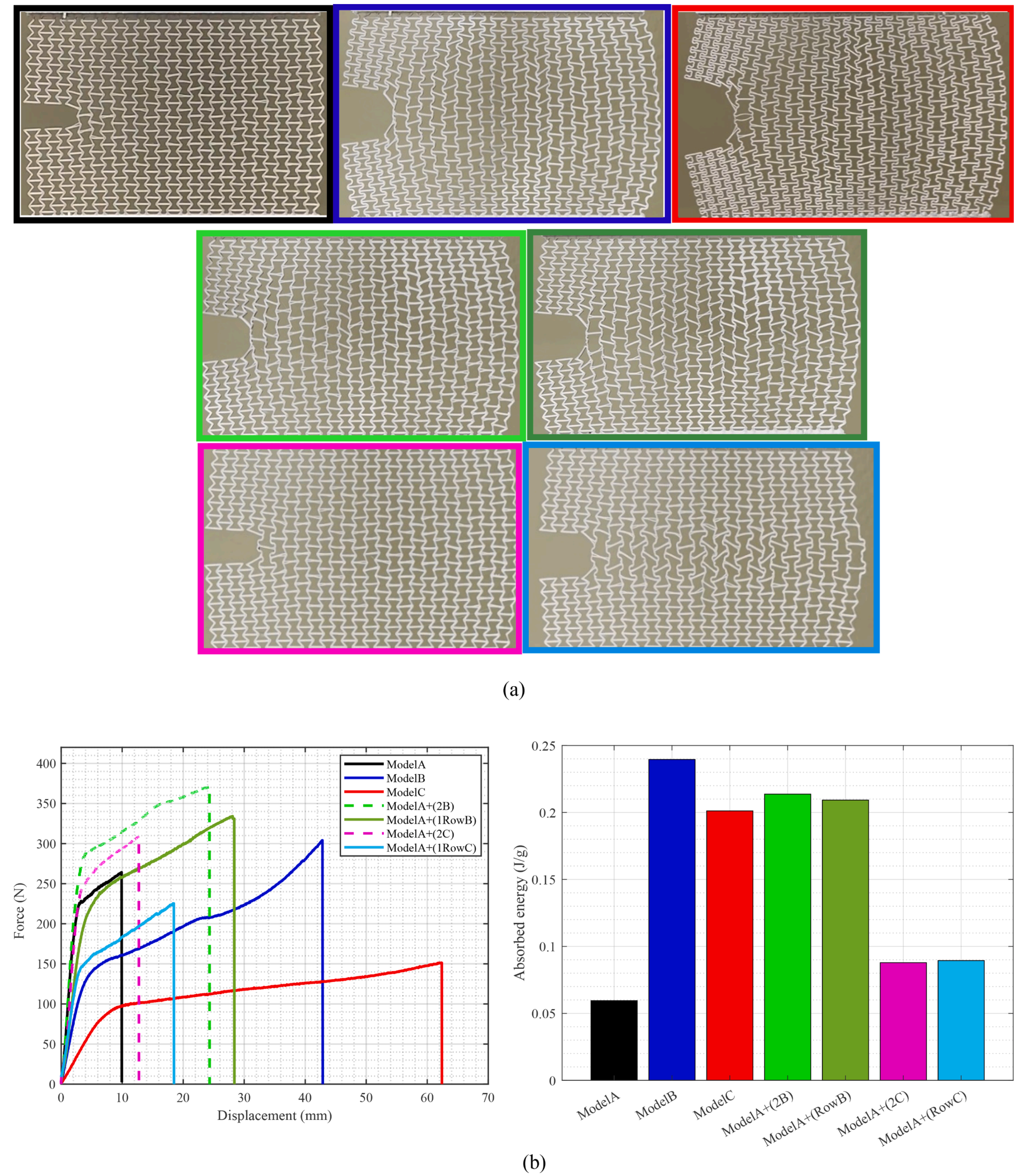


Fig. 8. Edge-notched metamaterials (a) deformation patterns prior to fracture, (b) force–displacement relations and energy absorption capacities.

with curvy unit cells based on the two approaches explained in Sec.2.2. The significant effect of healing areas on the notch arresting and blunting due to the arrangement of curvy unit cells can be seen in Fig. 8. It is observed that the model "A + 2B", "A + 2C", "A + 1 row of B" and "A + 1 row of C" exhibit more extension compared to model "A", resulting in more fracture resistance under tensile loads. The absorbed energy in models "A + 2B" and "1 row of B" increases by up to 259 % and 251 % compared to model "A", respectively. This means that the curvy unit cells are capable of arresting and blunting notch and provide a considerable delay in final failure. The reason for the considerable delay in the fracture is caused by the differences in structural stiffness. Due to the curved designs of unit cells "B" and "C", they show lower stiffness

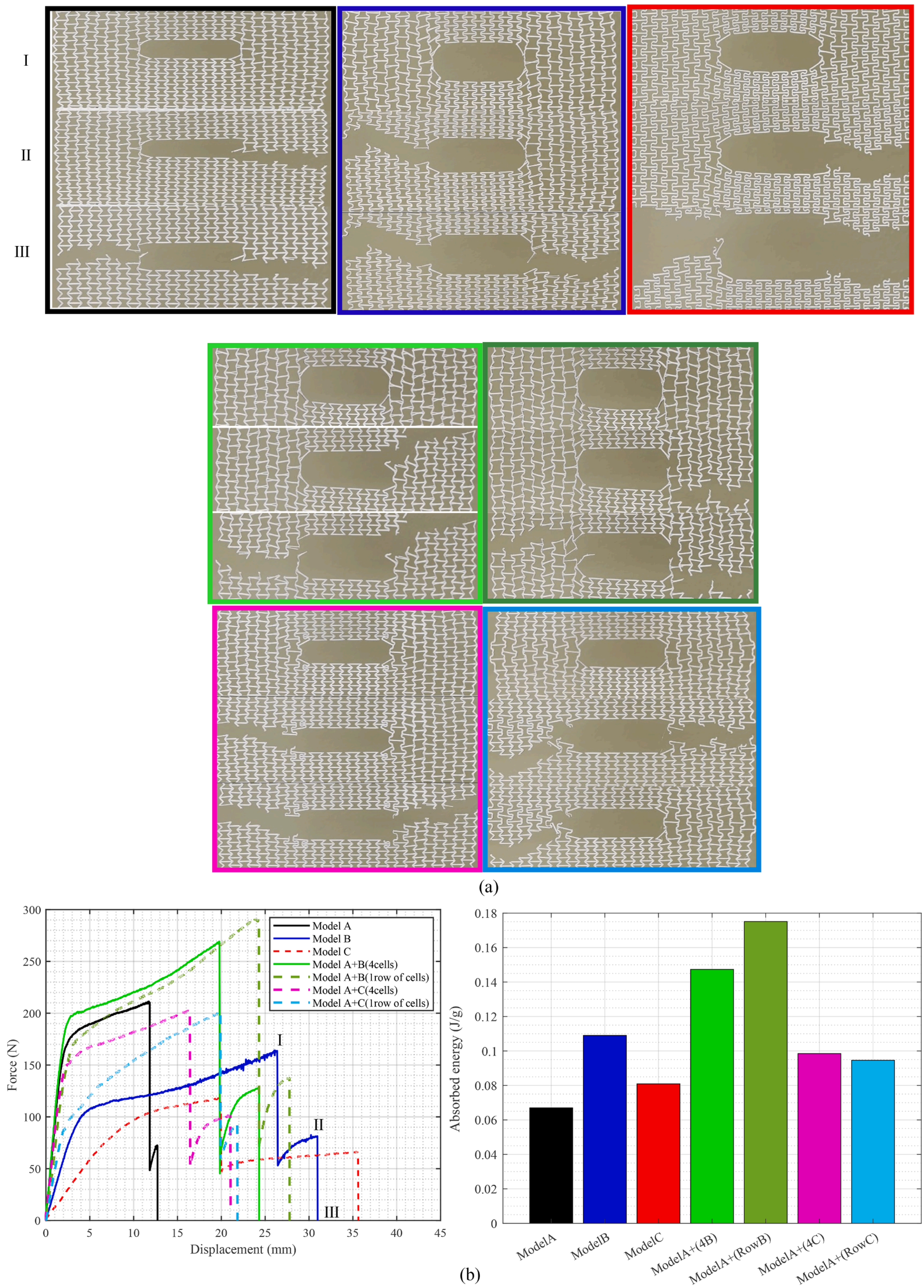


Fig. 9. Center-notched metamaterials (a) deformation patterns prior to fracture, (b) force–displacement relations and energy absorption capacities.

Table 5
Edge-notch metamaterials fracture toughness.

Structure	$P_{Critical}$ (N)	K_{IC} (MPa $\sqrt{m}$)	δ (mm)	J ($\frac{KJ}{m^2}$)
Model A	264	0.2858	9	8.01
Model B	303	0.328	43	20.64
Model C	151	0.1634	59	19.43
ModelA + 2B	370	0.4	22	19.58
ModelA + 2C	309	0.3345	11	7.04
Model A + 1 Row of B	334	0.3615	26	18.72
Model A + 1 Row of C	225	0.2435	17	7.8591

Table 6
Center-notch metamaterials fracture toughness*.

Structure	$P_{Critical}$ (N)	K_{IC} (MPa $\sqrt{m}$)	δ_1 (mm)	δ_2 (mm)	J ($\frac{KJ}{m^2}$)
Model A	211	0.5629	11	1.5	11.12
Model B	163	0.4348	25.5	4	14.16
Model C	118	0.3148	18	14	10.54
ModelA + 4B	269	0.7176	17	4	13.65
ModelA + 4C	202	0.5389	14	4	9
Model A + 1 Row of B	290	0.7736	23.5	4	14.57
Model A + 1 Row of C	201	0.5362	19	3	8.97

* $\delta 1$ and $\delta 2$ are related to the notch displacement at the first and second failures. This means: $\delta = \delta 1 + \delta 2$.

compared to unit cell “A”. Therefore, when a tensile load is applied, the low-stiffness parts tolerate the tensile loads first. After the extension of low-stiffness unit cells, the rest part of the lattice metamaterial containing unit cell “A” tolerates the tensile loads. For “B”, we can have full extension struts with straight shapes holding the load at large deformation, while for “C”, it is still curved under large deformation of the whole structure, and the stress must be held/handled by its neighbor high-stiffness design “A” cells leading to earlier failure. It is noted that the very soft and flexible unit cell at the structure critical location will not hold the stress concentration well, but transfer it to its neighbor rigid cells at large deformation. Too large curvature of the curvy unit cell with very low stiffness compared to its neighbour cells (or stiffness distribution singularity) is not good for fracture control and release. The larger extension of models “A + 1Row of B” and “A + 1Row of C” compared to models “A + 2B” and “A + 2C” is related to the uniform deformation mechanisms that occurred in curvy unit cells under tensile loads.

3.2. In-plane fracture behavior of center-notch metamaterials

This section investigates the same procedure as explained in the previous section, but for the center-cracked metamaterials. As expected, Fig. 9 shows the capability of curvy metamaterials to provide the simultaneous high extension and energy absorption capacity for the lattice metamaterials. The curvy lattice metamaterials, models “B”, and “C” exhibit more extension and more energy absorption capacity compared to the conventional lattice metamaterial, model “A”. The curvy unit cells “B” and “C” in homogenous lattices lead to a reduction in structural stiffness by 67.6 % and 86.7 % compared to the unit cell “A”. While the elongation increases by up to 144 % and 180 % when it comes to unit cells “B” and “C”. The absorbed energy in model “B” increases by up to 62 % compared to model “A”. Besides, the absorbed energy in model “A + 1row of B” increases by up to 161 % compared to model “A”, showing the significant effects of the healing areas. Two fractures occur in center-notch metamaterials during tensile loads, following stages I, II, and III on the force–displacement plot, see Fig. 9.

It is worth mentioning that the reasons related to a sooner failure of unit cells “C” compared to “B” are the same as those reasons explained in Sec.3.1. Tables 5 and 6 provide information on the fracture toughness of edge-notch and center-notch lattice metamaterials respectively, exhibiting the significant effect of the healing areas (unit cell “B”-based modified models) on fracture toughness. It is noted that with the symmetric layout of the center-notch structures, the unit cells above and under the notch do not tolerate mechanical loads. This could lead to different structural responses and phenomena compared with the edge-notch structures as studied in the previous section.

3.3. Out-of-plane (through-depth opening mode fracture) fracture control

This section sheds light on the out-of-plane (through-depth opening mode fracture propagation) control of fracture by consideration of multiple thin plates attached together, see Fig. 5. This novel sandwich method is proposed for the first time in the field of fracture mechanics. This sandwiching method proposes that it could be better to use multiple thin plates with different layouts instead of using just one thick specimen. Both edge-notch and center-notch metamaterials are considered. Two sandwich designs “A + A + B” and “A + B + A” are considered and compared with the conventional non-sandwich metamaterial design, model “A”. The results show a step-by-step fracture in sandwich designs compared to the one-step fracture occurring in “model A”, see Fig. 10. This means that sandwiching multiple thin plates leads to changing the fracture behavior from brittle to a ductile one. In other words, this sandwiching method presents an idea for the designer to attach multiple thin plates with different designs together containing multiple mechanical properties. For example, one thin plate can guarantee superior energy absorption capacity. Meanwhile, the other thin plates can provide considerable extension under tensile loads. Herein, the center-notch sandwich metamaterial, model “A + A + B”, shows 48 % higher energy absorption capacity, and edge-notch sandwich metamaterial, model “A + B + A”, shows 179 % higher energy absorption capacity compared to non-sandwich conventional model “A”. The fracture resistance and energy absorption enhancement effects from the multi-layer composite design are more prominent for the edge-notch case.

4. Potential applications and future study

The presented curvy lattice metamaterials in this study showed highly stretchable behavior with low stiffness, see Fig. 8b and 9b. Potential applications for these curvy metamaterials could be considered as artificial skins (biomechanical application) and the skin of shape-morphing airfoils (industrial application). Airfoil morphing refers to the ability of an airfoil (the cross-sectional shape of an aircraft wing) to change its shape and adapt to different flight conditions. In the context of airfoil morphing, flexible and stretchable metamaterials can be used to create adaptive structures that enable the airfoil to change its shape dynamically. By incorporating flexible metamaterials into the wing structure, engineers could design wings that adjust their shape in response to varying aerodynamic conditions, such as different flight speeds or angles of attack. The use of flexible metamaterials for example in airfoil morphing offers several potential advantages. These include:

1- Shape Adaptability: Flexible metamaterials could undergo large, elastic, fracture-resistance controlled deformations, allowing the airfoil to adjust its shape and optimize its aerodynamic performance based on the current flight conditions. This adaptability could improve lifetime, lift, reduce drag, and enhance overall efficiency (Zhilyaev et al., 2022).
2- Lightweight Design: Metamaterials can be engineered to have low densities while maintaining structural integrity. By utilizing lightweight flexible metamaterials with fracture-resistance features, the overall weight of the wing could be reduced, leading to improved fuel efficiency and increased payload capacity.
3- Simplified Mechanisms: Traditional methods of airfoil morphing often require complex mechanisms and actuators. In contrast, flexible metamaterials could provide intrinsic shape-changing

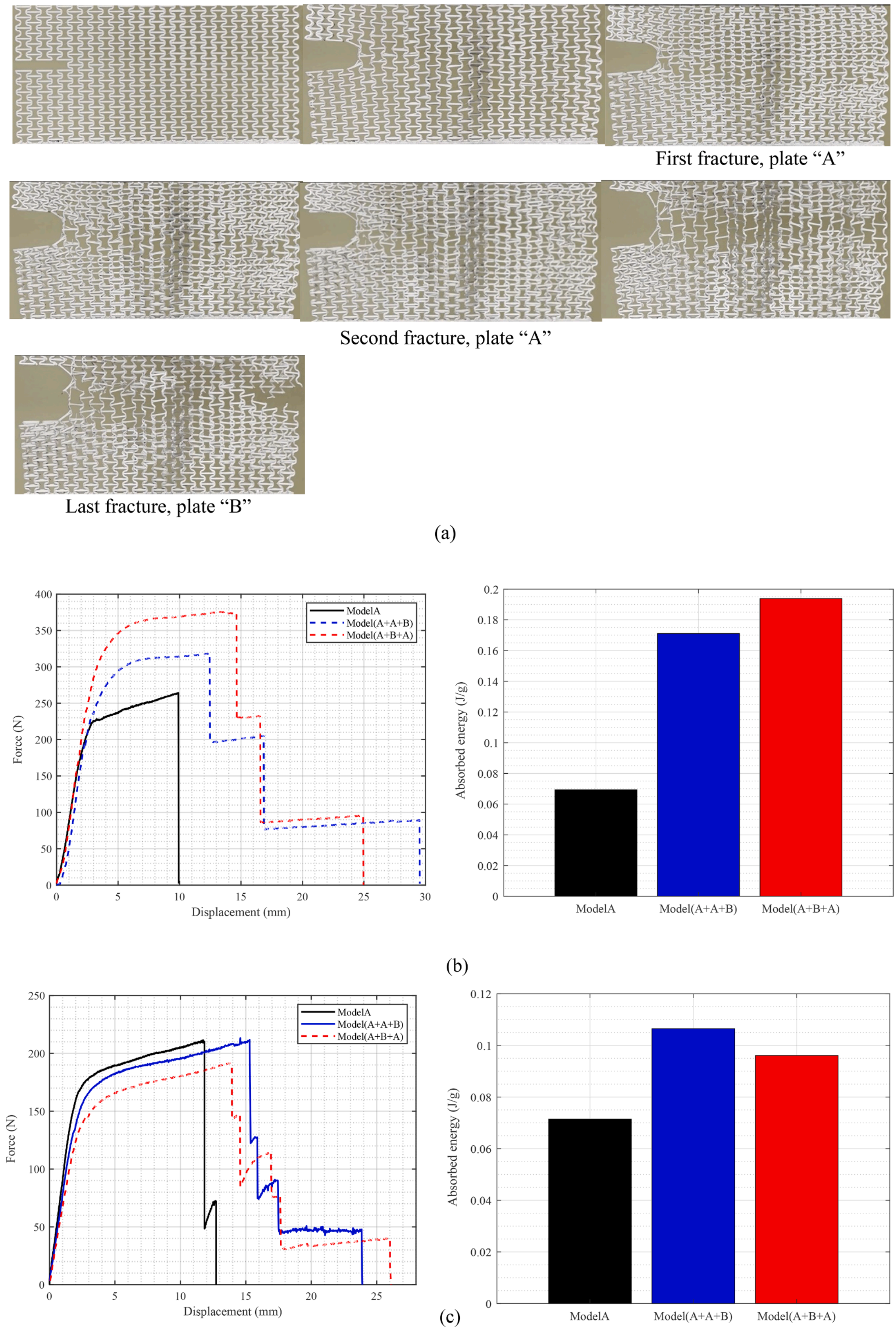


Fig. 10. (a) Step-by-step fracture of edge-notch composite design model “A + A + B”, force–displacement relation of (b) edge-notch, and (c) center-notch metamaterials.

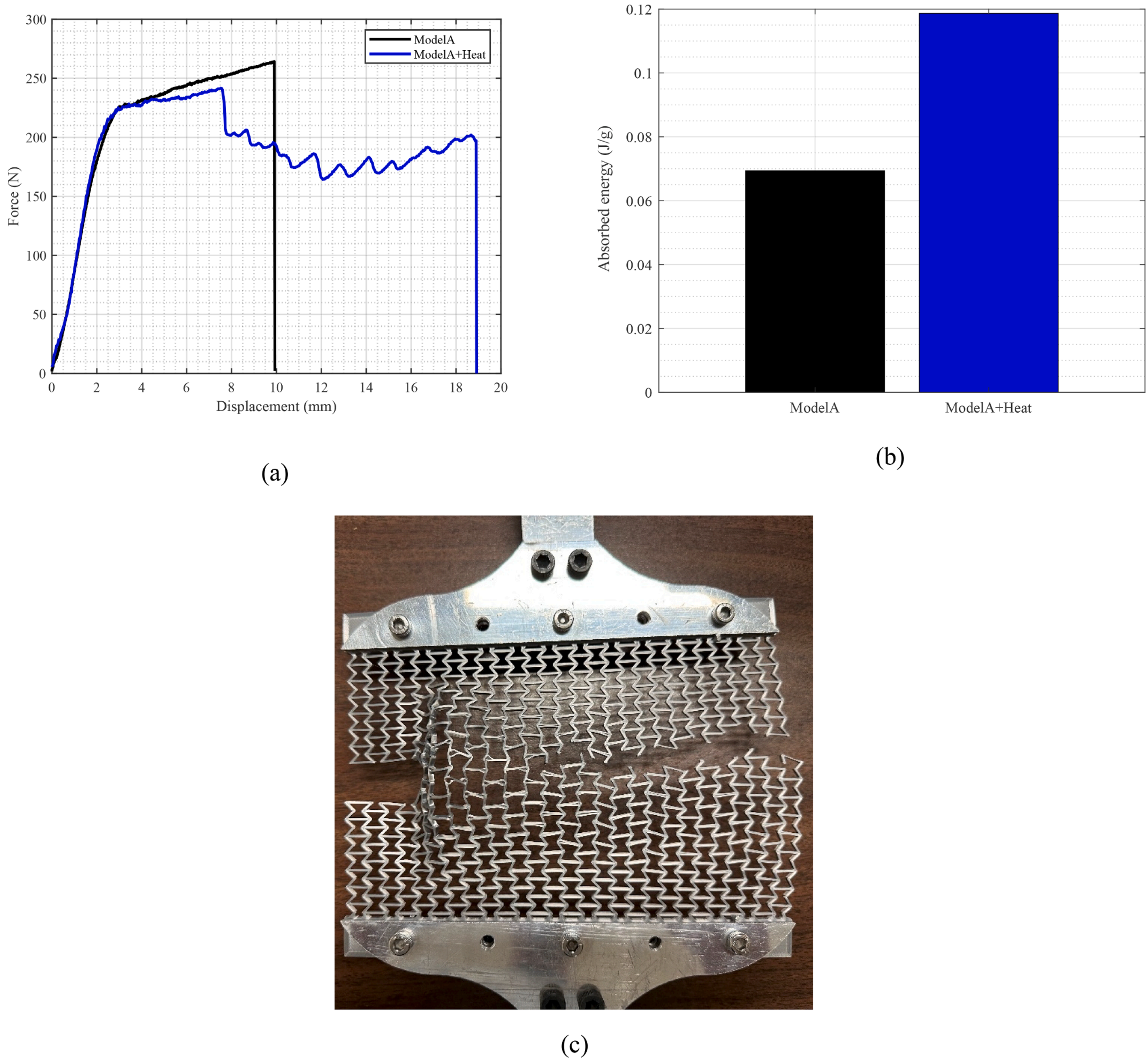


Fig. 11. Heat treatment effect on (a) force–displacement relation, (b) energy absorption, and (c) deformation pattern of an edge-notch lattice structure.

capabilities, eliminating the need for additional moving parts and simplifying the overall system design.

4- Damage Tolerance: Flexible metamaterials could exhibit enhanced damage tolerance compared to traditional materials. Their inherent flexibility allows them to absorb energy and distribute stresses more effectively, making them more resistant to structural failures caused by impacts or other mechanical stresses.

In future studies, it is worth putting efforts into the effect of heat treatment in the stress concentrations areas. Thermal effects can have a significant influence on fracture mechanics, affecting the initiation, propagation, and behavior of fractures in materials. There could be some key points regarding the thermal effect on fracture mechanics. Herein, we have carried out a simple heat treatment in notch areas. A heating flow via a "Black & Decker" heat gun with a 200 °C temperature within 5 s was applied to the notch area. This causes ductile behavior by softening the material, causing more toughness. Take the edge-notch model "A" as an example. Heat treatment in the notch region leads to enhancing energy absorption capacity by up to 75 %, and 90 % of elongation, see Fig. 11a and b. The fracture happened in the without notch area, see Fig. 11c. However, much needs to be done to see what happens from the material science point of view.

5. Conclusion

This paper proposed new thinking about considering curvy metamaterials to provide notch arresting and blunting in fracture mechanics and higher toughness under tensile loads. In-plane and out-of-plane (through-depth opening mode fracture) fracture behavior of lattice metamaterials were evaluated. The key points are summarized as follows.

- The curvy unit cells and their corresponding lattice structures, models "B" and "C", provided a considerable decrease in structural stiffness and more extension (ductility) before failure compared to the conventional lattice design, model "A".

- Curvy unit cell design can help to increase the structure ductility, fracture resistance, and energy absorption capacity during deformation. However, further increasing the curvature can cause a reduction in energy absorption capacity.
- For in-plane notch-based metamaterials, the local unit cells in the vicinity of the notch can be replaced with curvy unit cells, leading to arresting and blunting notch propagation and providing a considerable delay in final failure.
- Due to the simultaneous existence of high and low-stiffness unit cells in a lattice metamaterial, the low-stiffness part of the lattice tolerates mechanical loads first, then the rest part of the lattice containing the high-stiffness unit cell "A" tolerates the mechanical loads. This provided a controllable fracture behavior.
- A new sandwich method was proposed to enhance out-of-plane fracture (through-depth opening mode fracture), where multiple thin lattice metamaterials with different designs and fracture behavior can be sandwiched. This assembly method could change the brittle fracture behavior of a single metamaterial to ductile behavior by considering multiple thin lattices to provide step-by-step fracture.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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